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FUSION ENERGY DIVISION

Annual Progress Report

Period Ending December 31, 1983

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Executive Summary

EXECUTIVE SUMMARY

As a major component of the U.S. national fusion program, the Fusion Program of the Oak Ridge National Laboratory (ORNL) encompasses nearly all aspects of magnetic fusion energy research. The program involves collaboration among staff from ORNL, Union Carbide Corporation Nuclear Division (now contracted to Martin Marietta Energy Systems, Inc.), private industries, universities, and other fusion laboratories. This collaboration enjoyed continuing success in 1983 with the completion of several subprograms and advances in ongoing work.

This report summarizes the information obtained during 1983 and is issued as the *Fusion Energy Division Annual Progress Report*. For completeness, it also includes that part of the ORNL Fusion Program (approximately 15%) which is not located within the Fusion Energy Division (i.e., atomic physics and plasma diagnostics development, plasma-materials interactions research, the environmental assessment program, radiation materials testing, and neutron transport research).

The Fusion Program carries out work in a number of areas:

- experimental and theoretical research on two magnetic confinement concepts—the ELMO Bumpy Torus (EBT) and the tokamak,
- theoretical and engineering studies on a third concept—the stellarator,
- engineering and physics of present-generation fusion devices,
- development and testing of diagnostic tools and techniques,
- development and testing of materials for fusion devices,
- development and testing of the essential technologies for heating and fueling fusion plasmas,
- development and testing of the superconducting magnets that will be needed to confine these plasmas,
- design of future devices,
- assessment of the environmental impact of fusion energy, and
- assembly and distribution to the fusion community of data bases on atomic physics and radiation effects.

The interactions between these activities and their integration into a unified program are major factors in the success of the individual activities, and the ORNL Fusion Program strives to maintain a balance among these activities that will lead to continued growth.

EBT Research and Development

Significant changes occurred in the EBT program during 1983, including deferment of the EBT Proof-of-Principle (EBT-P) project in the face of budgetary and performance concerns. As a result of this deferral, a program was begun in March 1983 based on increasing EBT-Scale (EBT-S) performance, improving EBT physics understanding, and developing EBT configurations with better reactor prospects.

The experimental results from the EBT-S and theoretical efforts showed that significant improvements are unlikely in the $n\tau$ values obtained on EBT-S. However, the reactor improvement program resulted in a new configuration—the ELMO Bumpy Square (EBS)—that provides significant improvement in critical areas.

Toroidal Confinement Experiments

During 1983, studies continued on the Impurity Study Experiment (ISX-B) tokamak of the effects of plasma beta and toroidal plasma rotation on transport. Design and construction planning continued for the "next-step" Advanced Toroidal Facility (ATF) toratron, with more extensive definitions of the ATF program. Collaboration began with the Princeton Plasma Physics Laboratory on the Tokamak Fusion Test Reactor (TFTR) tokamak. This collaboration will reach its peak in 1985 while ISX-B is being dismantled to make way for the ATF.

Atomic Physics and Plasma Diagnostics Development

The Atomic Physics and Plasma Diagnostics Development program, which is supported by the Fusion Energy Division in the ORNL Physics Division, has focused on inelastic collisions of multiply charged ions with both electrons and neutral atoms in its experimental atomic collisions research, while the focus of its plasma diagnostics development work has been on optically pumped, continuous wave, far-infrared laser systems.

Significant progress in understanding electron-impact ionization of ions and the important role of indirect ionization mechanisms has been made in collision research, and the plasma diagnostics program has produced improved lasers and detection systems in pursuit of a viable multichannel Faraday rotation diagnostic.

Plasma Theory

The Plasma Theory Section searches for superior forms of both helical systems and bumpy tori—a search that this year netted new theories, models, and codes beyond the previous state of the art. With the goal of discovering more advanced configurations and improved methods to control plasma behavior in the tokamak, stellarator, and bumpy torus, this section pursued three major concerns:

- The development of equilibrium and stability codes proceeded under the impetus of the stellarator design effort with important applications to bumpy tori and to tokamaks with imperfect toroidal symmetry.
- The theoretical demonstration of critical roles played by the ambipolar electric fields in the confinement showed (1) more symmetric equipotential surfaces would provide great improvement in particle lifetime, (2) balanced radial particle flows predict long energy confinement time, and (3) the toroidal momentum appears to be related to enhanced electron transport.
- Improvement of the confinement concepts available for experimentation resulted in superior forms for both ATF and EBS.

Plasma-Materials Interactions

The Plasma-Materials Interactions program this past year emphasized (1) limiter and divertor erosion studies in ISX-B and ASDEX, (2) edge-characterization and wall-conditioning experiments in TEXTOR and the Joint European Torus (JET), (3) particle control with pump limiters in ISX-B, (4) advanced gettering development, and (5) graphite erosion studies at high temperatures.

Plasma Technology

Significant achievements were made in several areas by the Plasma Technology group in 1983: extended gyrotron operation; demonstration of long-pulse, continuous wave, high-power ion cyclotron heating (ICH) energy to a reactor-grade plasma; proposal of the ORNL Radio Frequency Test Facility (RFTF) to support concept selection and development of ICH launchers for tokamak reactors (DIII-D, TFTR, and TFCX); development of several candidate antenna configurations—including "cavity" and "ridge-loaded waveguide" concepts; pellet-fueling tests of the Advanced Mechanical Injector (AMI) and Advanced Pneumatic Injector (API) with whole-pellet transmission reliability greater than 70% (with the API achieving record pellet velocities in both the single-shot and steady-state modes); and incorporation of new accelerator designs into the surface ionization transverse extraction (SITEX) negative ion source.

Superconducting Magnet Development

Within the Superconducting Magnet Development area, the Large Coil Program (LCP) continued to manage the manufacture of three superconducting magnet coils that will be tested in the Large Coil Test Facility (LCTF). The General Dynamics-Convair coil was delivered last year; the General Electric coil structure reinforcement and assembly was initiated at the Oak Ridge Gaseous Diffusion Plant (ORGP); and the Westinghouse coil manufacturing procedures were completed and coil winding begun.

As Operating Agent for the international Large Coil Task (LCT), ORNL participated in day-to-day planning and execution of work at the LCTF, which met the last major milestone in November on schedule and within the 1981 projected budget.

Work by the Magnetics and Superconductivity Section in 1983 included significant progress in supporting the LCP, testing the conductor for the 12-T coil project, developing an advanced conductor, testing prototype coils for the EBT-P project, and developing coil concepts for the ATF.

Advanced System Studies

The Advanced System Studies activities at ORNL consist of work by the Fusion Engineering Design Center and the Fusion Environmental Assessment Program. In 1983 these activities included work on the preconceptual designs for the Tokamak Fusion Core Experiment (TFCX), an upgrade of the Mirror Fusion Test Facility (MFTF- α +T), the International Tokamak Reactor (INTOR), and the generic environmental impact statement (GEIS) that will be required as fusion technology approaches commercial reality.

Radiation Materials Testing

Development of materials for near-term and commercial fusion reactors is the goal of the Fusion Materials Program at ORNL, with particular emphasis on neutron-irradiation effects arising from deuterium-tritium or deuterium-deuterium reactions. Three major areas of research in the program are Alloy Development for Irradiation Performance (ADIP), Damage Analysis and Fundamental Studies (DAFS), and Insulators and Stabilizers for Superconducting Magnets (ISSM). In the ADIP area, very high fluence tests of the optimum microstructures of candidate materials have begun, having first determined the lifetimes and swelling resistances of stainless steel and prime candidate alloys. Serious embrittlement problems discovered in long-range-ordered alloys have resulted in decreased emphasis on the alloy class. In the ISSM area, studies have been completed of responses of different grades of copper to neutron irradiation with intermediate

anneals in several neutron spectra, showing a strong dependence on sample purity and degree of cold work. Improved measurements will be possible when the National Low-Temperature Neutron Irradiation Facility (NLTNIF) at the ORNL Bulk Shielding Reactor is completed.

Neutron Transport

The Neutron Transport program at ORNL includes both experimental and analytic phases. The experimental program is designed to provide the data needed to verify analytic methods and cross-section data used for fusion reactor neutronics design calculations. Experiments have been carried out to determine neutron and photon transport in typical fusion reactor shield materials and configurations and to determine the effects of penetrations in these shields; other work has been done in nuclear data evaluation and cross-section processing. In addition, the Radiation Shielding Information Center continues to provide a broad range of services to the fusion energy research community.

The diversity of the ORNL Fusion Program is reflected in this report, which summarizes the achievements in many different activities directed toward the common goal of commercial fusion power.

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Chapter 1

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1. EBT RESEARCH AND DEVELOPMENT

Summary of Activities

The past year has been one of significant change for the ELMO Bumpy Torus (EBT) program. Construction on the EBT Proof-of-Principle (EBT-P) project was indefinitely deferred because of budget constraints in the National Magnetic Fusion Program and because of increasing concern for the device's performance. [The magnetic development for the project is being completed to provide coils for the Radio Frequency Test Facility (RFTF).] As a result of these concerns and the conclusion of the Magnetic Fusion Advisory Committee that mainline reactor concepts had caught up with EBTs, a program with three major elements was initiated: (1) to increase EBT-Scale (EBT-S) performance, (2) to improve EBT physics understanding, and (3) to develop EBT configurations with better reactor prospects. An 18-month program focused on these objectives was begun in March 1983.

The parameter improvements effort was based on carrying out "proof-of-principle" experiments at a level that would allow judgment as to which technique would be most successful, while the physics program was based on obtaining data from a number of new and/or improved diagnostics. The results from both activities showed that significant improvements in the $n\tau$ values obtained on EBT-S were unlikely, based on the following reasons. (1) The 28-GHz microwave power used for creating rings and heating the core plasma was found to couple strongly to a localized anisotropic tail. Roughly half of this power is lost out of the tail without coupling to the core. (2) The ambipolar potential surfaces are asymmetric and are therefore inconsistent with good confinement. (3) Ring beta values are not high enough to clearly provide the strong stabilization associated with reversing the gradient of $\oint d\ell/B$.

As a result of the reactor improvement program, a new configuration, the ELMO Bumpy Square (EBS), has been developed that provides a significant improvement in each of the critical areas discussed previously. A modification of the initial and scaled EBT versions (EBT-I/S) to this configuration has been developed that will test these concepts and should provide an order of magnitude improvement in $n\tau$ to about $2 \times 10^{10} \text{ cm}^{-3}\cdot\text{s}$. This configuration, as well as several others that have been analyzed, offers reactor concepts that are two to three times smaller than previous configurations and that have two to three times higher wall loadings.

1.1 EBT-S EXPERIMENT

D. W. Swain

The past year has been marked by a significant increase in our ability to make critical measurements on the EBT plasma. This was brought about by the improvement of old diag-

nostics [e.g., adding radial scanning capability to an improved Thomson scattering system and installing a new computer-controlled heavy ion beam probe (HIBP)] and the installation of new systems (e.g., diagnostic measurements of plasma characteristics in the high-field region, microwave transmission, and absorption). The

data acquisition system was also significantly improved, as were the analysis techniques. In addition, information of a qualitatively different kind was obtained by observing the transient response of the plasma to externally applied changes, such as gas puffing and microwave or ion cyclotron heating (ICH) power modulation.

The results of the improved measurements and new experiments confirmed indications that the energy and particle confinement times were in the range 0.5 to 1 ms for typical EBT-S operation—significantly lower than earlier estimates. The major reason for the change is the determination that there exists a non-Maxwellian electron distribution function in the core plasma for electrons below 500-eV energy. For typical EBT operating conditions (100 kW of microwave power), there is a collisional, isotropic bulk component with a temperature of 70 to 100 eV. A much hotter ($T_e = 300\text{--}400$ eV), collisionless tail also exists. This component is anisotropic and consists primarily of mirror-trapped particles, with a density 10% to 30% of that of the bulk. New theoretical calculations by D. B. Batchelor and G. L. Chen of the Plasma Theory Section (see Chap. 4, Sect. 4.1) indicate that most of the electron cyclotron heating (ECH) power incident on the plasma is absorbed by this hot tail component. Some of the absorbed power is coupled via Coulomb collision to the bulk, while the rest (possibly up to 50% of the total) may be lost via direct losses to the wall due to particles being scattered onto unconfined drift orbits.

In addition to an improved understanding of the core electrons, experiments have been carried out utilizing new methods of plasma heating: high-field ECH (throat launching) and high-power slow- and fast-wave ICH. More work has also been done on ring studies, with an improved hard X-ray system that can determine ring extent in the toroidal direction. These and other experiments are described in the next subsections.

1.1.1 Hard X-ray Measurements of a Hot Electron Ring on EBT-I/S

O. E. Hankins

D. L. Hillis

Formation, heating, and loss processes for an energetic electron ring can be investigated by modulating the ECH power applied to the EBT device. The modulation of the ring is monitored by observing the hard X rays emitted from the ring electrons due to free-free bremsstrahlung.

Ring-decay measurements were made in both EBT-I and EBT-S operation. In EBT-I, the ECH power comes from klystrons with a frequency of 18 GHz. This system allows for the pulsing of a single cavity, while the rest of the machine is powered continuously. A single 28-GHz gyrotron is used for EBT-S operation. The gyrotron microwave distribution system allows only for modulation of the entire machine.

The X-ray measurements are made with an array of five 7.6- by 7.6-cm (3- by 3-in.) NaI detectors collimated to observe well-defined volumes along the toroidal extent of the ring (Fig. 1.1). Time-resolved spectroscopy techniques are used to synchronize the measurements of the X-ray energy distribution with the modulation of the microwave power. Figure 1.2 is a block diagram of the system. A start trigger is generated when the microwave power is pulsed. This starts from one to four analog-to-digital converters (ADCs) that measure the X-ray energy distribution after the trigger/start pulse. The ADCs can record data in intervals of 300 μ s to several seconds. For ring modulation, time intervals of 1 to 25 ms are used. The time-resolved spectroscopy system will continue to acquire data for up to 64 such time intervals. The data are routed to 256 K of histogramming memory located in a CAMAC crate. To acquire adequate statistics for a typical hard X-ray spectrum, several hundred to several thousand modulations of the microwave power level are required.

Fig. 1.1. The NaI detection system used on EBT for hard X-ray measurements.

Fig. 1.2. Block diagram of the time-resolved-spectroscopy system.

A typical central chord, steady-state EBT-I spectrum is shown in Fig. 1.3. There are two components to the spectrum. The hotter electron component has temperatures in the range of 150 to 200 keV. The other component has temperatures in the range of 30 to 50 keV. It is postulated that the lower-temperature component serves as a feed source for the hotter ring component. By modulating the ECH power, the relative decay of the two components is investigated.

The time variation of the hard X-ray signal from a modulated ring is shown in Fig. 1.4, where the hard X-ray count rate is plotted on a logarithmic scale as a function of time. The time dependence of the applied power is also indicated. Typical decay times are on the order of 250 ms for electrons of energies greater than 200 keV. For electrons with energies between 20 and 120 keV, decay times are less than 20 ms. Preliminary study of the temperatures of the two ring distributions indicates that the temperature of the hotter component rises as its population decays. The modulation experiments are still under investigation.

Fig. 1.3. Typical hard X-ray bremsstrahlung spectrum observed during EBT-I operation when single-frequency microwave heating was used to form the electron rings. The spectrum was obtained with the central NaI detector of the multichannel hard X-ray detection system.

Fig. 1.4. The hard X-ray count rate on a logarithmic scale as a function of time. The modulation of the applied power is also shown for reference.

1.1.2 The Heavy Ion Beam Probe on EBT

L. Solensten
J. R. Goyer

K. A. Connor
R. L. Hickok

The HIBP diagnostic on EBT underwent major modifications during 1983. Virtually all of the existing mechanical hardware was replaced with an improved design. In addition, most of the control and data acquisition electronics were replaced with CAMAC-compatible counterparts, allowing complete computer control as well as digital data acquisition and analysis. Fabrication of the vacuum hardware was completed during the first half of the year, followed by installation

and checkout in the third quarter. Actual potential measurements of the EBT plasma were initiated in the beginning of the fourth quarter. Software development and instrumentation upgrades occurred throughout the year and remain an ongoing effort to enhance the performance of the system.

Figure 1.5 is a block diagram of the HIBP. As yet, the CAMAC-based, phase-sensitive detectors and the primary beam detector in the bottom of the EBT cavity have not been implemented. The CAMAC crates, the power supplies, and the beam probe itself are located in areas not accessible during normal machine operation that may be continuous for several hours. The CAMAC system permits alignment, calibration, and data acquisition to be performed via CRT terminals in the control room. The phase-sensitive detection equipment is also located in the control room to allow

manual adjustments during EBT operation. The CAMAC crates are interfaced to a Digital Equipment Corporation PDP-11/24 minicomputer via a fiber-optic serial highway.

The new system enables two-dimensional (2-D) profiles of the space potential to be acquired in 10 min (~100 spatial locations). For each point, the computer adjusts the beam energy, radial sweep angle, analyzer angle, and nominal analyzer voltage to observe the desired charge state. The feedback system then adjusts the analyzer voltage until the beam is balanced on the split plates. The computer records all of the control and data signals, which are then used to calculate the potential. Since the PDP-11/24 is consumed with control and data acquisition tasks, the data are transferred to the Fusion Energy Division (FED) PDP-10 for analysis and plotting. A graphics terminal in the control room that is

Fig. 1.5. Block diagram of the new EBT HIBP system.

linked to the PDP-10 provides surface and contour plots of previous runs as new data are being acquired.

Figure 1.6 shows two potential profiles taken with the new system during an experiment in which the currents in the error field correction coils were varied. When no corrections are applied, as in Fig. 1.6(a), the potential is approximately a constant +200 V throughout the region in which data are available. Applying the normal correction fields causes a potential well of 200 V to form in the core, as shown in Fig. 1.6(b). The region of closed potential contours is typically elongated in the vertical direction and is roughly centered on the magnetic axis. The potential in the region radially outside the closed contours is flat, implying weak electric fields and poor confinement. Note that the steep gradients near the borders of both plots are an artifact of the interpolation program used to produce the contour plots. These areas are outside the region of the data points, which are illustrated in Fig. 1.6(c).

During the next year, the HIBP system will be used to document the space potential as a function of neutral pressure, magnetic field, applied microwave power, and other plasma

conditions. We are continuing our efforts to make 2-D measurements of the electron temperature and time-resolved measurements of potential during microwave modulation.

1.1.3 Neutral Density Measurements Using a Diagnostic Neutral Beam

J. C. Glowienka

W. A. Davis

The diagnostic neutral beam system, used on EBT to measure neutral density, has had upgrades in the electronics and upgrades in the detector systems during the past year. The electronics upgrades were made to provide a more reliable source operation. In addition, upgrades to the acceleration- and deceleration-electrodes switching electronics have provided much faster turnoff times for less ambiguity in measurement of fast ion decay times. In an effort to examine the effect of small-angle scattering, the viewing volume of the nitrogen stripping cell charge-exchange analyzer was made variable by construction of a set of variable-size apertures. Preliminary measurements using the variable apertures indicate a slight increase ($\sim 10\%$) of decay time with increased viewing solid angle.

Fig. 1.6. Space potential profiles with (a) no field corrections ($I_r = I_H = 0$) and (b) standard corrections ($I_r = 10$, $I_H = -6$) based on the data point location (c).

In addition, a new detector with a much larger viewing volume (approximately 10^4 larger than that provided by the standard aperture of the charge-exchange analyzer system) was constructed. Preliminary shakedown work indicates good signal-to-noise characteristics with the new detector, but no definitive information about decay time and neutral density is available.

1.1.4 Density Comparison of EBT-I and EBT-S

T. Uckan

The effect of ECH frequency f_μ on the electron density has been demonstrated on EBT-I ($f_\mu = 18$ GHz) and EBT-S ($f_\mu = 28$ GHz) by applying the same amount of microwave heating power [$P_\mu(\text{plasma}) \approx 32$ kW] to the plasma. Using the microwave interferometer, the line-density ($n\ell$) measurements are carried out for 18- and 28-GHz operation of the EBT device with $I_B = 4600$ A (EBT-I) and $I_B = 7250$ A (EBT-S) coil currents, respectively, so that the first and second harmonic heating locations are the same for both configurations. The variations of $n\ell$ are shown in Fig. 1.7 as a function of gas-fill pressure p_o for EBT-I and EBT-S.

The observations from these data follow.

1. The EBT plasma operating pressure range, bounded by the C-T and T-M transition pressures, is smaller for EBT-S (28 GHz) than for EBT-I (18 GHz); for example, $(p_o)_{T-M} (28 \text{ GHz}) / (p_o)_{T-M} (18 \text{ GHz}) \approx 1.58$, which is about the ratio of the heating frequencies (28/18 GHz).
2. The line density is higher in EBT-S [i.e., $n\ell(\text{EBT-S}) / n\ell(\text{EBT-I}) \approx 1.3\text{--}1.4$].

Therefore, we may conclude that higher ECH frequency (and, in turn, higher magnetic field) could provide lower operating pressures that are desirable from the standpoint of getting higher temperature, since $T_{e,i} \sim 1/p_o$, as well as higher plasma density.

Fig. 1.7. The variation of electron line density $n\ell$ with fill pressure p_o in the EBT-I and EBT-S plasmas with the same amount of microwave power $P_\mu(\text{plasma})$ applied.

1.1.5 EBT-S Throat Density Measurements

T. Uckan

The toroidal continuity of the density distribution is studied by a single-channel, 4-mm microwave interferometer in the mirror throat located in a split mirror coil opening as shown in Fig. 1.8. The simultaneous measurement of the cavity midplane electron line density $(n\ell)_{\text{mid}}$ and the throat line density $(n\ell)_{\text{throat}}$ is shown in Fig. 1.9 as a function of gas-fill pressure for an EBT-S plasma at 100 kW of 28 GHz. In this figure, we also plot the ratio of the densities, $(n\ell)_{\text{mid}} / (n\ell)_{\text{throat}}$. From the data we observe that (1) the throat line density has the same features as the midplane density versus pressure; (2) $(n\ell)_{\text{mid}} / (n\ell)_{\text{throat}} \approx 2$ during T-mode operation, which may indicate that the density is almost constant along field lines since $\ell_{\text{mid}} / \ell_{\text{throat}} \approx 2.2$; and (3) toward the T-M transition pressure, the line density ratio becomes larger, which is due to the decreasing population of passing electrons.

Fig. 1.8. The location of the interferometers for the midplane and throat line-density measurements. Here $\ell_{\text{mid}} \approx 50$ cm and $\ell_{\text{throat}} \approx 22$. This ratio is used for the $n(\text{mid})/n(\text{throat})$ comparison shown in Fig. 1.9.

Fig. 1.9. The variation of $(n\ell)_{\text{mid}}$ and $(n\ell)_{\text{throat}}$ and their ratio with the gas pressure for EBT-S. By making use of $\ell_{\text{mid}}/\ell_{\text{throat}} \approx 2.2$, $n(\text{mid})/n(\text{throat})$ stays almost constant in the T-mode.

1.1.6 Asymmetric Abel Inversion for EBT-S Density Profile Measurements

T. Uckan

The recent data on the phase shift profile (Fig. 1.10) obtained from a vertical view of the EBT plasma with the scanning microwave interferometer¹ indicates an asymmetry in line-density profile. The technique used to obtain the local electron density from this profile data follows.

The phase shift along the observation path $\overline{AB}$ as shown in Fig. 1.10, is

$$\Phi(x = \pm a) \approx 0, \quad (1.1)$$

Fig. 1.10. Typical phase shift profile $\phi(x)$ from the vertical observation of the plasma with the scanning microwave interferometer.

with

$$\Phi(x) = \alpha \int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} dy n(r, x) \quad (1.2)$$

Let us assume that asymmetry exists only in the direction perpendicular to the line of view; in this case, the local electron density $n(r, x)$ may be represented by

$$n(r, x) = F(x)N(r) \quad (1.3)$$

and here $F(x)$ is considered to be a figure of asymmetry with respect to a symmetric function $N(r)$. Using Eq. (1.3) in Eq. (1.1), we write

$$\Phi(x) = 2\alpha F(x) \int_0^{\sqrt{a^2-x^2}} dy N(r) \quad (1.4)$$

or

$$\Phi(x) = F(x)\Phi_o(x) \quad (1.5)$$

where

$$\Phi_o(x) = 2\alpha \int_0^{\sqrt{a^2-x^2}} dy N(r) \quad (1.6)$$

is the symmetric component.
With a change of variable

$$r^2 = x^2 + y^2 \quad ,$$

$$dy = dr \frac{r}{\sqrt{r^2 - x^2}} \quad ,$$

and

$$\Phi_o(x) = 2\alpha \int_x^a dr \frac{rN(r)}{\sqrt{r^2 - x^2}} \quad (1.7)$$

and from the Abel inversion, we find

$$N(r) = -\frac{1}{\pi\alpha} \int_r^a \frac{d\Phi_o}{dx} \frac{dx}{\sqrt{x^2 - r^2}} \quad (1.8)$$

Now, we need to find functions $\Phi_o(x)$ and $F(x)$, respectively. The function $\Phi_o(x)$ [Eq. (1.6)] represents the symmetric part of $\Phi(x)$; therefore,

$$\Phi_o(x) = \frac{1}{2} [\Phi(x) + \Phi(-x)] \quad (1.9)$$

which is an even function, $\Phi_o(x) = \Phi_o(-x)$.

Knowing $\Phi_o(x)$ from Eq. (1.9), we can also find $F(x)$ as

$$F(x) = \frac{\Phi(x)}{\Phi_o(x)} \quad (1.10)$$

To apply this technique to the EBT data, we assume that the line-density profile is relatively smooth so that it can be represented by, for example, a tenth-order polynomial in x . Having obtained the polynomial $\Phi(x)$ by fitting the measured data of line density, the local density

is then evaluated by using $\Phi(x)$ in Eqs. (1.9), (1.8), (1.10), and (1.4). In Fig. 1.11, EBT-S density profiles are presented with 100 kW of 28 GHz at high C-mode, C-T transition, and mid T-mode and low T-mode operating pressures. We may summarize the overall observations of the profiles as follows:

1. At the C-mode, $n(r)$ is almost flat.
2. At high-pressure T-mode, $n(r)$ is nonsymmetric and shifted toward the outside.
3. At low-pressure T-mode, $n(r)$ is symmetric about the ring center, which is about 1.5 cm inside the machine center.

1.1.7 Observations of Synchrotron Radiation from the Electron Rings

J. B. Wilgen
D. A. Rasmussen

D. A. Boyd*

Synchrotron emission from the relativistic electron rings in EBT is measured with a

highly directional quasi-optical viewing system. A focused viewing beam prescribed by Gaussian beam optics ($\omega_0 \approx 2$ cm) is used in combination with a viewing dump to isolate direct radiation from a localized volume element of the ring. The synchrotron emission is measured simultaneously at two frequencies (80 and 138 GHz), corresponding to high harmonics of the electron cyclotron frequency, 6 and 10 ω_c , respectively. Through the use of a rotating polarizer, both extraordinary (X) and ordinary (O) mode intensities are measured, characterizing the polarization state of the emission.

Polarization measurements have demonstrated that direct synchrotron emission from the electron rings in EBT is strongly polarized. Measured polarization ratios (X-mode intensity divided by O-mode intensity) at both observation frequencies are typically 5.0 to 5.2 for EBT-S conditions and 5.8 to 5.9 for EBT-I. These values are somewhat lower than predictions based on hard X-ray-measured ring parameters, particularly for EBT-I. The reason is that the viewing system is not perfect,

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Fig. 1.11. Electron density profiles at various fill pressures at 100 kW of 28 GHz in EBT-S. $r = 0$ corresponds to the peak in $|B|$ in the midplane and is 2 cm inside the nominal machine center.

and contributions from indirect emission, particularly for the O mode, reduced the measured ratio. Based on an assessment of the measured and calculated polarization ratios, it appears that with the present system and EBT-S conditions, ~90% of the X-mode polarization and 60% to 70% of the O-mode polarization are direct emissions from the viewed volume element of the electron ring. The remainder is indirect multiply reflected radiation.

This condition is to be compared to the situation that exists when a viewing dump is not used. If the focusing lens is offset to displace the viewing beam from the viewing dump, the polarization ratio is measured to be 1.25 at 80 GHz and 1.45 at 138 GHz. In this case, more than 90% of the emission is indirect multiply reflected signal that is only weakly polarized.

The synchrotron measurement is an excellent technique for observing instability activity in the electron rings. Ring fluctuations usually occur only at low pressure, where the ring stored energy is within 30% of the maximum value. Three types of fluctuations have been observed. First, during ring disruptions, the synchrotron emission decreases suddenly ($\ll 1$ ms) by as much as 25%, followed by a slow recovery lasting 50 to 100 ms. Second, small-amplitude sawtooth-like fluctuations have been correlated with bursts of whistler emission in the 3.4- to 3.5-GHz range. These fluctuations have an amplitude in the range of 1%-5% and an irregular repetition frequency of 100-300 Hz. Bursts of whistler emission coincide with the abrupt drop in the synchrotron sawtooth. The third type of fluctuation is a large-amplitude oscillation (5%-20%) at very low frequency in the range of 3 to 20 Hz. The frequency of oscillation varies continuously as a function of power and pressure, except for frequency jumps of a factor of 2. The fluctuations are ordinarily characterized by a nearly sinusoidal waveform, except near frequency jumps at which a strong second-harmonic component dominates the wave shape. Whereas the first two types of fluctuations are always

evident whenever EBT is operated with strong rings, the third type is very unpredictable.

1.1.8 Thomson Scattering

J. A. Cobble

More major upgrades were incorporated into the EBT Thomson-scattering system this year. A new detector scheme based on the Hamamatsu R943-03 GaAs (Cs) tube with pulsed dynode bias has replaced the Varian 192M tubes, which are no longer manufactured. The high gain "on time" is 25 μ s, which is down by a factor of 1000 from the "shutter open time" of the older system. However, the photocathode is still exposed to plasma light for the 7-ms open time of a newer, faster shutter. Having smaller photocathodes, the R943s require a lens to focus light from the fiber-optics bundles. This has been done with $f/1.2$ camera lenses in a light-tight box so that virtually all of the signal from the fibers hits the photocathodes.

Major improvements in stray light control have resulted in extremely good stray light rejection. A new grating configuration and an improved razor-blade viewing dump have yielded stray light levels at 6943 Å as low as 0.25 torr of nitrogen. It was found that flaps to protect the viewing dump were necessary to maintain these low levels, and flaps were installed near year's end. Without flaps, aluminum plating of the dump reduces its effectiveness within a few days.

Computer data acquisition has made analysis much easier. One improvement possible now is the calculation of the variance of data for weighted least-squares fits. The result has been the apparent lowering of measured plasma temperature with reference to unweighted fits (more on this later). Statistical variance of T_e and n_e may also be calculated, and the square root of variance is plotted as the error bars for the ten-shot spectra in Figs. 1.12 and 1.13. These values neglect errors in determining the scattering angle and

Fig. 1.12. Core electron temperature T_e vs pressure from weighted least-square fits of laser data.

Fig. 1.13. Core electron density n_e vs pressure from weighted least-square fits of laser data.

calibration errors, both of which are judged to be accurate to 10% or better. Absolute density measurements require more information, for example, response to Raman scattering, laser energy output, integrity of alignment, and system response.

The present low temperatures are based on three-point weighted fits (Fig. 1.14) and represent most of the electrons in the scattering volume. As seen in the sample spectrum, however, what could be a superthermal tail appears. A part of this feature may be due to systematic error—in particular, inadequate accounting of integrator shot noise. Nevertheless, given the history of soft X-ray measurements on EBT, to say that evidence for a tail exists is an extreme understatement. The task for the laser is to determine the tail-to-bulk density ratio—possibly along a plasma diameter. Because the tail density is of order 10^{11} cm^{-3} with a “temperature” of 500 to 1000 eV, to say that this determination will be difficult is another case of understatement.

1.1.9 EBT Computing Support

R. D. Burris

There were considerable advances in EBT computer support during the past year. The improvements with the greatest impact were

Fig. 1.14. A typical laser spectrum averaged over 11 shots with corrections for plasma light and stray light.

(1) the introduction of a VAX-11/780 computer system into the EBT environment, (2) the improvement of the Experiment Coordinator (EC) interface, (3) the development of a real-time XY plotting system, and (4) the implementation of a method for rapidly supporting the acquisition and analysis of data.

The introduction of the VAX had massive impact on the EBT experiment. We had, during 1982, become limited by the available computing capacity (five PDP-11 computers and one Nuclear Data 6600). When the VAX came on-line (which required rewrites of the graphics and data-translation software), we became able to move the EC interface and all tasks of common utility (such as the machine-condition sampling program) to it. We also moved all small diagnostic systems to the VAX and nearly all of the transient-mode data acquisition systems developed during 1983 to the VAX. As a result, our other computers have been dedicated to individual diagnostic systems, and there are no bottlenecks or deficiencies in computer power.

The EC interface has been considerably improved. Prior to the conversion to the VAX, our PDP-11 software had become limited by the available memory and processor power. Rather than just convert to the VAX, however, we also made many changes to the graphics system to provide improvements requested during the year. As a result of the greater processor power and the graphics changes, as well as the improvements in other software made possible by the VAX implementations, the new EC interface consumes few computer resources, has a menu system that is comfortable for the EC to utilize, and provides real-time displays of all representative data.

Another quantum improvement in our computer support resulted from the XY plotting system. In this software, the user is allowed to choose any datum being acquired by the machine-condition sampling program and to plot it in real time against any other such datum. For instance, the user can choose to plot $W_{\perp}$ as a function of pressure and view the results as pressure is varied by the EC.

Pressure scans, for instance, can be carried out in minutes instead of hours or days.

As 1983 progressed, it became clear that data acquired during steady-state operation were not sufficient to characterize EBT physics. Consequently, we placed major emphasis on the acquisition and analysis of transient-mode data. Historically, physicists have needed information quickly and without much warning to programming staff. Consequently, we needed a mechanism for generating diagnostic systems for such users with minimal delay. To address that need, we developed a generalized diagnostic system that would permit the development of a new diagnostic system (which used CAMAC hardware already supported within the system) in a few minutes. Extensive use of this system has been made.

Besides the larger improvements cited above, there were also several new specific diagnostic systems and evolutionary changes in all other diagnostics. New or greatly modified systems include:

- 28-GHz system monitoring and power calculation
- Residual Gas Analyzer (RGA)
- Pulsed Machine Diagnostic
- Pulsed Ring Diagnostic
- Multispectral Spectroscopy
- Fast acquisition of $W_{\perp}$ and pressure data
- Time-Resolved Spectroscopy
- Pulse-Height Analysis
- Thomson Scattering
- Multichannel Microwave Interferometer

In addition, we provide evolutionary support to the following diagnostic systems:

- Charge Exchange
- Pulsed Charge Exchange
- Microwave Interferometer
- Spectroscopy
- Pulse-Arrival Distribution
- Thermocouples
- Limiters
- Skimmer-Probe Position

Finally, we made many major improvements in support systems during the year, notably the

graphics, translation, and data-base systems. The functionality of the graphics and translation systems was greatly improved, and they were also supported on the VAX. The performance of the data-base system was improved greatly by the removal of System 1022 software from analysis programs (thereby making programs smaller and faster) and by the provision of an alternate index file that could be searched much more rapidly than 1022 files. All the data-base software was also transferred to the VAX system so that selected diagnostic systems can do all their computer processing on that system.

1.1.10 EBT-S Microwave Development

T. L. White
H. D. Kimrey
T. S. Bigelow

D. D. Bates
M. W. McGuffin

Routine operation of the 28-GHz, 200-kW, continuous-wave (cw) gyrotron into the EBT-S

mixed-mode midplane launch ECH system continued. Gyrotron dc-to-microwave conversion efficiency has been improved to 53%, up from 42% at 100 kW. ECH transmission efficiency is 80%, with half the losses due to absorbed reflections from the barrier window and distribution manifold. Figure 1.15 is a bar graph showing each system component loss into a matched load and the EBT-S plasma. In the presence of reflections, the gyrotron losses remain relatively unchanged, indicating adequate isolation of the gyrotron by the Varian and stainless steel mode absorbers.

Pulsed operation of the VGA-8000 28-GHz gyrotron is now routine for studying plasma decay times. Pulse or sine-wave modulation rates between 0.5 and 4000 Hz are possible for power levels between 0 and 150 kW. Power modulation is achieved by varying gun anode voltage.

A computer code has been implemented that monitors and displays each ECH system component loss. Power loss is monitored by

Fig. 1.15. EBT-S 28-GHz microwave system performance into a matched load and into the EBT-S plasma.

recording voltage outputs from thermocouples located on the supply and return water cooling lines of each component. The computer code monitors these outputs and updates a CRT display every 2 s. Work has begun to expand the capability of the computer code to include data storage and plotting routines to facilitate the study of gyrotron and ECH system performance.

Work continued on development and application of hardware for launching 28-GHz microwave energy from the high-field side into the core fundamental resonance. Initial experiments resulted in 6 kW cw of unpolarized mixed-mode power delivered to the EBT-S plasma from the high-field side. Later experiments resulted in 24 kW cw of polarized mixed-mode power delivered. In these experiments, microwave power was transmitted to the high-field side through the fundamental resonance via a vacuum waveguide without breakdown (1 kW/cm²).

Construction of a second 28-GHz, 200-kW cw ECH heating system was completed and tested to full power into a test load. The second ECH system will employ throat-launching hardware for high-field heating experiments.

In support of the throat-launching hardware development effort, a cold-test technique has been developed that measures the reflection and absorption coefficients of components in a mixed-mode environment. The technique involves using an untuned cavity as the cold-test microwave source and measuring perturbations of the cavity Q factor with various throat-launching hardware. Applying an iris to the cavity to achieve the same Q perturbation allows one to calculate the effective cross-sectional area of the particular component and, hence, the reflection coefficient. Good agreement has been observed between this technique and hot-test performance.

1.1.11 FIR Laser Scattering

W. H. Casson

J. B. Wilgen

The cw far-infrared (FIR) laser scattering system on EBT has undergone major modifica-

tions and upgrading during this year. The CO₂ pump laser has been replaced by a newer configuration (Fig. 1.16) designed by D. P. Hutchinson's group at ORNL for use on the Impurity Study Experiment (ISX). Although the available CO₂ output power is near 100 W, much work was necessary to reduce the output noise and improve mode stability. Even after successfully reducing the noise substantially, operating reliably still requires considerable effort to minimize mode jumping in the CO₂ laser.

To reduce noise from building vibrations, the optics table that holds the laser system has been mounted on adjustable air shocks and vibration isolation pads. A Freon cooling system has been added to cool the Brewster windows, reflection grating, and output couplers to reduce thermal transitions. Power and mode stability are aided by a lock-in stabilizer that samples the bias current generated by the local oscillator signal on the diode detectors. These improvements allow more time for collecting data and will allow for future remote system control from the EBT control room. The FIR cavity was replaced by a cavity with dimensions more suitable for lasing at 447 μ m (CH₃I). All the optics were replaced, and the system was successfully tested. Output power achieved at 447 μ m ranged from 20 to 60 mW, with the system typically operating at 40 mW.

The remainder of the system, which includes waveguides, scanning mirrors, and focusing lenses (Fig. 1.17), has been installed, and tests show satisfactory transmission efficiency through the waveguide and the EBT cavity. The beam power focused into the plasma was measured to be near 4 mW, with 40 mW of laser power. The three scanning mirrors give the system the ability to scan across the plasma and vary the scattering angle (though one cannot be changed without changing the other). Scattering angles range from 5° to 60°, corresponding to fluctuation wavelengths λ_f of ~ 5.5 –0.5 mm. Only k_θ fluctuations are observable with this geometry, and for each position in the plasma, there are only three scattering angles.

Fig. 1.16. Current configuration of the CO₂ pump laser and the FIR resonance cavity installed on EBT.

Fig. 1.17. Scattering geometry and waveguide system showing positions of mirror, beam splitters, and lenses in relation to the EBT cavity, lasers, and detector.

Several detectors were tested, and two new detectors were acquired. The newer detectors (GaAs Schottky diodes) combined low noise with higher sensitivity, providing a marked improvement over other detectors tested. The amplified detector output can be spectrum analyzed or the integrated power recorded via a radio-frequency (rf) crystal detector. Because the density in EBT is low (10^{12} cm^{-3}), the scattered power is expected to be very low, and synchronous detection methods have been incorporated. To observe localized density fluctuations, a 10-Hz beam chopper has been added in front of the EBT cavity, and signals are synchronously detected with a lock-in amplifier. To observe driven waves between 5 and 50 MHz, the chopper is not used, but a high-frequency, lock-in amplifier synchronized with the ion cyclotron resonance heating (ICRH) antenna is used. The entire system is now complete, and system checkout is continuing. Scattered signal has been observed from the EBT plasma. The remainder of the EBT-I/S operating time will be used to document the scattered power over as large an area of parameter space as possible.

1.1.12 Lyman-Alpha Laser Scattering

R. Mahon

A Lyman-alpha laser scattering experiment is being installed on EBT in order to make a point measurement of atomic neutral density in the plasma. The motivation is to resolve the discrepancy between neutral beam and spectroscopic data. The 1216-Å radiation undergoes resonant scattering of ground-state atomic hydrogen for detection at 90°. A 20-mJ dye laser, pumped by a XeCl excimer laser, has been aligned on the torus, and Rayleigh scattering on nitrogen has been detected at 3650 Å. When frequency-tripled by the krypton-argon gas cell, up to 100-W pulses of L_α radiation are produced.

It has been discovered that the L_α transmission of the MgF_2 collimating lens is extremely sensitive to accumulated radiation dose from the plasma, so that the lens becomes useless

after just a few hours of exposure. This and other problems are currently being addressed, and results are expected soon.

1.1.13 EBT Ion Cyclotron Resonance Heating

F. W. Baity

T. L. Owens

W. A. Davis

A new fast-wave ion cyclotron range of frequencies (ICRF) antenna was installed to perform heating experiments at high cw power levels. The antenna was equipped with a new Faraday shield of improved design, with integral cooling of each blade of the shield. Previous cw experiments had been limited to 20 kW due to Faraday shield heating. With the new shield, cw power levels of 100 kW were achieved in C-mode operation. In T-mode operation, cw power levels were limited to 30 kW by voltage breakdown in the matching circuit as a result of the decreased plasma loading resistance in the T-mode compared to the C-mode.

At higher power levels, ion heating (as measured by charge exchange) continues to increase, particularly in cavities far removed from the antenna toroidally. This observation is evident from Figs. 1.18 and 1.19, which show the higher-energy ion tail produced by the rf for several power levels up to 100 kW. Figure 1.18 shows the ion heating observed in a cavity 60° toroidally away from the antenna, and Fig. 1.19 shows the heating 150° around the torus. This data was taken at 30 MHz in a deuterium plasma and represents heating at the third and higher harmonics of deuterium. At this frequency, wave propagation toroidally does occur, as observed on electrostatically shielded loop probes located in several cavities. The charge-exchange data for all three analyzers on EBT-S are summarized in Fig. 1.20. The ordinate is the total ion energy in the 200-eV to 4.2-keV range for the three analyzers. This represents a high-energy tail on the 20-eV bulk ion distribution. The density of the ion tail is estimated to be 10% to 50% of the bulk density, so the ion tail carries the majority of the total ion energy in the plasma for the higher power levels.

Fig. 1.18. Ion heating vs ICH power 60° around EBT (N1) from the antenna (W3) in a C-mode deuterium plasma.

In addition to ion heating, study of the effect of ICRF heating on the relativistic electron rings was continued with the 5-channel hard X-ray detector. This detector is located in the cavity adjacent to the antenna, but the effect of ICRF on the rings in other cavities has been observed from the diamagnetic loop probes on each cavity. The enhancement of ring parameters observed depends both on the amount of power coupled by the antenna and on the extent of wave propagation. Figure 1.21 shows the toroidal profile of the ring beta for four cases, including two different power levels of ECH alone. The two ICRF cases represent about the same amount of power coupled to the plasma, due to the variation of antenna loading as a function of frequency. The enhancement at 48 MHz is greater than at 28 MHz because of increased wave propagation. Little change is apparent in the ring pro-

Fig. 1.19. Ion heating vs ICH power 150° around EBT (E1) from the antenna (W3) in a C-mode deuterium plasma.

file, but a doubling occurs of the ring beta for the 48-MHz case. The mechanism of the ring enhancement due to ICRF heating is not understood.

In September a "Nagoya Type III" antenna was installed for preliminary plasma production experiments. This antenna consists of an unshielded radiating element passing through a mirror throat and oriented in the toroidal direction. In order to use the large ports on standard EBT-S cavities, the antenna was installed on the outside and at 45° above the horizontal relative to the mirror cross section. Preliminary results showed a substantial increase in $n_e \ell$, as measured by the microwave interferometer, with the application of 100 kW

Fig. 1.20. The ion stored energy from 0.2 to 4.2 keV vs ICH power observed with three different charge-exchange detectors in cavities W3, N1, and E1, respectively 0°, 60°, and 150° around EBT from the antenna.

Fig. 1.21. Ring beta measurements vs toroidal extent for different ECH and ICH power and frequency levels.

of ICH during gas puffing for fundamental-resonance-mode operation (7250 G at the cavity midplane on-axis and 18-GHz ECH). These results confirmed the Nagoya Bumpy Torus (NBT-1M)* results on plasma production. Little experimental time was devoted to the plasma production experiments during 1983. A two-antenna experiment at 200 kW is planned for 1984.

*Located at Nagoya University, Nagoya, Japan.

1.1.14 Langmuir Probe Data

G. R. Haste

D. A. Rasmussen

This is a summary of some Langmuir probe data on EBT. Radially resolved data were desired, which required that the probe be inserted to the plasma center. Because of concerns for the probe viability, it was decided to operate at very low power. As a consequence, the operation was at quite low pressure because the operating pressure tends to vary with the square root of the microwave power.

For these measurements, a Langmuir probe was installed in one of the split mirror coils (Fig. 1.22). These experiments were carried out with 18-GHz power alone and at low power levels. Only one value (5 kA) of the magnetic field was used; this value is the standard field for 18-GHz operation. A plot of the $n\ell$ product (phase shift) and stored energy in one cavity is shown in Fig. 1.23 for operation with 4 kW. Several features of this figure deserve attention. First, the $n\ell$ values, though small, show the "break" characteristic of the C-T transition at a gage pressure of 4.7×10^{-6} torr. The stored energy at the transition is small but finite. The T-M transition occurs at 2.7×10^{-6} torr, which gives a smaller operating window for the T-mode. At such a low power level, the M-mode is relatively innocuous: $n\ell$ drops to zero, the stored energy drops to small average values, and the plasma light disappears.

Fig. 1.22. Location of Langmuir probe in EBT split mirror coil.

Data were acquired at seven different pressures: 3.8×10^{-6} torr and 10×10^{-6} torr. In general, data were taken for four radial points. At one pressure (5×10^{-6} torr) eight points in radius were obtained. The data consisted of scope photos of the probe current as the probe voltage was repeatedly swept.

One of the scope photos is shown in Fig. 1.24, together with an analysis of the

probe current on a semilog plot. (Note that a straight line is a very good fit to the data points, so there is little room for error in the fitting process.)

A problem occurs in trying to obtain absolute values for the density from the probe data: there is an arbitrary constant relating the density to the quotient of ion saturation current to the square root of the electron temperature.

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Fig. 1.23. Line integral of density (triangles) and stored energy (circles) as a function of ambient pressure (for 4-kW input power).

Fig. 1.24. Typical Langmuir probe signal.

This arbitrary constant was estimated by numerically integrating the density profile (obtained from the probe data), then equating it to the $n\ell$ value from the interferometer signal.

The radial profiles of the electron temperature are shown in Fig. 1.25. The curves are labeled with numerals that indicate the pressure for that scan. The density profiles are shown in Fig. 1.26, and the product of the density and temperature is shown in Fig. 1.27.

The temperature data show the expected trend with gage pressure in that the temperature increases as the pressure is lowered. The radial profiles show a surprising feature in that the temperatures are highest on the *outside* of the plasma. The peak position is about 9 cm. When the field line through 9 cm is projected back to the midplane, it passes through the third harmonic resonance region, as shown in Fig. 1.28. Because the rings are located at the second harmonic position, the temperature peaks *outside* the rings.

The density peaks at the center and falls more or less monotonically with radius. The

Fig. 1.25. Profile of electron temperature for various pressures.

Fig. 1.27. Profile of energy density for various pressures.

Fig. 1.26. Profile of electron density for various pressures.

density "calibration" is made by numerically integrating the density profile. The results of this calibration are shown by the solid circles in Fig. 1.29. This measurement implies that the multiplier for the density values in Fig. 1.27 is 10^{10} , within a factor of 2. The density-temperature product, which is simply related to the plasma pressure, also falls with radius, but is much flatter. There are some "wiggles" in the vicinity of the ring projection that may have some significance.

In equilibrium, the particle confinement time must equal the ionization time. The temperature data allow determination of the $\langle \sigma v \rangle$ that enters the ionization rate. If the neutral density were known, then the ionization time could be calculated. Assuming a simple relation between neutral density and gage pressure, neutral density ($\text{molecules} \cdot \text{cm}^{-3}$) = $1.1 \times 10^{17} \times P_{\text{gage}} (\text{torr})$. With this assumption, the ionization time can be calculated (Fig. 1.30).

Fig. 1.28. Relation between resonance locations and probe position.

In calculating the power balance, the losses due to ionization and excitation must be included. At low electron temperatures, these losses are quite important and even dominant. In an attempt to include these losses in a simple parameter, an energy *replacement* time is defined:

$$T_{ER} = \frac{3}{2} \frac{n(T_e + 30) \text{ Vol.}}{P_\mu}$$

This definition differs from the usual definition of the energy *confinement* time in that the extra losses due to excitation and ionization (30 eV) are sometimes not included in the latter. The value of 30 eV is somewhat arbitrary. Its justification is: 14 eV for ionization, 10 eV for excitation to the first level, and 6 eV for miscellaneous excitation. It has been suggested that the 30-eV value should be raised to 50 eV, to take into account the additional loss processes (dissociation and molecular radiation) available in the molecule.

Fig. 1.29. Comparison between line integral of electron density and numerical integration (solid circles) of the density profile.

Fig. 1.30. Ionization time, determined from electron temperature at various probe locations.

The energy replacement time is plotted in Fig. 1.31. Notice that this time is approximately equal to, but somewhat greater than, the ionization time (shown in Fig. 1.30). The trends with pressure, however, are opposite because the density drops as the M-mode is

approached, and the reduced density leads to a reduction in the energy replacement time, while leaving the ionization time unaffected.

Fig. 1.31. Energy replacement time at various probe locations.

1.1.15 EBT-S Limiter Experiment

R. E. Juhala

D. W. Swain

Larger EBT devices will be operated with several megawatts of power with vacuum wall heat loading and erosion rates that make replaceable plasma limiters desirable, if not essential, to afford protection of the vacuum vessel. Also, previous experiments on EBT-I/S that have involved the introduction of probes into the surface plasma region have resulted in a reduction of electron ring stored energy in the sectors that were probed. Thus, it became clear that an experiment to (1) determine the effect limiters have on the core and ring plasma and (2) provide a base of information necessary for the design of both the toroidal vacuum vessel and a suitable limiter configuration in larger EBT devices would be desirable. Results of a limiter experiment conducted on EBT-S in a collaborative effort between ORNL and McDonnell Douglas Astronautics Company (MDAC) are briefly summarized below.²⁻⁶

These experiments are the first attempt to study an EBT plasma under the influence of an adjustable boundary, as provided by the limiters. They entailed probing the plasma with a pair of water-cooled aluminum limiters, both located in the same sector off the midplane near a cavity sidewall. The limiter design afforded essentially 360° coverage in the poloidal angle; thus, in effect, a new plasma boundary could be established. The location of the limiters at the so-called "Standard Position" (SP) are shown in the vertical plane in Fig. 1.32 and with respect to the vacuum magnetic field lines and mod- B contours in the equatorial plane in Fig. 1.33.

Included in this experiment were measurements of the plasma power absorbed by the limiters as a function of their position under various operating conditions of background pressure, microwave power, and magnetic fields. Also determined were the electron ring stored energy, background radiation level, line density ($n_e l$), and ambipolar potential as the limiter position was varied. In some cases,

Fig. 1.32. View from the side of the limiters at the "standard" operating position.

Fig. 1.33. Plan view of a cross section through the EBT equatorial plane, showing magnetic field lines (dashed curves), contours of constant B (solid curves), and the limiter positions. The hatched curve across the coil throat is the fundamental resonance zone ($\omega_{ECH} = \omega_{ce}$); the two hatched curves in the middle are the second harmonic resonance zone ($\omega_{ECH} = 2\omega_{ce}$).

measurements of core and ring plasma temperatures and densities were obtained.

Measurements of limiter power in T-mode operation are shown in Fig. 1.34 for each limiter separately. It can be seen that more power is received by the limiters at the lower magnetic field ($I_{TF} = 6515$ A) and by the inboard limiter (IBL) when they are located at equal distances from the center of the connected toroidal field (TF) window (as depicted in Fig. 1.32). These results reflect the change in the regions of resonant microwave power absorption at lower field and also a slight inward shift of the plasma temperature profile. Measurements of limiter power as a function of pressure (not shown) peak in the mid T-mode and fall off roughly inversely with pres-

sure in the C-mode, consistent with more power absorbed in the ionization process as the density increases. There is some interference between limiters; that is, a fraction (at most 20%) of the core plasma power will be absorbed by the "nearest" limiter. Otherwise, the power deposition is unique to each limiter. This would be characteristic of particles scattering out of the mirror traps onto vertical drift orbits within the loss cone. The vertical drift orbits are, of course, obtained from the toroidal curvature of the vacuum field for particles in the transitional region. The limiter measurements are thus consistent with the condition that no substantial component of well-confined, passing particle plasma fills out the entire volume interior to the electron rings.

Ambipolar potential measurements are made three cavities away from the limiter cavity. Measurements of the change in the negative ambipolar potential well are shown in Fig. 1.35. It can be seen that the well essentially disappears as the limiters just cross the field lines containing the electron rings. This produces no significant change in the core plasma temperature and density, providing evidence that the resulting self-consistent radial

Fig. 1.34. Limiter power to the inboard limiter (solid curves) and outboard limiter (dashed curves) vs limiter position, for 28-GHz microwave power of 50 and 100 kW, and different magnetic fields (7250 A corresponds to the resonance zones shown in Fig. 1.33).

Fig. 1.35. Variation in plasma potential for inner and outer limiter scans. Solid curves are depth of well ($\Delta\phi = \phi_{\min} - \phi_{\max}$); dashed line is central potential [$\phi(r=0)$].

electric field offers no significant improvement to the toroidal confinement of plasma in EBT-S.

The three major results of the limiter experiments are summarized as follows.

1. Limiter power:

- The measured power to either limiter rises almost linearly as a function of the limiter position once the entire leading edge of the limiter intersects connected TF lines. The power measured by either limiter is not strongly affected by the location of the other.
- The power to the limiters is higher on the inboard limiter when equal areas are exposed to the connected TF-line window, but the rise in limiter cavity pressure is equivalent for either.
- The measurements of the limiter power in the T-mode imply that changes are occurring in the radial plasma temperature and density profiles as a function of background pressure.

2. Shielding the magnet sidewall:

- The limiters provide adequate protection for the magnet sidewall, provided they overlap the edge of the magnet aperture by ~ 1 cm.
- A reduction of $\sim 50\%$ in temperature at the hot spot in the magnet aperture is observed as the electron ring and trapped core plasma in the limiter cavity are attenuated.

3. Limiter-core plasma interaction:

- The negative ambipolar potential well disappears and the potential becomes positive as either limiter crosses the field lines containing the electron ring.
- Fluctuations in density are reduced and $n_e l$ increases slightly for limiter positions midway between fully out and the electron ring flux surface.
- With the inboard limiter almost completely blocking the passing particle region, the core density and temperature (n_e and T_e) are reduced by 50%, and

fluctuations increase dramatically. The outboard limiter, which when fully inserted does not protrude into the passing particle region, causes the core density to increase by 50%, while the core electron temperature decreases by $\sim 50\%$.

The measurements of plasma power absorbed by the limiters have made important contributions to the understanding of plasma confinement in EBT-S. The measurements support a two-component plasma (trapped and passing), with regions of confinement defined principally by vacuum field drift orbits but somewhat distinct from each other, being separated by the loss cone. In addition, the limiters provide a means of perturbing the plasma in a way that has allowed a distinction to be made between trapped and passing particle phenomena, as evidenced by the effect of the limiters on the ambipolar potential.

1.1.16 Low-Frequency Fluctuations in EBT

S. Hiroe

Line-integral density fluctuations are measured with the fast-time-response interferometer. The frequency range is from 0 to 500 kHz. In C-mode, the low-frequency fluctuations ($f < 20$ kHz) are dominant. When the ambient pressure decreases, the hot electron population starts to increase and the low-frequency fluctuations start to drop. At the T-C transition, the low-frequency fluctuation level reaches a minimum, but the high-frequency fluctuations ($f > 100$ kHz) still remain low. When the ambient pressure is decreased more, the hot electron stored energy increases and the space potential forms a well, and both the low- and high-frequency fluctuations grow. At the mid T-mode, the low-frequency fluctuation level reaches a maximum, and it decreases when the pressure is lowered further. This general tendency is the same over the whole frequency range in the T-mode. The higher-frequency fluctuations, however, reach a maximum at lower pressures.

These results can be explained by (1) the charge-uncovering effect of the hot electrons (C to C-T transition), (2) the destabilization by the shallow potential well (high-pressure T-mode), and (3) the stabilization by the deep potential well (low-pressure T-mode).^{7,8} The larger power loss, measured by the limiter, is well correlated with the higher levels of the high-frequency fluctuations.

1.1.17 "Observation of Hot Electron Ring Instabilities in ELMO Bumpy Torus"—Abstract

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T. Uckan
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A high-frequency, hot electron instability is observed in EBT plasmas when the hot electron-to-ion density ratio exceeds 0.4. Both the real frequency and the imaginary frequency are larger than the ion cyclotron frequency. The azimuthal mode number (m) is 7, and the instability rotates in the hot electron curvature drift direction. This instability is identified as a curvature-driven mode. When it is strongly excited, the equilibrium of the hot electron annuli and confined core plasmas is destroyed (disruption). Extensive ion heating and neutron bursts are associated with this instability.

*Plasma Theory Section.

1.1.18 Measurement of the Microwave Losses to the EBT Cavity Walls

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T. S. Bigelow
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O. E. Hankins

Single-pass microwave absorption by the plasma in EBT is weak enough for the microwaves to undergo multiple reflections from the cavity walls before being absorbed. With each reflection, some of the microwave

energy is dissipated in the aluminum cavity walls. A set of measurements was made to determine this loss. The technique employed was to determine the microwave energy stored in the cavity with and without a plasma present. The stored energy was determined from measurements of the power coupled out of a 7.6-cm (3-in.) port in one of the cavities and into a water-load microwave calorimeter.

Two models were used to fit the data obtained. An intercavity radiation transport code was used to predict the power coupled to the calorimeter, for various configurations of cavity microwave feed and loss due to open diagnostic port holes and for various assumed values of the single-reflection wall loss coefficient. The EBT microwave power balance model¹⁰ was compared to calorimeter measurements for the case in which plasma was present.^{11,12} This model includes ring, core, surface, and wall absorption.

The data obtained without plasma were taken with the torus backfilled with nitrogen to atmospheric pressure. The total microwave power fed to the torus was held to ~ 400 W. The input microwave frequency was swept ± 25 MHz about the central 18-GHz frequency, in order to scramble standing wave modes, thereby spatially averaging the power received by the calorimeter.

Power was fed to the torus at different cavities or sets of cavities to study the transport to the cavity with the calorimeter. A second set of measurements was made after nine 10-cm-(4-in.-)diam port covers were removed to artificially increase the microwave losses. The transport code was used to model the experimental results. It was found that a wall loss coefficient of 0.7% per wall bounce matched the data quite well.

To determine the power lost to the wall in the presence of a plasma, the microwave power balance model was modified to include a wall loss coefficient. For a wall loss coefficient of 0.7%, the power balance model predicts a total (multibounce) wall loss of $\sim 5\%$ of the input microwave power. Thus, the wall losses can be considered an almost negligible microwave loss.

After a prolonged period of operation, the inner wall of the EBT vacuum vessel becomes coated with layers of aluminum "flakes." The measurements reported above were obtained after the vessel had been "deflaked." A second set of measurements will be performed with the aluminum flakes present.

1.1.19 Low-Power Microwave Absorption Experiments

D. A. Rasmussen
T. S. Bigelow

D. B. Batchelor

A diagnostic has been developed to test the basic microwave transmission and absorption properties of the EBT plasma. Two broadband systems (18–26.5 GHz and 26.5–40 GHz) use highly directive transmitting and receiving antennas in order to measure the single-pass absorption/transmission of a low-power test wave (<1 W) for a horizontal midplane path through the plasma (Fig. 1.36). Trans-

mission/absorption was studied for both polarizations at the second harmonic resonances.

The results of EBT-I (18–26.5 GHz) experiments were compared directly to theoretical ray-tracing calculations to provide a more accurate determination of the EBT microwave power balance. The single-pass, ray-tracing predictions fall in the range of 1 to 2 times the measured absorption values (~8% absorption at 20 GHz for a 4.0-J ring with $T_H = 120\text{--}200$ keV, $n_{\text{ring}} = 1.1\text{--}1.7 \times 10^{11} \text{ cm}^{-3}$, $P_{18} = 36$ kW). When these ray-tracing values are input to the EBT-I microwave power balance model,¹⁰ they yield a total (multipass) ring absorption of 15% to 30%. In contrast, a simple calculation of ring power based on the measured ring energy (4 J) and decay rate (~100 ms) would yield a total ring absorption of 4.5%. This decay result can be in error because it only considers the decay time of high-energy particles greater than 100 keV and not that of the lower-energy population.

Fig. 1.36. Schematic of the single-pass microwave absorption experiment.

Experiments are planned in EBT-S (26.5–40 GHz) to determine the absorption scaling with ring temperature and density. An additional system will be used to evaluate various throat and midplane launch configurations and antennas (Fig. 1.37).

1.1.20 High-Field Microwave Throat Launch

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Throat-launch experiments were initiated on EBT (at 28 and 18 GHz) in order to increase

the microwave absorption at the fundamental resonance by launching power from the high-field side. Power was transmitted with waveguide that snaked from inside the mirror cavity around the magnet coil case, passing through the fundamental resonance to a windowless polarized launching structure on the high-field side (Fig. 1.38). Experiments thus far have shown that at least 24 kW (1.0 kW/cm^2) of 28-GHz power and 1.2 kW (1.0 kW/cm^2) of 18-GHz power can be transmitted without breakdown in the guide at the fundamental resonance. In both cases, the maximum power was source limited.

To provide efficient coupling to the core plasma, a microwave launcher with good polarization purity (extraordinary mode) and directivity was developed. Preliminary results indicate that, contrary to initial expectations,

Fig. 1.37. Experimental arrangement for fundamental resonance absorption measurements.

Fig. 1.38. Plasma diagnostics for high-field throat-launching studies.

the microwave coupling to the circulating core plasma was not increased; instead, the trapped ring-stored energy was substantially increased in the throat-launch cavity. These results are consistent with recent Fokker-Planck calculations of ECH heating that show preferential heating of tail electrons.

The throat-launch experiments were very difficult to analyze because there was no independent control of the midplane and throat-launch powers. Experiments are planned to utilize a second gyrotron exclusively for throat launching, thereby providing the necessary control.

1.1.21 Multifrequency Heating on EBT

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D. A. Rasmussen
D. L. Hillis
O. E. Hankins

By providing power at a number of microwave frequencies, the group at TRW, Inc.,

working with the symmetric mirror (SM) device, has demonstrated improved ring parameters.¹³ The ring density increased as more frequencies were used. When using only two frequencies, an optimum frequency separation was found, which corresponded to the bounce frequency for intermediate energy electrons—about 1 keV.

Techniques similar to those used on SM have been used on EBT—in an effort to improve the ring parameters there as well. The 18-GHz system was used (Fig. 1.39). In general, this system is driven by an oscillator at 18 GHz, which drives a Traveling Wave Tube (TWT) amplifier. The output of the amplifier is divided four ways to drive the klystron amplifiers. For these experiments, the single drive from the oscillator was augmented by a second, operating at a slightly different frequency. Since the frequency of the second source could be controlled, the response of the system to the frequency separation could be studied. In practice, the separation was limited

Fig. 1.39. Microwave power generation for EBT, with two-frequency heating.

to less than 50 MHz, due to the narrow bandwidth of the klystron amplifiers.

Figure 1.40 shows the results of these experiments. When operating with the maximum separation, an increase of up to 20% in ring-stored energy could be seen. This was primarily due to an increase in density, since the ring temperature did not change. Smaller frequency separations resulted in smaller increases.

The reason advanced for the parameter improvement in SM is that the ECH results in "superadiabatic" particles. These particles, which bounce between the mirror points in SM, experience a slow change in the phase between their cyclotron motion and the applied microwave field. When their motion is in phase, they are heated, and they are cooled when out of phase. Their energy is therefore limited, above and below, at the points where they begin to move out of phase or in phase, respectively. Since they are locked into this energy range, they are termed superadiabatic. The effect of multiple frequencies is to break this superadiabatic behavior, since there is now more than one frequency to establish phase coherence with. Multiple frequencies are therefore expected to improve the effectiveness of ECH in a simple mirror.

In the canted mirror, represented by a single sector of a bumpy torus, these effects should

not be so pronounced. This is because the distance between the mirror points varies azimuthally: the mirror points are closer together on the inside of the torus and further apart on the outside. There is then not a unique bounce frequency, as there is in the simple mirror, and it is more difficult to establish phase coherence. Thus, simply canting the mirrors breaks the superadiabatic behavior, and multifrequency heating may not be so effective in EBT. This is the present understanding for the difference in the effectiveness of the two devices.

1.1.22 Energy Confinement Experiment Using Microwave Power Modulation

R. K. Richards

J. B. Wilgen

The purpose of these experiments is to establish a second (and independent) technique for determining the electron energy confinement time in the EBT. The energy confinement time is calculated from the time-dependent behavior of the electron density and electron temperature. From the power balance equation, these will have a time dependence according to

$$\frac{d}{dt} \langle nT \rangle = H - \frac{\langle nT \rangle}{\tau_E}$$

Fig. 1.40. Ratio of stored energy using two-frequency heating to that with single-frequency heating in each of the EBT cavities.

For a step change in the microwave heating, the density and temperature product will exhibit an exponential equilibration with a time constant of τ_E .

The diagnostics used in this experiment include the microwave interferometer for determining the electron density and a spectroscopic measurement of an aluminum line ratio¹⁴ for determining the electron temperature. Results show the confinement time increases with decreasing fill-gas pressure and approaches 1 ms near the T-M transition.

A more detailed study of the confinement properties involves a sine-wave modulation of the microwave power. Under these conditions, the variation of the confinement time during the modulation process can be examined. Experimental results show that the energy-flow process is very complicated. The resonances and time delays observed in the stored energy suggest a strong and nonlinear coupling among different groups in the plasma, each with distinct confinement properties.

1.1.23 Electron Confinement Studies for Pulsed EBT-S Operation Using Soft X-ray Techniques

D. L. Hillis

K. G. Young

Electron heating and loss mechanisms for the core plasma of EBT-S are investigated by modulating the 28-GHz microwave power to EBT, which results in a periodic formation and decay of the energetic core-plasma electrons within EBT. The 28-GHz gyrotron is square-wave modulated between 150 and 90 kW with a repetition rate of 30 Hz. Modulation of the microwave power at these rates produces a minimal perturbation of the hot electron rings. The effects of pulsing the microwave power on the core plasma of EBT-S are studied via time-resolved soft X-ray measurements.

The soft X-ray energy distribution, arising from the core plasma, is measured via a 5-channel windowless Si(Li) detector that views a single EBT cavity midplane through a collimated, evacuated tube. The soft X-ray

detection system is shown in Fig. 1.41. Time-resolved spectroscopy techniques are used to synchronize the measurement of the X-ray energy distribution with the modulation of the microwave power. A start trigger is generated when the microwave power makes a transition from 150 to 90 kW. This starts from 1 to 4 ADCs that measure the X-ray energy distribution every $300 \mu\text{s}$ after the trigger/start pulse. The time-resolved-spectroscopy system will continue to acquire data for up to 64 such time intervals.

The data handling system for these time-resolved-spectroscopy measurements is described in Sect. 1.1.1 and Fig. 1.2 by Hankins and Hillis. To acquire adequate statistics for a typical soft X-ray spectrum, several thousand modulations of the microwave power are required.

The square-wave modulation of the 28-GHz gyrotron and the associated trigger pulses are shown in Fig. 1.42. The time-resolved soft X-ray energy distributions are measured during the microwave power modulations. These soft X-ray bremsstrahlung energy distributions are then analyzed to yield electron temperature and electron density measurements for the core

plasma during the plasma modulations. The electron temperature and electron density measurements for the EBT plasma during the modulation of 28-GHz microwave power are shown in Figs. 1.43 and 1.44. As can be seen, these measurements provide detailed information for the electron temperature, density formation, and decay rates when the microwave power makes a transition between power levels. For this case with the microwave power modulation between 150 and 90 kW at a filling pressure of 7×10^{-6} torr, the characteristic electron temperature decay time is about 1.5 ms, while the characteristic electron density decay time is about 1.2 ms. Further investigations of the plasma response to modulation of the microwave power are presently in progress.

1.1.24 Soft X-ray Measurements in the Mirror Throats of EBT-S

D. L. Hillis

O. E. Hankins

Traditionally, electron temperature T_e and electron density n_e measurements on EBT-S

Fig. 1.41. The soft X-ray detection system.

Fig. 1.42. The 28-GHz gyrotron is square-wave modulated between 150 and 90 kW with a repetition rate of 30 Hz.

Fig. 1.43. Electron temperature response to microwave power modulation.

Fig. 1.44. Electron density response to microwave power modulation.

have been possible only on the plasma components that could be viewed through diagnostic ports available at the cavity midplane. Recently, new "split mirror" coils have been installed on EBT-S that have allowed diagnostic access to the EBT plasma present in the coil throat.

A soft X-ray diagnostic has been installed on one of the split mirror diagnostic ports to provide both T_e and n_e measurements of the plasma component present in the mirror throat.

The split mirror soft X-ray diagnostic is shown in Fig. 1.45. This diagnostic measures the soft X-ray energy distribution (0.4–6.5 keV) on EBT-S using an 80-mm² "windowless" Si(Li) detector. The detector is liquid-nitrogen cooled and has an energy resolution of ~180 eV. The windowless Si(Li) detector is collimated to view the plasma along one of seven chords in the mirror throat of one of the EBT mirror coils. The plasma chord that is viewed is determined by a scanning lead aperture

Fig. 1.45. The scanning split mirror soft X-ray diagnostic system on EBT-S.

(Fig. 1.45). This soft X-ray system is capable of measuring both T_e and n_e plasma profiles by Abel inversion of the measured free-free bremsstrahlung X-ray energy distribution.

Shown in Fig. 1.46 is a typical mirror-throat soft X-ray spectrum, as compared to the soft X-ray spectrum as measured in the cavity mid-plane. Typically, T_e and n_e in the cavity mid-plane are found to be about 495 eV and $5.9 \times 10^{11} \text{ cm}^{-3}$, respectively, for a microwave power input of 150 kW and a hydrogen filling pressure of $8.0 \times 10^{-6} \text{ torr}$. In the mirror throat one finds that $T_e \approx 460 \text{ eV}$ and $n_e \approx 7.4 \times 10^{10} \text{ cm}^{-3}$.

These first electron temperature and electron density measurements in the mirror throat indicate that $T_e(\text{throat}) \approx T_e(\text{midplane})$; however, $n_e(\text{throat}) \approx 0.10 n_e(\text{midplane})$. These results are a good indication that the electron temperature component of $T_e \approx 500 \text{ eV}$ is rather anisotropic. Further measurements are in progress to further verify these observations.

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Fig. 1.46. Comparison of the mirror throat soft X-ray spectrum to that found in the cavity midplane on EBT-S.

1.2 EBT-P PROJECT

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1.2.1 Introduction

Detailed design of the descoped EBT-P device continued during early 1983, along with supporting technology development. The descoped device, as tentatively approved by the Department of Energy (DOE) in October 1982, retained the basic configuration of 36 superconducting magnets but with a number of cost-saving modifications, including only 28-GHz ECH sources in the initial installation and a simplified magnet cryogenic cooling arrangement that limited the maximum upgrade magnetic field to that required for 60-GHz operation.

Project activities were reduced drastically in response to DOE direction in May 1983. The action taken curtailed work on the proposed design but does not terminate the project, pending evaluation of alternative EBT configurations and a possible decision to complete the project in the event that a suitable, improved configuration is identified by October 1984.

The Title II design effort at McDonnell Douglas Astronautics Company (MDAC) was brought to an orderly halt by October 1983. Design tasks in progress were carried to the nearest logical stopping point and terminated with appropriate documentation. Technical

support tasks were phased down and terminated in a similar manner, except for two development tasks that are being completed because of generic benefit to the fusion program.

A phasedown project status report¹⁵ was prepared that gives the status of each system design, including a summary of work completed, current open issues, a summary of work deferred, and references to project documentation. This document will serve as a primary reference if work is resumed.

1.2.2 Technology Development

The continuing development consists of completing the fabrication of toroidal vessel prototype modules and the manufacture and final testing of three EBT-P development magnets for use in the proposed RF Test Facility (RFTF) at ORNL.

The EBT-P toroidal vessel is a stainless steel, double-wall design that features integral cooling passages. Development planned¹⁶ in support of the design included fabricating vessel prototype modules, thermal and mechanical testing of the modules, and using them for developing assembly procedures. Under the phased down EBT-P project, fabrication of the prototype modules was completed, but all testing and assembly development was deferred.

A prototype module consists of a mirror cavity and a vacuum liner (magnet throat region). Two sets of prototype components were completed—one by Varian Associates and one by Perkin-Elmer Ultek, Inc. The double-wall shells for all units were fabricated by Paul Mueller Template Division. The completed prototype mirror cavities are shown in Fig. 1.47.

The successful fabrication of the prototype modules demonstrated the feasibility of fabricating the toroidal vessel as designed and contributed to the development of fabrication procedures. The modules are stored at MDAC in

^{*}Engineering Division.

[†]Plasma Theory Section.

[‡]Magnetics and Superconductivity Section.

ORNL PHOTO 6815-84

Fig. 1.47. EBT-P prototype mirror cavity modules fabricated by Perkin-Elmer Ultek, Inc. (left) and by Varian Associates (right). (Photo courtesy of MDAC, St. Louis.)

St. Louis and will be available for testing or other use if the occasion arises.

The EBT-P superconducting magnet development program is a joint effort by ORNL, MDAC, and General Dynamics Convair Division (GDC) to provide the technical basis for detailed design and fabrication of the EBT-P mirror magnets. As planned for EBT-P, the development program consisted of the design, fabrication, and testing of three magnets, one of which was to be a prototype for the EBT-P device. Testing of the magnets is performed in the EBT-P magnet test facility at ORNL.

Following curtailment of the EBT-P project, the magnet development effort was refocused to aim directly at testing and adapting the EBT-P magnets for use in the RFTF proposed

for construction at ORNL. The test facility will use two of the EBT-P magnets, and the third will be a spare.

Testing of development magnet D-1, which began in December 1982, was completed in January 1983. The magnet produced fields as high as 7.4 T, which is 50% greater than the field required for EBT-P. It was charged up to the design field of 5.0 T in less than 2 min and operated stably in the presence of 20 W of induced heating—both values being significantly better than design requirements. Helium boiloff rates due to heat leakage were close to predicted design values.

Assembly of magnet D-2 was completed by GDC in July 1983, and this magnet was tested successfully at ORNL in November 1983 at

fields up to 7.4 T. Again, performance levels were significantly better than design requirements, and there was no evidence of any problem from the broken copper "fingers" believed to be present in the dewar.

Preparations are under way for a two-magnet test of development magnets D-1 and D-2. These tests, which should be completed by April 1984, are intended to demonstrate that the magnets will perform acceptably under the mechanical loadings expected in the RFTF application.

A prototype magnet coil was completed by GDC in January 1983 and was tested in an open dewar at ORNL in March 1983. The performance of the prototype coil in these tests at fields up to 7.4 T was better than the open-dewar test performance of the coils for D-1 and D-2. The improved performance is believed to be related primarily to improvements in the conductor. Two aspects of the conductor changed between the development coils and the prototype.

1. The development coil conductor is a 100% compacted cable, while the prototype conductor is a monolith.
2. The development coil conductor was uncoated, while the prototype conductor is coated with Ebonol C.

GDC is assembling the prototype coil into a development-type dewar so that the completed magnet (D-3) will be interchangeable with magnets D-1 and D-2 and, therefore, suitable for the RFTF. It is desirable that one of the RFTF magnets contain the prototype coil in order to gain operating experience with this apparently superior coil and to have the benefit of the experimental opportunity afforded by the internal voltage taps incorporated in this coil. When magnet D-3 is completed in early 1984, it will be further tested at ORNL to qualify it for service in RFTF.

1.3 EBT ADVANCED CONCEPTS

1.3.1 EBT Reactor Studies—Abstracts

N. A. Uckan

Reactor studies based on the conventional ELMO Bumpy Torus (EBT) concept have been completed. The following abstracts of various papers and reports summarize the results of this study.

1.3.1.1 EBT Reactor Analysis¹⁷

N. A. Uckan

E. F. Jaeger*

R. T. Santoro†

D. A. Spong

T. Uckan

L. W. Owen‡

J. M. Barnes‡

J. B. McBride**

This report summarizes the results of a recent EBT reactor study that includes ring and core plasma properties, with consistent treatment of coupled ring-core stability criteria and power balance requirements. The principal finding is that constraints imposed by these coupling and other physics and technology considerations permit a broad operating window for reactor design optimization. Within this operating window, physics and engineering systems analysis and cost sensitivity studies indicate that reactors with $\langle\beta_{\text{core}}\rangle \sim 6\% - 10\%$, $P \sim 1200 - 1700 \text{ MW(e)}$, wall loading $\sim 1.0 - 2.5 \text{ MW/m}^2$, and recirculating power fraction (including ring-sustaining power and all other reactor auxiliaries) $\sim 10\% - 15\%$ are possible. A number of concept improvements are also proposed that are found to offer the potential for further improvement of the reactor size and parameters. These include, but are not limited to, the use of (1) supplementary coils or noncircular mirror coils to improve magnetic geometry and reduce size, (2) energetic ion rings to improve ring power requirements, (3) positive potential to enhance confinement and reduce size, and (4) profile

*Plasma Theory Section.

†Engineering Physics Division.

‡Computer Sciences.

**Science Applications, Inc., La Jolla, Calif.

control to improve stability and overall fusion power density.

1.3.1.2 "EBT Reactor Characteristics Consistent with Stability and Power Balance Requirements"¹⁸

N. A. Uckan

R. T. Santoro*

This paper summarizes the results of a recent EBT reactor study that includes both ring and core plasma properties and consistent treatment of coupled ring-core stability criteria and power balance requirements. The principal finding is that constraints imposed by these coupling and other physics and technology considerations permit a broad operating window for reactor design optimization. A number of concept improvements are also proposed that are found to offer the potential for further improvement of the reactor size and parameters.

*Engineering Physics Division.

1.3.1.3 "Plasma Engineering Analysis of an EBT Reactor Operating Window"¹⁹

R. T. Santoro*
N. A. Uckan

J. M. Barnes†

The operating space for EBT reactors is calculated using a newly developed systems code that incorporates recent advances in EBT physics. The calculation includes a self-consistent treatment of coupled ring-core stability and power balance requirements. The essential elements of the systems code are reviewed, including magnetics, stability, ring power, power balance, confinement time, and cost calculations. Finally, a typical reactor systems analysis is summarized for a family of EBT reactors that falls within the allowed operating space.

*Engineering Physics Division.

†Computer Sciences.

1.3.1.4 "Transport Scaling Studies for EBT Reactor"²⁰

T. Uckan
E. F. Jaeger*

N. A. Uckan

Transport simulation and modeling studies for the EBT reactor are carried out by using zero-dimensional (0-D) and one- and one-half-dimensional (1½-D) transport calculations. The time-dependent 0-D model is used for global analysis, whereas the 1½-D radial transport code is used for accurate determination of density, temperature, and ambipolar potential profiles and of the role of these profiles in reactor plasma performance. Analysis with the 1½-D transport code shows that profile effects near the outer edge of the hot electron ring lead to enhanced confinement by at least a factor of 2 to 5 beyond the simple scaling that is obtained from the global analysis. The radial profiles of core plasma density and temperatures (or core pressure) obtained from 1½-D transport calculations are found to be similar to those theoretically required for stability.

*Plasma Theory Section.

1.3.1.5 "Assessment of Energetic Ion Rings Versus Electron Rings for an EBT Reactor"²¹

J. B. McBride*
N. A. Uckan

R. J. Kashuba†

This paper summarizes the results of a preliminary assessment of energetic ion rings for use in an EBT reactor. The properties of ion rings are compared with those of electron rings. Ion rings appear to require sizable devices and magnetic field strengths for stable, adiabatic confinement. Stable windows for steady-state ion ring operation having acceptable power requirements, determined mainly by

*Science Applications, Inc., La Jolla, Calif.

†McDonnell Douglas Astronautics Company, St. Louis.

Coulomb drag on the background electrons, appear to exist for EBT reactors. Power requirements for ion rings can be quantitatively lower than those for electron rings, provided the ion ring volume does not greatly exceed the electron ring volume. Some stability properties of ion rings are also discussed. Results of parametric trade-off studies for ion rings versus electron rings using an EBT reactor systems code are presented.

1.3.1.6 "Analysis of Alpha Particle Behavior in EBT Reactors"²²

M. E. Fenstermacher*

N. A. Uckan

A formalism has been developed in terms of a drift kinetic equation with a Fokker-Planck collision operator to calculate alpha particle loss and energy deposition rate coefficients for one position in space and for steady-state operating conditions in an EBT reactor. Pitch-angle and energy-scattering terms were retained in the collision term so that the analysis provides information on alpha particle behavior due to pitch-angle scattering into loss regions in velocity space and information on alpha energy deposition during slowing down in the device. A square well magnetic field shape is assumed, and the resulting particle loss rates and energy deposition rates are calculated. For typical EBT reactor parameters, results show that while 80% to 90% of the alpha particles are scattered into a pitch-angle loss region and lost from the device, more than 70% of the alpha particle energy is deposited in the core plasma and about 1% to 2% goes to alphas retained in the plasma as ash. Parametric studies are performed, and the sensitivity to plasma potential, the pitch angle, the width of loss regions, and computational procedures are analyzed.

*University of Michigan, Ann Arbor.

1.3.1.7 "Particle Confinement in EBT Reactors with Noncircular Mirror Coils"²³

L. W. Owen*

N. A. Uckan

Methods of improving single particle confinement in the vacuum magnetic field of an EBT reactor have heretofore focused on enhancement of the effective magnetic aspect ratio through the addition of relatively low-current supplementary coils to the basic EBT configuration of toroidally linked circular mirror coils. This method of aspect ratio enhancement (ARE) is reviewed and compared to the use of noncircular, D-shaped mirror coils. A critical parameter in this evaluation is the required radial thickness δ of the blanket-shield assembly in the coil throat. Results indicate that D-coils represent an attractive alternative to the supplementary coil configurations if future neutronics calculations show that $\delta \leq 1.1$ – 1.2 m gives adequate neutron shielding and acceptable minimal breeding ratio under the coils. D-coils are shown to be extremely effective in symmetrizing mod-*B* in the mid-plane, thereby giving good trapped particle confinement, hot electron ring centering, and reactor volume utilization. In addition, magnetics systems with D-coils are significantly less complicated, with easier assembly, maintenance, and access than configurations in which there are two supplementary coils per sector.

*Computer Sciences.

1.3.1.8 Transport Simulation for EBT Reactor²⁴

T. Uckan

E. F. Jaeger*

N. A. Uckan

Transport simulation and modeling studies for the EBT reactor are carried out by using 0-D and 1½-D transport calculations. The time-dependent 0-D model is used for global

*Plasma Theory Section.

analysis, whereas the 1½-D radial transport code is used for accurate determination of density, temperature, and ambipolar potential profiles and of the role of these profiles in reactor plasma performance. Analysis with the 1½-D transport code shows that profile effects near the outer edge of the hot electron ring lead to enhanced confinement by at least a factor of 2 to 5 beyond the simple scaling that is obtained from the global analysis. The radial profiles of core plasma density and temperatures (or core pressure) obtained from 1½-D transport calculations are found to be similar to those theoretically required for stability.

1.3.2 Advanced Bumpy Torus Configurations

N. A. Uckan

1.3.2.1 Advanced Bumpy Torus Concepts—Summary of the Workshop²⁵

N. A. Uckan

Introduction. The U.S.-Japan Workshop on Advanced Bumpy Torus Concepts was held at Rancho Santa Fe, California, July 11-13, 1983. It was attended by about 60 participants (55 from the United States and 5 from Japan). The purpose of the workshop was to provide a forum for discussion of recent developments in advanced bumpy torus concepts. The technical coverage in the workshop was very broad. In a total of 25 papers presented, there were many creative new concepts.

The papers presented fell into the following categories:

- Magnetics—Closed Field-Line Devices (five papers)
- Magnetics—Closed Flux-Surface Devices (five papers)
- Interpretation and Supporting Theory (six papers)
- Electric-Field-Enhanced Confinement (three papers)
- RF Heating (three papers)
- Ring Physics (three papers).

It is convenient to review the workshop under these categories.

Magnetics—Closed Field-Line Devices. The papers in this session addressed the magnetics of closed field-line devices. This property of a magnetic field is found in the conventional bumpy torus, which consists of a toroidal array of circular coils. The objective of these advanced concepts is to make the drift surfaces of the trapped and passing particles and the surfaces on which the quantity $\oint d\ell/B$ is constant more concentric and centered near the minor axis of the device so as to maximize the plasma volume utilization and minimize the neoclassical transport. They also have the objective of minimizing direct particle loss due to particles on unconfined drift surfaces. These geometries depend on the *bumpiness* of the field to provide the poloidal drifts that result in closed drift surfaces and to achieve an equilibrium. The hot electron rings that characterize an EBT are still required for plasma stability.

Three of the advanced concepts that were presented consisted of a toroidal array of non-circular coils. The first advanced concept, presented by R. L. Miller,^{*} is identified as the EBTEC (EBT with enhanced confinement). The EBTEC configuration consists of a toroidal array of racetrack-shaped coils ("Andreoletti coils") whose major axes are alternately oriented vertically and horizontally. By adjusting the elongation of the coils and the relative radial shift in the centers of alternate coils, it was possible to obtain nearly concentric trapped and passing particle drift surfaces. The second alternative, presented by L. P. Mai and G. Gibson,[†] is the Bumpy Bean Torus (BBT) that consists of a toroidal array of bean-shaped ("Pacman") coils. A third noncircular coil option, inverted D-shaped (ID) coils, was presented by M. Fujiwara and coworkers.[‡]

^{*}Applied Microwave Plasma Concepts, Inc., Encinitas, Calif.

[†]Westinghouse Electric Corp., Pittsburgh.

[‡]Nagoya University, Japan.

Another class of advanced concepts presented consisted of linear sections of magnetic mirrors connected by curved, high-field regions. All toroidal effects are concentrated in the high-field *corners*. L. W. Owen and coworkers at ORNL have considered racetrack, triangle, and square geometries. However, an in-depth analysis was carried out for the ELMO Bumpy Square (EBS). The Japanese team (Fujiwara et al.) reported on analyses of racetrack and octagon geometries. Westinghouse (Mai and Gibson) proposed the Bumpy Polygon. Results by Owen et al. indicated that the neoclassical confinement time should be an order of magnitude larger for the EBS than for an EBT of comparable size. It was noted that several heating techniques may be more practical for the geometries with linear mirror sections.

Magnetics—Closed Flux-Surface Devices. Papers presented in this session fell into two categories: the design of a new device with closed flux surfaces and the use of EBT principles in closed flux-surface devices. Papers presented by J. F. Pipkins et al.,^{*} R. J. Schmitt et al.,^{*} and M. Fujiwara et al. discussed the use of rotational transform in bumpy tori. A. H. Boozer[†] and J. W. Van Dam[‡] discussed the use of high-energy electrons to enhance the stability of stellarators and tokamaks, respectively.

Pipkins and Fujiwara both described racetrack geometries composed of two straight bumpy sections connected at each end by semi-tori with rotational transform. In these configurations the bumpiness of the field provides favorable poloidal drifts and equilibrium, and the hot electron rings (in the straight sections) provide the stability. Rotational transform in the device described by Pipkins is produced by twisting the racetrack to form a twisted racetrack (TRT).

Fujiwara and coworkers considered a helical bumpy torus (HBT), which is a racetrack geometry that uses toroidal connectors with Wobig coils (the idea of the modular coil stellarator) to produce a rotational transform in a closed line system.

The ELMO Snakey Torus (EST) described by Boozer is a helical-axis (displaced toroidal coil) stellarator that takes advantage of a hot electron component in the initially low-beta startup plasma to provide magnetohydrodynamic (MHD) stability until the core plasma pressure becomes high enough to sufficiently perturb the flux surfaces (Shafranov shift) and produce an MHD-stable configuration. This configuration becomes stable at a beta of about 10% but is unstable at lower beta without the hot electrons. The hot electrons would be produced by ECH, and the hot electron distribution would lie in a band spiraled (or *snaked*) around the torus. Because the device would be stable at its operating beta without the hot electrons, the ECH power could be turned off and, in a reactor, would not contribute to the circulating power fraction.

A similar application of hot electrons to tokamaks was discussed by Van Dam. The tokamak has a stable regime at low beta and also at high beta (second stability regime), but there is an unstable regime at intermediate beta. Again, the hot electrons are required only in the transition phase to access the second stability regime and are not needed during operation at high beta.

Interpretation and Supporting Theory. Papers presented in this session discussed possible means of optimization and/or improvement of bumpy torus plasma parameters, as well as supporting theoretical calculations in the area of equilibrium, stability, and transport.

Discussions by H. Ikegami^{*} concentrated on the optimized operation of bumpy tori. Ikegami noted that the relatively low density feature of the Nagoya Bumpy Torus (NBT) and EBT may be due to their steady-state operation (where particle confinement time is

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[†]Princeton Plasma Physics Laboratory, N.J.

[‡]Institute for Fusion Studies, University of Texas, Austin.

determined by the ionization time), and tokamaks and other devices may run into similar problems as they approach steady state. Showing some experimental results from NBT, Ikegami indicated the possibility of obtaining increased (factor of 3 to 4) plasma density and average ion energy with pulsed ICH and gas puffing.

C. L. Hedrick of ORNL examined the equilibrium and stability properties of modified EBT magnetic configurations, especially those of EBS. It was pointed out that magnetic equilibria are not a theoretical problem for closed field-line systems. One characteristic of the equilibria of EBS is the existence of localized parallel currents in the sides (straight sections) and corners. The effect of corners on the stability was examined, and the results indicated stability at core betas in EBS up to 10%, which was no more stringent than a conventional bumpy torus.

D. E. Hastings of ORNL presented a formalism for calculating transport coefficients for bumpy field-line devices with noncircular flux surfaces. It was shown that the performance of bumpy torus plasmas can be substantially improved by better centering of the $\oint d\ell/B$ surfaces and by making the pressure surfaces elliptical.

J. B. McBride and coworkers[†] described the interaction of rf waves with plasma particles in the magnetic precessional drift frequency range and showed that the transport caused by this process is selective for a single sign of charge or energy component. This active means of altering diffusion could have both near-term (improved confinement, etc.) and future (α -ash removal, etc.) applications.

K. Nguyen and T. Kammash[‡] examined the macroscopic stability of an EBT plasma, assuming that the hot electron rings were adiabatic. Strong line-tying stabilization was observed due to hot electron compression.

A paper by H. Sanuki^{**} considered the effects of ambipolar field on the electrostatic drift waves and showed that a strong ambipo-

lar field (positive or negative) has a stabilizing influence.

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[†]Science Applications, Inc., La Jolla, Calif., and Jaycor, San Diego.

[‡]University of Michigan, Ann Arbor.

^{**}University of California at Los Angeles and Nagoya University, Japan.

Electric-Field-Enhanced Confinement. Papers presented dealt with the possibility of improving the performance of EBT plasmas by maintaining a positive ambipolar potential (positive electric field), by generating rf-induced ponderomotive forces, and/or by employing an alternate startup scenario via externally applied electric fields.

C. S. Chang^{*} showed that EBT plasmas with positive radial electric fields could achieve densities and confinement times as much as an order of magnitude larger than plasmas with negative radial electric fields. In order to generate the positive potential equilibrium, the plasma heating should be concentrated in the plasma center.

H. Hojo et al.[†] examined the possibilities of using ponderomotive forces to confine and stabilize plasmas.

J. R. Roth[‡] reviewed the history of the National Aeronautics and Space Administration-Lewis Research Center (NASA-Lewis) Electric Field Bumpy Torus (EFBT). In that device, electrodes in the plasma generated radial electric fields that confined the plasma. Roth proposed modification of EBT-S to add electrostatic confinement (electrodes).

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[†]Hiroshima University, Japan.

[‡]The University of Tennessee, Knoxville.

RF Heating. Papers presented in this session also dealt with the possibility of improving performance. In this case, however, alternative heating schemes and better launching techniques were discussed.

T. Sato et al.^{*} described recent experiments on the RFC-20 device at Nagoya University. The ICRF waves were applied (by a rotating antenna) both to build up a high-density plasma and to sustain it. It was argued that such a procedure could generate a target plasma in EBT for other heating mechanisms.

D. B. Batchelor (ORNL) examined the effects of controlling the polarization and directivity of the applied ECH waves. It was argued that appropriate wave launching in the EBT-S mirror throat (high-field region) instead of the mirror midplane (low-field region) should allow varying the ratio of ring plasma to core plasma heating.

Ring Physics. Highly energetic particles have been used for stabilization in various devices. Papers in this session discussed the possibility of controlling ring parameters and power losses, as well as the possibility of forming hot electron rings in a modular stellarator.

S. Hamasaki et al.[†] presented a series of model calculations for the power requirements of ring production. It was shown that because the core power requirements scale with the square of the density, whereas ring power scales linearly with density, the idea of using alternative heating schemes for core plasma heating would be more economical than ECH, especially for a reactor.

Combining the features of stellarators, tokamaks, bumpy tori, etc., opens new approaches to configurational optimization (some of which were discussed in previous sections),

as well as introduces new questions. A paper by J. A. Rome et al. (ORNL) addressed one of these questions: Can the hot electron rings be produced in the desired magnetic configuration? The answer seemed to be "yes" in a modular stellarator.

1.3.2.2 "Reactor Assessments of Advanced Bumpy Torus Configurations"²⁶—abstract

N. A. Uckan
L. W. Owen*
D. A. Spong
R. L. Miller†

W. B. Ard
J. F. Pipkins‡
R. J. Schmitt‡

Recently, several innovative approaches were introduced for enhancing the performance of the basic EBT concept and for improving its reactor potential. These include planar racetrack and square geometries, Andreoletti coil systems, and bumpy torus–stellarator hybrids (which include twisted racetrack and helical-axis stellarator–snakey torus). Preliminary evaluations of reactor implications of each approach have been carried out based on magnetics (vacuum) calculations, transport and scaling relationships, and stability properties deduced from provisional configurations that implement the approach but are not necessarily optimized. Further optimization is needed in all cases to evaluate the full potential of each approach.

Results of these studies indicate favorable reactor projections, with a significant reduction in reactor physical size compared to conventional EBT reactor designs carried out in the past. Specifically, with these advanced configurations, reactors with $R \approx 20 \pm 3$ m

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are found to be possible; this is almost a factor of 2 reduction in size compared to recent EBT reactor design points with $R \approx 40 \pm 5$ m (which utilizes symmetrizing coils for an ARE) for comparable power outputs. (Here R is defined as $2\pi R$ -equivalent major radius.) This makes it possible to operate at high wall loadings ($\sim 2\text{--}4$ MW/m², instead of $\sim 1\text{--}1.5$ MW/m²) and increased engineering fusion power density.

1.3.3 ELMO Bumpy Square— Reconfiguration of EBT-S

N. A. Uckan
L. A. Berry
W. E. Bryan
C. L. Hedrick
T. J. McManamy
L. W. Owen*

R. T. Santoro†
D. A. Spong
P. B. Thompson‡
T. Uckan
W. L. Wright

1.3.3.1 Description of EBS

During the past year, several advanced bumpy torus configurations (discussed in Sect. 1.3.2) have been identified and studied in detail as confinement experiments and as reactors. Among these configurations, the EBS has been selected for near-term study because of

1. its ability to address and resolve critical EBT issues,
2. its intrinsic desirability as a reactor configuration, and
3. its contribution to the physics and technology of fusion in general.

A specific EBS configuration discussed here is a reconfiguration of the EBT-S device (Fig. 1.48), which utilizes hot electron rings in bumpy straight sections, combined with high-field corners to minimize the toroidal effects. The EBS realizes the advantages of EBT

without using size as a scaling factor. This specific EBS configuration (Fig. 1.48) is such that straight sides of the square are constructed from EBT-S mirror coils (five mirror coils per side, with a mirror ratio of 1.9), and each corner is formed by eight new half-size EBT-S coils that generate a field with negligible field ripple in the corners. Figure 1.49 shows the plan view of the EBS device within the actual EBT-S enclosure.

The EBS configuration offers a number of distinct advantages over a conventional EBT with respect to *particle confinement*, heating, transport, ring production, and stability. In EBS the particle drift orbits are nearly concentric for trapped and passing particles (Fig. 1.50). The velocity-space loss region for transitional particles (near the boundary between trapped and passing zones) at high energy is greatly reduced, leading to improved volume utilization (Fig. 1.51), significantly reduced direct particle losses, more symmetric potential surfaces, and increased microwave heating efficiency. For an isotropic distribution, more than 95% of the particles are

Fig. 1.48. Geometry of an EBS configuration indicating the coil arrangements (top view).

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†Engineering Physics Division.

‡Engineering Division.

Fig. 1.49. Site-plan view of an EBS device within the original EBT-S enclosure and support structures.

confined in EBS as compared to $\sim 50\%$ confinement in EBT-S (see Fig. 1.51).

The combination of nearly concentric particle drift orbits and the small radial displacements in the high-field corners gives an order-of-magnitude reduction in neoclassical diffusive losses (Fig. 1.52). In addition, Monte Carlo calculations (Fig. 1.53) indicate that symmetric potential surfaces (as expected for EBS) increase diffusion lifetime more than an order of magnitude over those obtained with asymmetric potentials (observed in EBT-S). The orbits of the deeply trapped particles ($V_{\parallel}/V \approx 0$) and core plasma pressure surfaces ($\oint dR/B$ contours) almost coincide and are cen-

tered on the minor axis. There being no shift, hot electron rings will be exceedingly well centered in EBS, with little or none of the radial broadening of the ring that occurs in EBT-S. This should make it easier to form an average magnetic well in EBS than in EBT-S.

Detailed calculations in the areas of equilibrium and stability indicate that equilibria exist (shifts are smaller in a square configuration than in a torus) and that the stability limits (especially those associated with the corners) are no more restrictive than those studied for a conventional EBT (Fig. 1.54).

Reactor projections for EBS indicate the possibility of a substantial reduction in reactor

Fig. 1.50. Vacuum field single-particle drift orbits (dashed lines) and $f dR/B$ contours (solid lines) for EBT-I/S (top) and EBS (bottom), in the reference midplane. Deeply trapped ($V_{||}/V = 0$), extreme passing ($V_{||}/V = 1$), and transitional particles near the boundary between the trapped and passing zones (worst-confined drift orbit) are shown. Note the absence of transitional particle orbits in EBT-I/S (i.e., worst orbit does not close within the volume) and its existence in EBS.

physical size (a factor of 2 to 3), compared to past EBT designs (Fig. 1.55). Further reductions are anticipated as the concept continues to develop.

Conceptual design of the EBS, involving the modification and reconfiguration of the EBT-S, has been completed. At present, there are no uncertainties (other than budgetary) associated with the operation, technology, research and development, construction, and projected cost and schedule.

In summary:

1. EBS responds to specific confinement issues raised by EBT-S and provides direct and crucial information to the development of the EBT concept.

Fig. 1.51. Volumetric efficiency curves for EBT-I/S and EBS as a function of pitch angle $V_{||}/V$ at the limiting flux line in the midplane indicate containment of more than 95% of particles in EBS, compared to ~50% in EBT-I/S (i.e., the direct-loss fraction is less than 5% in EBS and ~50% in EBT-I/S for vacuum fields).

2. EBS uses existing EBT-S site and enclosure, hardware, and facilities (mirror coils, heating systems, power supplies, control systems, utilities, data acquisition, etc.) and is, therefore, cost effective.
3. EBS allows the EBT program to continue its many benefits to the overall fusion program.

Fig. 1.52. Particle transport coefficient D_n as a function of collisionality ν/Ω_e for EBT-I/S and for EBS. Similar curves are obtained for D_T , K_n , and K_T with the same ratio of improvements in EBS, compared to EBT-I/S. Note that $\tau(\text{EBS})/\tau(\text{EBT-I/S}) \sim D(\text{EBT-I/S})/D(\text{EBS}) \sim 5-15$.

Fig. 1.54. Stability of bumpy square is examined using a ballooning mode equation derived from generalized kinetic energy principle. Results indicate that the core-beta limit is determined by ring-core interaction (LVN limit) in the sides and not by ballooning modes in the corners. Note that, for $M_G \geq 4$, bumpy square and bumpy cylinder (torus) results are essentially identical; for $M_G \leq 2$, stability boundaries begin to deteriorate and corners start to play an important role.

Fig. 1.53. Monte Carlo calculations indicate that (a) symmetric potential surfaces (as expected for EBS) increase diffusion lifetime more than an order of magnitude over those obtained with (b) asymmetric potentials (observed in EBT).

Fig. 1.55. The development of new EBT configurations has continued the trend to smaller EBT reactor systems.

1.3.3.2 Contributions of EBS to overall fusion program

The EBT concept offers significant diversity from other geometries, specifically because it is (1) steady state, (2) nonaxisymmetric, and (3) microwave heated and has (4) ambipolar fields

and (5) closed field lines. Historically, the EBT program has contributed to the development of fusion in a broad sense, including:

- ECH physics and technology,
- nonaxisymmetric transport (ambipolar potential),
- heavy ion beam diagnostics,
- steady-state plasma-wall interaction,
- stabilization by hot electrons and physics of very high temperature plasmas, and
- steady-state, modular reactor concepts.

The EBS will allow the EBT program to continue those contributions and further advance the following areas:

- kinetic stabilization by hot electrons in higher-pressure and pressure-gradient systems,
- control of ambipolar potential,
- effect of high fields on confinement,
- rf-driven transport, and
- advanced configuration design.

For example, in the area of stability theory, EBT provided the major impetus for recent extensive studies of the spatial stability properties of energetic particle plasmas. These studies have been fruitful in (1) extending the fundamental theory of stability and (2) obtaining fusion-relevant stability criteria for EBT, mirrors, and tokamaks. EBT inspired the development of a new variational principle and detailed eigenmode analyses valid in the previously unexplored low-frequency regime of modes that grow on the curvature-drift time scale. EBT was a motivation for generalizations of the gyrokinetic equation to arbitrary

frequencies and relativistic energies. These theories are applied to EBT and had (and continue to have) productive applications to both mirrors and tokamaks.

For mirrors, the hot particle-stabilization method of EBT has been proposed as a means to have stable axisymmetric end cells in a tandem mirror. Another application of the new formalism, to low-frequency compressional instability in a mirror (without energetic particles), subsequently led to a separate major investigation of trapped-particle modes in tandem mirrors.

In tokamaks, introduction of EBT-type, high-energy particles was proposed and predicted to enhance stability by providing access to the high-beta "second stable" regime. The new low-frequency theory was applied to moderately energetic trapped ions to show that the internal MHD kink mode can be destabilized by their drift resonance; this mechanism was successfully employed to explain *fishbone* oscillations observed in beam-heated tokamaks.

The electrostatic potential has a major impact on the particle transport in nonaxisymmetric devices. This includes devices such as rippled tokamaks, stellarators, and tandem mirrors. In the EBS, as in EBT-S, the potential is probably connected with the presence of the energetic electrons. The EBS will provide an experimental means to test whether or not the potential can be controlled by controlling the energetic particles. This technique, if successful, could have major implications of potential control in other devices and could be used to substantially improve the transport in other confinement systems.

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Chapter 2

Toroidal Confinement Experiments

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2. TOROIDAL CONFINEMENT EXPERIMENTS

Summary of Activities

This chapter details the progress that has been made in the area of our toroidal confinement experiments. The principal program elements are (1) the Impurity Study Experiment (ISX-B) tokamak; (2) work toward design and construction of our next experimental facility, the Advanced Toroidal Facility (ATF) torsatron, and toward more extensive definitions of the ATF program; and (3) our collaboration with the Princeton Plasma Physics Laboratory (PPPL) on the Toroidal Fusion Test Reactor (TFTR) tokamak.

The reader will note that the ORNL/PPPL collaboration is a new program element. It is the means by which a number of our staff will continue their contributions to the national fusion program during the gap in availability of our own experimental facility. The construction schedule for ATF requires that ISX-B cease operations in September 1984; ATF becomes operational in October 1986. We will maintain a significant presence at PPPL during that interval.

As detailed here and in the following sections, each of the program elements proceeds well:

- ISX-B has given emphasis to the roles of plasma rotation and potential in confinement, to confinement improvement with deliberate introduction of some low-Z impurities, and to particle control with pump limiters and pellet injection. As of April 1984, the facility will have switched to test of a beryllium limiter under a work-for-others contract with JET (the Joint European Torus), and last year's preparations for this experiment are described.
 - The ATF project is on schedule, and several developments this past year have increased our confidence in its anticipated performance.
 - The collaboration on TFTR already has involved numerous of our personnel making short working visits to Princeton. The results speak well for the future of this endeavor.
-

2.1 THE ISX-B EXPERIMENTAL PROGRAM

The ISX-B experimental program in 1983 has emphasized three major areas: (1) the roles of plasma rotation and potential in confinement, (2) confinement improvement with deliberate introduction of some low-Z impurities, and (3) particle control with pump limiters and pellet injection. These studies are aimed at better understanding of mechanisms governing confinement in beam-heated discharges and at improvements of performance of large tokamaks with limiters.

The studies of roles of plasma rotation in confinement have been facilitated by an additional neutral beam injector, oriented counter to the two pre-existing injectors, to provide separate control over the energy and momentum inputs. "Balanced" injection with cobeams plus counterbeams at equal power eliminate toroidal plasma rotation. However, there is no improvement in either global energy confinement τ_E^0 or in the electron thermal diffusivity χ_e . Therefore, the deteriorated confinement observed with coinjection is not due to a rotation effect. Momentum and plasma particle

and impurity transport are affected by the momentum input and its direction.

A heavy ion beam probe (in collaboration with the Rensselaer Polytechnic Institute) has been used to measure plasma space potential and electric field associated with different momentum inputs. In ohmically heated (OH) plasmas, a negative potential well is formed with $E_r \approx -30$ V/cm in the bulk of the plasma. With coinjection the potential becomes negative, and there is a reversal of E_r . These results are in qualitative agreement with the expectations of a momentum balance using measured rotation velocities and pressure profiles.

As previously observed in ISX-B, the presence of small quantities of some low-Z impurities in beam-heated discharges tends to improve energy confinement relative to the ISX-B scaling obtained with clean discharges in the gettered torus. This phenomenon (referred to as the "Z-mode") has been studied using comparisons between discharges with and without gettering and between gettered discharges with and without neon injection. Relative to clean, gettered discharges, both nongettered and neon-injected discharges are characterized by (1) τ_E^* up to 80% higher and linearly dependent on density, (2) improved particle confinement, (3) only a small increase in Z_{eff} (1.5 to 2), (4) reduced χ_e , and (5) reduced fluctuation levels. These studies suggest the exciting possibility of creating a controlled radiating mantle in large tokamaks with limiters while simultaneously improving the energy and particle confinement.

Tests have been made on ISX-B of particle control using pump limiters and four-shot pneumatic pellet injection in beam-heated discharges. Upon activation of the gettered modules within the pump limiters, the plasma density is decreased by factors of 2 in ohmic discharges and 1.4 in beam-heated discharges. The exhaust efficiency (the ratio of the removed particle flow rate to the total flux in the scrape-off layer) has been determined to be 5%. The smaller density change observed in

the beam-heated discharges is consistent with a lower recycling coefficient (~ 0.8 , as opposed to ~ 0.9 in ohmic discharges) due to higher particle energies. The pellet injector delivers a programmable sequence of one to four 1-mm (or 1.5-mm) pellets at velocities ranging between 0.5 and 1.0 km/s. The pressure in the pump limiter increases proportionately to the density in pellet-injected plasmas. The techniques and their combination provide particle-control options for future long-pulse devices.

The ISX-B experimental program, which began in July 1978, will be terminated at the end of this fiscal year. The remaining operating time will be used to carry out a test of beryllium limiters for JET.

2.1.1 Plasma Rotation and Impurity Transport

2.1.1.1 Plasma rotation measurements

R. C. Isler

Studies of plasma rotation were extended to include scaling experiments and to investigate the effects of opposing injection. The studies were made possible by equipping the normal incidence spectrometer with a vibrating mirror so that the shapes of vacuum ultraviolet lines could be scanned once every 10 ms and the doppler shifts measured. The use of vacuum ultraviolet (VUV) spectrum allowed charge-exchange excitation (CXE) lines to be used for the central rotation and the $^3\text{P} \rightarrow ^3\text{S}$ transitions of the helium-like ions of recycling impurities to be used for the rotation at large minor radii.¹ The central rotation was measured during coinjection sequences as a function of beam power, electron density, and plasma current. Figures 2.1, 2.2, and 2.3 illustrate $v_\phi(0)$ for these parameter scans. The dependence on the external, controlled parameters is seen to be weak for all cases. In particular, it is surprising that the rotation velocity increases by only about 20% as the injected power is changed from 200 kW to 1.2 MW. This result indicates that the momentum confinement time

Fig. 2.1. Central rotation and energy content as functions of input power.

Fig. 2.2. Central rotation velocities as a function of density for 900-kW input.

Fig. 2.3. Rotation velocities of O IX and O VIII as a function of plasma current for 900-kW input.

degrades with beam power similar to the global energy confinement time. Measurements using opposing beams confirm this conclusion. Figure 2.4 shows the central rotation during a

Fig. 2.4. Central rotation velocity for 900-kW co-injection and 450-kW counterinjection.

discharge employing 950 kW of coinjection power and 450 kW of counterinjection power. The net momentum of 450 kW would be expected to yield a velocity near 10^7 cm/s from the data shown in Fig. 2.1 if the momentum confinement times were the same. The lower measured experimental value ($5-6 \times 10^6$ cm/s) indicates that the momentum confinement is a function of the total input, rather than of the directed input. Actually, the net momentum transferred to the plasma from the counterinjection beam is calculated to be less than the 450 kW entering the plasma because of the fast-ion losses. Therefore, the extent to which the toroidal rotation slows down is even more strongly dependent on the beam power when calculated from the input alone. As a result, balanced amounts of coinjection and counterinjection power tend to reduce the rotation velocity to zero within the experimental uncertainties, despite the fact that significant differences are

expected for the fast-ion losses from the two beams. The results for balanced injection are shown in Fig. 2.5. One of the prime motivations for investigating discharges having no net momentum transfer was to determine whether eliminating rotation would improve the global energy confinement time. All experiments have shown, however, that this quantity is unaffected by stopping the rotation. Figure 2.6 illustrates τ_E^* for the discharge characterized by Fig. 2.5 with the so-called ISX-B phenomenological scaling law. The deviations are within the experimental uncertainties.

Fig. 2.5. Central rotation velocity for 900-kW balanced injection. The velocity is zero within $\pm 1.5 \times 10^6$ cm/s with both beams operating.

As in all other tokamaks, the toroidal rotation is much lower than expected if neoclassical viscosity is the only mechanism for transporting momentum radially out of plasmas. Monte Carlo calculations of the momentum transferred individually to the plasma ions and the oxygen impurity are used in conjunction with the measured rotation speeds to deduce confinement times. These are typically 25 ms for the deuterium and 5 ms for the oxygen, if it is assumed that $v_\phi(0)$ is identical for both species; however, the calculations for individual species are very sensitive to the differences of $v_\phi(0)$.

Fig. 2.6. Measured global energy confinement time (solid lines) and the phenomenological scaling (dashed lines) for balanced-beam injection.

But this quantity cannot be measured, since it is estimated to be on the order of 10^5 cm/s (smaller than the experimental uncertainties by almost an order of magnitude and smaller than v_ϕ itself by almost two orders of magnitude). It is more sensible to calculate an average momentum confinement time by summing the contributions from the main ions and the impurities and dividing by the total momentum input. This average value is 16 ms for the cases that have been analyzed using the Monte Carlo code. To obtain another measurement of the confinement time, an experiment was performed in which the beam was turned off before the end of the shot and the decay of the rotation was measured. The time behavior is shown in Fig. 2.7 for neon that is seeded into the plasma as a test impurity. The rotation returns to zero within 50 ms after injection stops. The decay is not exponential, but an effective $1/e$ time is 35 ms. This time is twice as long as that inferred from the steady-state velocity, but once the fast-ion slowing down time (≈ 20 ms) is taken into account, the two measurements appear to be consistent. The

Fig. 2.7. Near-central rotation velocity showing the decay after the beam is turned off.

decay rates computed from a standard neoclassical formulation are much longer, up to 1 s (ref. 2). Therefore, a large anomaly of the momentum transport is indicated, despite the fact that both the ion conductivity and the impurity transport exhibit neoclassical-like behavior.

2.1.1.2 "Impurity Transport and Plasma Rotation in the ISX-B"³—abstract

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Recent calculations have shown that when external momentum sources and plasma rotation are included in the neoclassical theory, the standard results for impurity transport can be strongly altered. Under appropriate conditions, inward convection is reduced by coinjection and enhanced by counterinjection. In order to examine the theoretical predictions, several observations of impurity transport have been made in the ISX-B tokamak during neutral

beam injection for comparison with the transport seen with ohmic heating alone. Both intrinsic contaminants and deliberately introduced test impurities display a behavior that is in qualitative agreement with the predicted beam-driven effects. These correlations are particularly noticeable when the comparisons are made for deuterium, where the impurity transport in the OH discharges exhibits neoclassical-like characteristics (i.e., accumulation and long confinement times). Similar but smaller effects are observed in beam-heated hydrogen discharges; neoclassical-like behavior is not seen in OH hydrogen sequences. Emphasis has been placed on measuring toroidal plasma rotation, and semiquantitative comparisons with the theories of beam-induced impurity transport have been made. It is possible that radial electric fields other than those associated with momentum transfer and increased anomalous processes during injection could also play a role.

2.1.2 "Confinement Improvement in Beam-Heated ISX-B Discharges with Low-Z Impurity Injection"⁴—Abstract

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Results are reported on improved confinement in the ISX-B neutral-beam-heated plasmas when a small amount of neon is injected shortly after the start of beam heating. The scaling of energy confinement is modified by

the introduction of a dependence on line-averaged density. Calculations show the improvement is primarily caused by a reduction in electron heat conduction.

2.1.3 Transport Studies

2.1.3.1 Thomson scattering and transport studies on ISX-B

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Electron temperature and density measurements in ISX-B were continued during 1983 with the Thomson scattering diagnostic, ScatPak II. Approximately 3000 ISX-B shots were taken with T_e and n_e values at up to 15 local points along a vertical chord. Among these were approximately 100 sequences of 15 to 40 reproducible shots during which the vertical chord was radially scanned. These profile data were analyzed with the transport analysis code ZORNOC, and the results were stored with the raw data in the Thomson Scattering Data Management System (TSDMS). Three issues are of special interest relating to transport properties of the ISX-B plasmas: (1) characteristics of Z-mode discharges, (2) effects of plasma rotation in confinement, and (3) estimation of momentum confinement and space potential.

The presence of small quantities of some low-Z impurities, either intrinsic or externally injected, substantially increases both electron and ion energy content.⁴ Power balance shows that χ_e in the confinement region ($0.4 \leq P/a \leq 0.8$) in these discharges is substantially lower than that in the corresponding clean, gettered discharges. It also shows that the increase in ion energy content results primarily from a larger fraction of beam power transferred to better confined ions, rather than from reduction of χ_i itself. Efforts at estab-

lishing the connection between the χ_e improvement and edge behavior are continuing.

The studies of roles of plasma rotation and electric field in confinement have been facilitated by balanced beam injection, since it eliminates toroidal plasma rotation (see Sect. 2.1.1). A detailed comparison between balanced and coinjection discharges with equal beam power (1.6 MW) shows that global energy confinement times are about equal and that the overall energy balance in both discharges is dominated by electron heat conduction. In both cases, the experimental ion temperature $T_i(0)$ determined from the active charge-exchange and neutron-flux analyses (detailed in Sect. 2.1.4) is about equal to that predicted by ion power-balance calculations using the neoclassical ion transport coefficient [i.e., $1.0 \times \chi_i$ (Chang-Hinton)] without including any rotation effects. The large electron losses and uncertainties in the ion temperature values make the results somewhat inconclusive regarding the question of whether ion confinement is affected by rotation as theory predicts; nonetheless, the absence of any improvement in either overall energy confinement or in electron thermal diffusivity with balanced injection has been firmly established.

The data analysis code ZORNOC has been modified to treat some aspects of plasma rotation and associated plasma potential.⁵ It now incorporates the parallel momentum balance equation to calculate perpendicular viscosity and the radial force balance equation to calculate the flux-averaged ambipolar potential $\langle \phi(r) \rangle$. The potential has been calculated for typical coinjection, counterinjection, and balanced injection, as well as for OH discharges, using plasma rotation velocities from Doppler-shift measurements of impurities (refer to Sect. 2.1.1). The calculated $\langle \phi(r) \rangle$ values are sensitive to uncertainties in $V\phi(r)$ and $T_i(r)$, but they change substantially as beam-injection geometries are changed. Gross features of potentials measured with the heavy ion beam probe for OH coinjection and counterinjection discharges are in agreement with the predicted changes.

2.1.3.2 *Experimental Results on Finite-Beta Limits and Transport in the ISX-B Tokamak*⁶—abstract

A. J. Wootton	J. F. Lyon
S. C. Bates	C. H. Ma
C. E. Bush	P. K. Mioduszewski
B. A. Carreras	M. Murakami
W. A. Cooper	L. E. Murray
J. L. Dunlap	G. H. Neilson
P. H. Edmonds	V. K. Pavlenko
O. C. Eldridge	M. J. Saltmarsh
A. C. England	S. D. Scott
W. L. Gardner	J. Sheffield
J. T. Hogan	D. J. Sigmar
W. A. Houlberg	J. E. Simpkins
H. C. Howe	K. A. Stewart
D. P. Hutchinson	W. L. Stirling
R. C. Isler	C. E. Thomas
T. C. Jernigan	J. B. Wilgen
R. R. Kindsfater	W. R. Wing
P. W. King	J. D. Bell
R. A. Langley	L. A. Charlton
E. A. Lazarus	R. M. Wieland

A summary of experimental results pertaining to plasma energy and particle transport in the ISX-B tokamak is presented. Emphasis is placed on results with neutral beam heating, usually in the "co" direction (aligned with the plasma current), and the relative roles of various energy-loss mechanisms are discussed. The derived electron thermal diffusivity and the predictions of various models have been compared. The measured values are within a factor of 2 of the values expected to result from resistive pressure-driven modes. Evidence for the presence of these modes is discussed.

Values of ion thermal diffusivity are compared with the predictions of neoclassical theory. Anomaly factors (the ratio of experimental value to theoretical value) between 1 and 5 are found. Comparisons between experimental results and theoretical predictions are also made for cases with increased toroidal field ripple, produced using only 9 of the 18 toroidal field (TF) coils.

Convection is shown to play a small role in energy transport, except at the plasma periphery. The behavior of both plasma and impurity particles is discussed and shown to be strongly dependent on the direction of the plasma current relative to the neutral beam (coinjection and counterinjection). Results obtained for impurities are in qualitative agreement with the expectations of models that include the effects of toroidal mass rotation and direct momentum transfer.

Beta limits are discussed. The maximum values obtained for both β_T (~ 2) and $\langle \beta \rangle$ ($\sim 2.5\%$) are not thought to be limited, except by the restricted power available for heating.

2.1.4 Impurity and Energy Flux Studies

2.1.4.1 Energy flux studies on ISX-B

C. E. Bush	B. G. Peterson
M. Murakami	

Characterization continues of ISX-B based on measurements of total and radial and toroidal variation of radiated power from the plasma and energy flux to limiters. A variety of experiments were carried out; however, some areas of impurity and energy flux studies are currently of specific interest. These include determination of general scaling trends of radiated power on fueling, heating, and impurity control. Specific experiments with gettering, impurity gas puffing, neutral-beam-injection heating and pump limiters are to be described briefly and in the context of energy flux behavior. Energy flux diagnostics available for most of these studies have been (1) an array of radially collimated detectors for determining the radial distribution of volume impurity radiation, (2) a sparse array of toroidally collimated detectors to determine toroidal symmetry (or asymmetry) of radiated power, and (3) for the first time on ISX-B, time-resolved and spatially resolved measurements of the surface temperature at, and thus energy flux to, a TiC-coated graphite pump limiter. Descriptions of the radiometer arrays were given in

the previous annual report⁷ and will not be repeated here; however, brief descriptions of the temperature measurement technique and results for the pump limiter are included.

General behavior of impurity radiation observed in earlier ISX-B experiments continues to be valid. As before, in general, radiation is not the dominant energy-loss mechanism in ISX-B. For ungettered discharges, with $\bar{n}_e \approx 4 \times 10^{13}$, the total power radiated is $\sim 40\%$ for ohmic heating alone, and as beam power increases, this fraction decreases to $\sim 20\%$ at neutral beam power levels of about 2 MW. With titanium gettering, the fraction radiated is reduced significantly. For example, with 1 MW of beam power injected into a gettered discharge ($\bar{n}_e \approx 4 \times 10^{13}$), the fraction of power radiated is $\sim 15\%$, compared to $\sim 25\%$ for ungettered discharges. This difference is due to reduced volume emission throughout the plasma minor cross section. This is clear from Fig. 2.8, which includes plots of impurity radiation emission versus minor radius. For both cases, emission from the outer portion of the plasma is dominant. However, for the ungettered case, the radiated power at the edge is higher and is from a thin shell with the peak occurring at a slightly

Fig. 2.8. Comparison of volume impurity radiation emission between ISX-B discharges with and without titanium gettering. For both discharges, $P_{inj} \approx 1$ MW and $\bar{n}_e \approx 4 \times 10^{13}$. The vertical dashed lines show locations of the centers of the minor cross sections of the two plasmas.

larger radius than for the ungettered case. Also, there is more power radiated from the central core in the ungettered case (though it is still only a small fraction of the total radiated power and an even smaller fraction of the total input power) than in the gettered discharge.

Neon-injection experiments were done principally for Z-mode studies, and they help in efforts to understand the role of recycling in ISX-B. However, in interpreting the radiated power for impurity injection, density dependence of impurity radiation must be accounted for or biased out. This is shown by the fact that without impurity injection (i.e., with only intrinsic impurities), radiated power increases with increasing density, both for pure OH and beam-heated plasmas. For ungettered deuterium discharges with plasma current of 180 kA and $P_{inj} \approx 0.9$ MW, the fraction of power radiated increased from 18% at $\bar{n}_e \approx 2.3 \times 10^{13} \text{ cm}^{-3}$ to $\sim 38\%$ at $\bar{n}_e \approx 6 \times 10^{13} \text{ cm}^{-3}$. In addition, as noted in the last annual report,⁷ though bulk plasma impurity radiation doubles over this density range ($\bar{n}_e$ increases by 2.5 times), there is very little change in the radiated power at the limiter. When neon is puffed into these plasmas, the radiated power increases—but so does $\bar{n}_e$. Therefore, comparisons with and without neon injection are done between discharges with essentially the same density histograms. For example, radiated powers for gettered neutral-beam-heated discharges with and without neon (and similar density levels and behavior) are shown in Fig. 2.9, along with their respective $\bar{n}_e$ histograms. In this case, radiated power from the bulk plasma nearly doubles with neon injection, while that at the limiter only increases by $\sim 25\%$. Since the ratio of radiated power at the limiter to that of the bulk plasma is ~ 10 , the 25% increase at the limiter with neon injection can be accounted for by the increased radiation from the bulk plasma, also implying that no enhanced recycling of the injected neon takes place at the limiter.

Pump-limiter experiments may provide additional opportunity for studying recycling near

Fig. 2.9. Total radiated power P_{rad} with and without neon puffing. For both discharges, $P_{inj} \approx 1$ MW and $\bar{n}_e \approx 4 \times 10^{13}$ at $t \approx 250$ ms.

limiters. In these experiments, the upper and lower pump limiters are mounted in a sector $\sim 40^\circ$ toroidally from the main ISX-B outer "mushroom" and inner rail limiters. The main and pump limiters are all made of graphite coated with a thin layer of titanium carbide. The energy flux to the main limiters may be changed by inserting the pump limiters beyond the tips of the main limiters. Most of the pump-limiter experiments have been done with the pump limiters at positions to yield a 22-cm-radius plasma; the normal radius determined by the inner and outer limiters is ~ 26 cm. With the upper and lower pump limiters located at ± 22 cm, the radiated power may be measured at the main limiter sector and other points around the torus and the results compared with those obtained with the pump limiters withdrawn. Concurrently, time-resolved measurements of the surface temperature of the bottom limiter are made using an infrared camera (AGA 680).

A schematic (Fig. 2.10) illustrates the use of the infrared camera to measure the surface temperature of the bottom pump limiter. Since the pump limiters are mounted on ports

Fig. 2.10. Schematic showing the technique for measuring the surface temperature of the bottom limiter using the AGA 680 infrared camera.

directly opposite each other, viewing with the camera must be done off-axis at an angle of $\sim 11^\circ$ from the vertical. To facilitate viewing, components such as the gold-coated front surface mirror and the calcium fluoride window are used because they are, respectively, highly reflecting and transmitting in the 1- to $7\text{-}\mu\text{m}$ range of the infrared optical spectrum. The camera scans the limiter along a diameter of the projected circle of the limiter, which is parallel to the toroidal direction. There is one scan each $625\text{ }\mu\text{s}$, and due to limited data storage, only one scan every 5 ms is digitized. Each scan provides the time-resolved temperature profile across the surface of the limiter, and 110 points per scan are digitized. Temperature profiles for four different instants during a beam-heated ISX-B discharge are given in Fig. 2.11. For this particular discharge, the

Fig. 2.11. Spatially resolved bottom pump-limiter surface temperatures for four instants of time into an ISX-B discharge (0, 180, 240, and 300 ms). $P_{inj} = 1$ MW and top and bottom limiters are at ± 22 cm, respectively. The center of the limiter is at $s = 0$ cm. (Shot 51455.)

left half of the figure represents temperatures on the "left" half or ion side of the limiter for the coinjection-heated plasma, and the right half of the figure represents the "right" side. For nearly every case of coinjection, the heating pattern was asymmetric, as indicated by the figure, with higher temperatures occurring on the ion side. Inversion of the time-resolved and spatially resolved limiter surface temperature data yields information about energy flux to the limiter. Power per unit area as a function of distance behind the tip of the pump limiter is plotted in Fig. 2.12.

Inserting the pump limiters beyond the main limiters would also be expected to change the toroidal variation of impurity radiation. To what extent this occurs is not clear.

The radiated power at the main limiter section is somewhat reduced; however, it appears to be much less reduction than expected. This observation would seem to indicate that significant energy flux is getting beyond the tips of the pump limiters and into the scrape-off region, where some of it impinges on the main

Fig. 2.12. Energy flux to the bottom pump limiter vs distance behind its tip for the same discharge as that for the temperature data of Fig. 2.11. For this figure, energy flux is assumed to be at normal incidence to the limiter surface.

limiters, which are about 3 to 4 cm within the shadow of the pump limiters. On the other hand, this condition would be in agreement with pump-limiter temperature measurements that show peak surface temperatures significantly lower than those expected for ~ 1 MW of neutral beam heating.

Additional measurements of pump-limiter surface temperatures and of impurity radiation are to be carried out in future ISX-B experiments. These will be made in support of studies aimed at further understanding the transport of energy to the edge plasma and of impurity recycling at the limiter and between the walls and the bulk plasma.

2.1.4.2 "Effects of Neutral Beam Co- and Counter-Injection on Impurity Radiation from ISX-B Plasmas"⁸—abstract

C. E. Bush
S. C. Bates
J. L. Dunlap
E. A. Lazarus
M. Murakami

V. K. Paré
C. E. Thomas
B. Thomas, Jr.
R. M. Wieland

In addition to heating, neutral beam injection modifies the impurity transport in ISX-B

plasmas. Radiometric data show the effects of coinjection and counterinjection on impurity radiation profiles to be significantly different. Data from an array of 12 collimated detectors and an uncollimated monitor (all pyroelectric) show the radial distribution of volume impurity emission to be peaked at the center of the discharge with counterinjection and at the plasma edge with coinjection, especially for $P_{inj} > 1$ MW. At high coinjection power, only 20% of the total input power is lost as impurity radiation. Also, coinjection-heated discharges reach an equilibrium shortly after beam turn-on, whereas counterinjection-heated discharges do not reach equilibrium and usually terminate disruptively. It is conjectured that the disruption is due to modification of the plasma current distribution resulting from the extreme cooling at the plasma core.

2.1.5 Particle Control—Abstracts

2.1.5.1 "Particle Removal with Pump Limiters in ISX-B"

P. K. Mioduszewski
L. C. Emerson
J. E. Simpkins
A. J. Wootton
C. E. Bush
A. Carnevali
J. L. Dunlap
P. H. Edmonds
W. L. Gardner
H. C. Howe
D. P. Hutchinson
R. C. Isler

R. R. Kindsfather
R. A. Langley
E. A. Lazarus
C. H. Ma
M. Murakami
G. H. Neilson
V. K. Paré
S. D. Scott
C. E. Thomas
J. B. Whitley
W. R. Wing
K. E. Yokoyama

First pump-limiter experiments were performed on ISX-B. Two pump-limiter modules were installed in the top and bottom of one toroidal sector of the tokamak. The modules consist of inertia-cooled, TiC-coated graphite heads and Zr-Al getter pumps, each with a pumping speed of 1000 to 2000 L/s. The objective of the initial experiments was the demonstration of plasma particle control with pump limiter. The first set of experiments was performed in ohmic discharges (OH) in

which the effect of the pump limiters on the plasma density was clearly demonstrated. In discharges characterized by $I_p = 110$ kA, $B_T = 15$ kG, $\bar{n}_e = 1.5 \times 10^{13}$ cm⁻³, and $t = 0.3$ s, the pressure rise in the pump limiters was typically 2.0 mtorr with the pumps off and 0.7 mtorr after activating the pumps. When the pumps were activated, the line-average plasma density decreased by up to a factor of 2 at identical gas flow rates. The second set of measurements was performed in neutral-beam-heated discharges [neutral beam injection (NBI)] with injected powers between 0.6 and 1.0 MW. Because of a cooling problem on one of the Zr-Al pumps, the NBI experiments were carried out with one limiter only. The maximum pressure observed in NBI discharges was 5 mtorr without activating the pumps (i.e., approximately twice as high as in OH discharges). The exhaust efficiency, which is defined as the removed particle flux over the total particle flux in the scrape-off layer, is estimated to be 5%.

2.1.5.2 "Experience with Zr-Al Getter Pumps in the ISX-B Tokamak"

L. C. Emerson
P. K. Mioduszewski

J. E. Simpkins

The pump limiters on ISX-B require a hydrogen pumping speed of approximately 1000 to 2000 L/s at the neutralizer plate. With the given restrictions (i.e., pumping port diameter and magnetic field environment), the only practical choice was to install Zr-Al getter cartridges directly behind the limiter head inside the main vacuum vessel. Laboratory tests had shown that this arrangement maintained pumping speeds in excess of 10^3 L/s at pressures as high as 10 mtorr, which is typical during pump-limiter operation. When the pumps are in operation, each getter cartridge absorbs a few hundred torr-liters of hydrogen over a day's operation. This represents only a small fraction of the total capacity of 4×10^3 torr·L and can be outgassed easily. Problems arose, however, under the following conditions:

1. When the pumps were fully activated, regular discharge cleaning could not be performed. Self-inerting, as reported by the Princeton Plasma Physics Laboratory (PPPL), was not observed on ISX, resulting in a hydrogen uptake close to the embrittlement limit of the alloy.
2. After the Zr-Al cartridges were exposed to air and assumed to be passivated, some process caused a minute activation of the getter, resulting in a pumping speed of about 1.0 L/s or 10^{-3} of the rated pumping speed.

This did not present a problem during regular plasma operation or discharge cleaning, but it was not compatible with the calibration process for the Thomson scattering diagnostics as performed on ISX. This calibration procedure requires a hydrogen pressure of 12 torr in the tokamak vessel for several hours. Even though the pumping speed of the Zr-Al pumps was minute, the high pressure led to embrittlement of the pumps within about 15 min. Consequently, the pumps were taken out of the tokamak for further laboratory tests. The total hydrogen recovered by outgassing was 10^4 torr-L per pump (i.e., more than the reversible sorption capacity). Activation of the pumps at 700°C resulted in pumping speeds for H_2 and CO which were comparable to that of new pumps. Attempts to reproduce the process of activating the pumps without heating them (i.e., through exposure to a plasma) are under way.

2.1.6 Hydrogen Pellet Injection into ISX-B

D. D. Schuresko
S. L. Milora

C. H. Ma
M. Murakami

A four-shot pneumatic pellet injector has been installed and operated on ISX-B. At 2.5 MPa breech pressure, the injector can deliver four 1.0-mm-diam by 1.0-mm-long hydrogen pellets (4×10^{19} atoms) at 0.9-km/s velocities (0.6 km/s for deuterium pellets at the same pressure). The firing sequence for the four pellets is programmable, allowing 0- to 20-ms delays between successive shots.

Pellet ablation studies have been carried out in both ohmic and neutral-beam-heated plasmas. In low-density ohmic plasmas ($\bar{n}_e \sim 1.5 \times 10^{13} \text{ cm}^{-3}$), single 1.0-mm pellets penetrate to the magnetic axis [Fig. 2.13(a)], producing a central line-averaged density increment of $4.2 \times 10^{13} \text{ cm}^{-3}$ [Fig. 2.14(a)]. In neutral-beam-heated plasmas, the fractional penetration [Fig. 2.13(b) and (c)] is 0.7 to 0.8 for $P_B = 0.7$ MW and 0.5 to 0.6 for $P_B = 1.7$ MW (coinjection, $E_{\text{BEAM}} = 30$ kV); the line-averaged density increments are typically $1.5 \times 10^{13} \text{ cm}^{-3}$ at $P_B = 0.8$ MW.

Fueling with pellets has been compared to fueling by gas puffing from the vacuum vessel wall. For a 27-cm, rail-limited hydrogen plasma, a density increment [Fig. 2.15(a)] of $2.0 \times 10^{13} \text{ cm}^{-3}$ ($t = 200$ ms) was produced by the injection of pellets at $t = 180$ ms and $t = 184$ ms (1 torr-L additional hydrogen). The same density increment was achieved with a 2.5-torr-L additional gas puff burst of 60-ms duration, in place of the pellets. The incremental density decayed faster in the pellet injection shots than in the gas superpuff shots due to the reduced flux of recycled hydrogen from the walls. The plasma energy increased by 1.9 kJ with the pellets or with the gas superpuff [Fig. 2.15(b)], reflecting the improvement in energy confinement with density observed in ungettered ISX-B discharges.

2.1.7 Magnetohydrodynamic (MHD) Studies

2.1.7.1 MHD fluctuation in beam-heated plasmas

J. D. Bell
E. T. Blair
J. L. Dunlap

V. K. Paré
A. J. Wootton

We describe here extensions of the fluctuation studies beyond those previously published.¹¹⁻¹³

A distinctive feature of the Mirnov oscillations is the high-frequency tail (50–250 kHz) in the frequency spectrum of $\tilde{B}_\theta$. This tail has two components, a smooth general background spectrum and fast $\tilde{B}_\theta$ transients associated with

Fig. 2.13. D-alpha light emitted during pellet ablation: (a) single pellet into ohmic plasma, (b) single pellet into low-power NBI-heated plasma, (c) three pellets into high-power NBI-heated plasma, (d) orientation of pellet trajectory with respect to plasma current.

sawtooth collapse. Evidence that the level of the general background tracks the behavior of gross energy confinement continues to accumulate. The shape of this background spectrum is constant, so on-line monitoring of the amplitude has been implemented by band-pass filtering (around 150 kHz) the signal from one of the wideband Mirnov coils. When the results are smoothed in time, to account for a temporal variation of the amplitude that is like an "outside" sawtooth, the quantity $\delta B_\theta / B_\theta$ (where δB_θ is the amplitude of the filtered signal and B_θ is the dc field from one of the equilibrium loops) consistently decreases with improving confinement. This correlation is observed in beam power scans (with decreasing P_b), in current scans (with increasing I_p), and in

Z-mode experiments (with increasing neon injection).

The number of wideband Mirnov coil assemblies were increased to permit measurements with poloidally displaced coils at three locations around the torus—all on the outside wall. Strong local coherence is observed in both toroidal and poloidal directions for the general background spectrum and for the fast transient. For the general background, it has not been possible to resolve a discrete n -mode structure because there is no phase difference in signals measured at different toroidal locations. Large toroidal mode numbers ($n \geq 10$) have been identified in the case of the fast transients. We still lack a definitive connection with theoretical modes.

Fig. 2.13(e). Camera location (current into page).

2.1.7.2 "Electron Thermal Diffusivity in ISX-B from Observations of Sawtooth Oscillations"¹⁴—abstract

J. D. Bell

Significant interest exists in studying energy confinement in tokamaks. Previous analyses of the power balance in the ISX-B tokamak have suggested that electron thermal conduction is the largest energy-loss channel and have deduced values for χ_e , the electron thermal diffusivity, which increase as the auxiliary (neutral beam) heating power is increased. The goal of the research presented here is to obtain an independent value for χ_e from analysis of

"sawtooth" oscillations, which generate electron "heat pulses" that propagate from the core to the outside of the tokamak plasma.

The heat pulse is observed via soft X rays (SXR) of 0.5 to 5 keV, whose emission depends on local electron temperature (which undergoes ~20% fluctuations during a sawtooth cycle) and on local electron density (which shows much smaller fluctuations in the cases studied). The X rays are collected by arrays of collimated surface-barrier diode detectors, and their time histories are recorded.

In previous work on this problem, χ_e values were obtained by comparing SXR data (from oscilloscope photos) with T_e values from simulations based on analytic models of the heat pulse. The present research employs digital SXR data from many detectors. To get χ_e , two simulations are done. The first solves a diffusion equation in electron temperature to track the heat-pulse propagation for a specific value of χ_e ; the second uses this electron temperature solution to model line-integrated SXR signals, whose characteristics are compared to the same characteristics of the experimental signals. We iterate on χ_e until a match is obtained. The value of χ_e from heat-pulse propagation can then be compared with the value from the power-balance analysis. Also, the simulations allow us to study their sensitivities to various assumptions included in the model.

The heat-pulse χ_e values for six ISX-B cases studied are in good agreement with the power-balance analysis, confirming the importance of electron thermal conduction in ISX-B's energy transport mechanisms.

2.1.7.3 "Reconnection in Tokamaks"¹⁵—abstract

V. K. Paré

In a tokamak, the superposition of an externally applied toroidal magnetic field and the field of a toroidal current induced in the plasma results in field lines that go helically around the torus. The equilibrium structure consists of toroidal surfaces nested around a

FUELING PROFILES FOR OHMIC AND NBI HEATED PLASMAS

ORNL-DWG 84-2042R FED

Fig. 2.14. Line-averaged density changes during pellet injection: (a) single H₂ pellet at 206 ms into ohmic plasma, (b) two H₂ pellets ($t = 180$ ms and 184 ms) into 0.8-MW NBI-heated plasma, and (c) FIR chord position.

toroidal magnetic axis. Often a plasma instability will cause an "island" (a separate set of nested surfaces with a helical magnetic axis) to form by reconnection. These structures usually rotate toroidally and can be observed as oscillations in local X-ray emission. Resistive MHD theory shows that one type of island can grow and—in a second reconnection—"take over" from the original magnetic axis. Sequential two-dimensional (2-D) images generated from arrays of X-ray detectors show both the rotation and the growth of these islands and also the "takeover."

2.1.8 Electron Cyclotron Heating (ECH)

2.1.8.1 Electron cyclotron heating on ISX-B

A. C. England
J. S. Levine
O. C. Eldridge

A. G. Kulchar
F. S. McDermott
J. C. Ezell

During 1983, a 35-GHz gyrotron from the Naval Research Laboratory (NRL) was present at ISX-B and undergoing conditioning in preparation for experiments on ISX-B. The existing long-pulse, high-voltage power supply at ISX-B used on previous experiments was

Fig. 2.15. Comparison between pellet and gas fueling. Plasma energy and line-averaged density for ungettered, NBI-heated plasma with (a) injection of two H_2 pellets and (b) additional gas super puff (2.5 torr · L).

being used for long-pulse conditioning. No equivalent power supply was available to NRL for these tests.

The gyrotron was built with a complex cavity and was designed for operation at 300 kW for pulse lengths up to 40 ms. The operating mode was set to be TE_{04} . During the course of the testing, it became apparent that the tube was incapable of high-power long pulses and that the output mode was not TE_{04} . It was returned to NRL for further tests. A new gyrotron with a simple cavity was returned to ORNL. This gyrotron also proved to be unsatisfactory due to mode jumping and low power. The experiment was terminated at the end of

the fiscal year, and the gyrotron was returned to NRL for further study.

2.1.8.2 *Electron Heating and Superthermal Electron Enhancement due to Electron Cyclotron Heating in ISX-B at 28 GHz*¹⁶—abstract

G. B. Elder
H. Hsuan
A. C. England
G. R. Dyer
O. C. Eldridge
J. C. Ezell

E. A. Lazarus
C. M. Loring
C. E. Thomas
J. B. Wilgen
A. G. Kulchar

A series of ECH experiments was performed with a 28-GHz gyrotron on the ISX-B tokamak at ORNL. Up to 70 kW of microwave power was injected into ISX-B from the high-field side. Bulk heating was observed with a central temperature rise of $\sim 370 \text{ eV}$ from an original temperature of $\sim 600 \text{ eV}$, as measured by Thomson scattering. With ECH and under low-density conditions, large non-thermal signals were observed on electron cyclotron emission diagnostics at the first, second, and third harmonics. These signals sometimes became quite large after the end of the ECH pulse. The effects observed can be attributed to relatively small changes in the electron distribution function. The temporal behavior of the enhanced emission is tentatively attributed to the pitch-angle scattering of superthermal electrons.

2.1.8.3 *Preionization and Startup in the ISX-B Tokamak Using Electron Cyclotron Heating at 28 GHz*¹⁷—abstract

A. G. Kulchar
O. C. Eldridge
A. C. England
C. E. Bush
P. H. Edmonds

G. G. Kelley
C. M. Loring
Y-K. M. Peng
J. B. Wilgen
S. K. Borowski

A 28-GHz gyrotron was used to produce a plasma at the electron cyclotron resonance in the ISX-B tokamak. The influence of the toroidal magnetic field magnitude, error fields,

gas pressure, microwave power, microwave pulse length, and microwave timing was studied for experiments with magnetic field and gas only. Also, experiments with preionization followed by capacitor discharges were carried out in which these quantities were varied, as were the capacitor bank voltages. Optimum conditions of preionization for some of the parameters were determined. A theoretical model that adequately reproduces the data is given. Calculations based on this model show the temporal evolution of the electron temperature and density, the neutral density, and the plasma current. The model adequately accounts for present and previous experimental results and can be used to make predictions for future experiments.

2.1.8.4 "Electron Cyclotron Heating Experiments in Tokamaks and Stellarators"¹⁸—abstract

A. C. England

This paper reviews the application of high-frequency microwave radiation to plasma heating near the electron cyclotron frequency in tokamaks and stellarators. Successful plasma heating by microwave power has been demonstrated in numerous experiments. Predicted future technological developments and current theoretical understanding suggest that a vigorous program in plasma heating will continue to yield promising results.

2.1.9 Fast-Ion Studies

2.1.9.1 Charge-exchange measurements of the ion rotation velocity and distortion of the ion distribution function on ISX-B

C. E. Thomas
S. D. Scott

A. Carnevali
M. L. Simpson

It is possible to infer an ion rotation velocity from measurements of charge-exchange spectra along two or more different chords in a plasma.¹⁹ For the past two years, there has

been a puzzling discrepancy between the rotation velocity inferred from spectroscopic measurements³ and that inferred from charge exchange. Recent experiments on the ISX-B tokamak may have resolved this discrepancy. By using neutral beam injection first clockwise and then counterclockwise (changing the current direction so that coinjection was done in both cases), we have found an apparent distortion in the ion distribution function parallel to the direction of neutral beam injection. This distortion is of a magnitude sufficient to explain the apparent difference between spectroscopic and charge-exchange measurements of rotation velocity in ISX-B. Because the data are relatively recent and still under analysis, our conclusion must be regarded as preliminary and subject to change.

2.1.9.2 Fast-ion confinement in ISX-B

C. E. Thomas
M. L. Simpson

S. D. Scott
J. A. Moore

A systematic investigation of fast-ion confinement in ISX-B was started in 1983. Although the final data analysis and comparison with theoretical models will be completed in 1984, some preliminary results can be presented.

In experiments with coinjected input power of up to 2 MW, no deterioration of fast-ion confinement with increasing beam power was observed. Experimental and calculated fast neutral spectra agree fairly well at high plasma current, whereas the agreement worsens at low current, which is consistent with enhanced losses in this regime.

Enhanced losses from the plasma core of fast counterinjected deuterons with respect to coinjected deuterons were experimentally measured to be $\geq 15\%$ at a relatively high plasma current (190 kA).

Fluctuations in the fast neutral flux of up to a factor of 3 correlate well with sawtooth internal disruptions. The beam-target neutron output during injection of H₂ beams doped

with D_2 , on the other hand, shows no such oscillations, leading us to conclude that the sawtooth MHD activity merely redistributes the fast ions to a larger average radius, rather than causes direct losses. Furthermore, no evidence of higher-frequency fluctuations in the fast neutral flux has been found (up to 10 kHz).

Deuterium-doped injection experiments were used also to verify that the fast ions slow down according to classical theory—by following the decay of the neutron output after a sharp beam turn-off. The decay-time constant was always found to be in good agreement ($\sigma \sim 10\%$) with that predicted by a Fokker-Planck calculation.

In summary, our preliminary analysis seems to indicate that the degradation of the global energy confinement time in ISX-B with increasing beam power is not caused by enhanced fast-ion losses.

2.1.10 Impurity Studies

R. C. Isler

Impurity studies during the past operating period have concentrated on the behavior of fully ionized light elements during various types of injection. The metallic elements have been studied in detail for coinjection and counterinjection,³ but the dominant species (O^{+8} , N^{+7} , and C^{+6}) were not observable under most circumstances until recently. The situation has been changed by the addition of a third neutral beam and the installation of a normal incidence spectrometer which is used primarily for plasma rotation measurements. Figure 2.16 illustrates the arrangement of the three spectrometers on ISX-B. The grazing-incidence instrument is located so that its field of view crosses the south beam near its aperture into the tokamak. This orientation permits easy detection of spectral lines formed by

Fig. 2.16. Experimental arrangement of spectrometers on ISX-B.

charge exchange between the hydrogen in the beams and the fully stripped ions.²⁰ This atomic process leaves a hydrogenic ion in an excited state that then decays radiatively. Similarly, the recently installed normal incidence spectrometer views the west beam at a location where it is not severely attenuated; because of the geometry, the CXE signal encompassed by the field of view of this spectrometer is localized within a few centimeters of the center of the machine. Figure 2.17 shows typical behavior of the oxygen for coinjection, counterinjection, and two modes of balanced-beam injection. The initial rise and narrow peak in the signal for the coinjection case [Fig. 2.17(a)] track the shape of the beam current pulse (i.e., of the rise time of the neutral density). It is assumed that only minor changes in the impurity transport occur in the first 10 ms, so that the initial portion of the signal represents the O^{+8} content in the OH plasma immediately before injection. The arrows indicate these initial rises for each of the traces shown. The subsequent evolution then reveals the changes of the oxygen density during the remainder of the discharge. In the usual method of operating ISX-B, the electron density rises continually during the beam pulse and attenuates the neutral beam current passing in the field of view of the spectrometer. Therefore, some corrections to the raw signals are necessary to relate them directly to the oxygen density; usually these are no more than 20% to 30%. Figure 2.17(a) is then interpreted as indicating that the oxygen density in the interior of a coinjected discharge increases little, if any, throughout the shot. By contrast, the density rises rapidly during the counterinjection discharges after the beam turns on. The central impurity accumulation quickly leads to a disruption. In the particular experiment illustrated by Fig. 2.17(b), the disruption is followed by reconnection and another cycle of impurity buildup. This behavior is identical to that observed previously for the metallic elements and confirms prior conclusions that indicate neoclassical-like effects for the impurity transport in ISX-B. However, the CXE results

Fig. 2.17. Charge-exchange excitation signals from O VIII for several injection conditions: (a) coinjection, 1 MW at 100 ms, nongettered; (b) counterinjection, 1 MW at 165 ms, gettered; and (c) balanced injection. Solid trace—coinjection at 100 ms, counterinjection at 165 ms, nongettered; dashed trace—coinjection at 100 ms, counterinjection at 200 ms, gettered.

are less complicated to analyze than the electron excitation of the metals, because calculations of the distribution of the ionization stages are much simpler.

Balanced injection also leads to disruptions, just as counterinjection does, because of impurity accumulation. Although this phenomena was not observed previously (because only unidirectional injection could be employed), it was predicted from similar observations in OH, nonrotating plasmas. Typical data are shown by the solid line in Fig. 2.17(c), where the rise of the oxygen density is apparent after the start of injection, but at a slower rate than for pure counterinjection. This discharge was not gettered. Only by employing titanium gettering to reduce the source rate and by operating the discharge in such a manner that large fluctuations occurred in the particle densities near the edge could disruptions be avoided. The signal from such a discharge is shown by the dashed line in Fig. 2.17(c), where the buildup during the balanced-injection part of the shot is much slower than that taking place in the nongettered discharge. Presumably, the edge fluctuations introduce enough rapid transport at the boundary to avoid a steady influx into the interior.

2.1.11 Microwave and Far-Infrared (FIR) Scattering

2.1.11.1 Microwave and FIR scattering on ISX-B

W. H. Casson
O. C. Eldridge
A. C. England

D. P. Hutchinson
C. H. Ma
J. B. Wilgen

The density fluctuations in the ISX-B plasma have been studied with millimeter-wave ($\lambda = 2.14$ mm) and FIR ($\lambda = 447$ μm) scattering. Preliminary results from the microwave scattering at large angles (70° and 110°) have been previously reported.²¹ For these measurements, the signal-to-noise ratio has been increased to ~ 35 dB, and the scattered spectrum has been examined to a frequency of 1.5 GHz. No evidence is found for density fluctuations near the ion cyclotron frequency (~ 20 MHz) or its harmonics or in the frequency range of the drift-hybrid mode (100–800 MHz). Large density fluctuations are

observed with frequencies in the ± 1.5 -MHz range. The spectra are symmetric about zero frequency, with a shape that is intermediate between a Lorentz spectrum and an exponential spectrum. These density fluctuations are believed to be the result of a strong, nonlinear, drift-wave turbulence. There is no observable Doppler shift, implying an upper limit of 200 m/s for the poloidal rotation velocity of the plasma.

Measurements of the frequency spectrum for far-forward scattering have been made with the 2-mm system and with the FIR system that is also used for interferometry and for the measurement of the Faraday rotation produced by the poloidal magnetic field. The FIR system can measure the density fluctuation level along several chords through the plasma. The spectra for both systems show symmetric wing broadening that is similar to the scattered spectra at large angles. The amplitude and width of the wings increase with increasing density and with neutral beam power. The transmitted power of the millimeter-wave system is attenuated by up to 4 dB on a millisecond time scale, with 10-dB fluctuations on a 0.1-ms time scale. On the millimeter-wave system, low-frequency (20- to 50-kHz) oscillations are seen in a fast Fourier transform (FFT) of the forward-scattering amplitude. These oscillations are in the frequency range of MHD oscillations. They are correlated in time with the MHD activity but do not have the same frequencies. There are some preliminary indications that the character of spectra is changed when low-Z impurities such as neon are injected into the plasma.

2.1.11.2 Preliminary Results from Microwave Scattering on ISX-B: Evidence for Short Coherence Times, Evidence Against Poloidal Rotation²¹— abstract

O. C. Eldridge
A. C. England

J. B. Wilgen

The density fluctuations on ISX-B with 2 MW of neutral beam heating were measured by microwave scattering at a frequency of

140 GHz. The measurements were made at angles of 70° and 110° , which correspond to fluctuation wavelengths of 1.9 and 1.4 mm, respectively. The spectra were measured out to a frequency of 50 MHz by a heterodyne receiver and a spectrum analyzer swept for a time period of 20 ms. Strong scattering was seen over a frequency range of ± 1 MHz, with signals that were 15 to 20 dB above the noise level interpreted as scattering from spatially and temporally coherent density fluctuations in the interior of the plasma. The spectra were very symmetric in frequency with broad wings. There was no evidence for weakly damped plasma waves. There was no observable Doppler shift, which is interpreted as evidence against a poloidal rotation velocity of more than 200 m/s. The maximum width of the spectrum, with 2 MW of neutral beam injection, was 260 kHz at the half-power level. The line shape is interpreted as evidence for a very short coherence time ($\sim 1\mu\text{s}$) for the widest fluctuation spectra. From a comparison with the data of other scattering experiments, a short coherence length of about 1 to 2 cm is also inferred.

2.1.12 Extraordinary Mode Absorption and Electron Cyclotron Emission

Measurements at $\omega = 2\omega_{ce}$ in ISX-B

F. S. McDermott

2.1.12.1 Introduction

A direct measurement of the extraordinary mode absorption at $\omega = 2\omega_{ce}$ in a hot tokamak plasma is presented. These measurements are compared to the analytic calculation of Antonsen and Manheimer²² and to the predictions of a fully relativistic numerical simulation.²³ The accuracy of the models is examined in light of their use as predictive tools for establishing the proper conditions for application of ECH at $\omega = 2\omega_{ce}$ in future devices. The effect of a nonthermal electron distribution is considered by including a very hot, diffuse, second electron population in the

numerical simulation. Such a nonthermal electron distribution can be produced by quasi-linear diffusion during high-power electron cyclotron resonance heating (ECRH) or, in the case of the present work, by runaway electrons. Finally, a measurement of the electron cyclotron emission at $\omega = 2\omega_{ce}$ is performed. As expected, when the absorption is strong, the corresponding emission at $\omega = 2\omega_{ce}$ is approximately at the blackbody level.

2.1.12.2 Extraordinary mode absorption

The experiments were performed on the ISX-B tokamak. Figure 2.18 is a diagram of the experimental arrangement. A transmitting antenna located on the high-field side of the ISX-B vacuum vessel launches a wave along the equatorial plane of the torus and polarized in the extraordinary mode. The wave can be partially absorbed at the $\omega = 2\omega_{ce}$ layer.

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Fig. 2.18. A poloidal cross section of the ISX-B tokamak showing the transmitting and receiving antenna for the extraordinary mode absorption measurement at $\omega = 2\omega_{ce}$. Ray trajectories calculated by the numerical simulation are shown by the solid lines. The dotted line gives the plasma boundary.

After passing through the plasma, the transmitted intensity is monitored by a receiving antenna located opposite (on the low-field side of the torus). The receiver is capable of operating at three distinct local oscillator frequencies simultaneously (diagrammed in Fig. 2.19). For absorption measurements, only

Fig. 2.19. Diagram of the receiver apparatus: (a) waveguide and component arrangement and (b) list of components in use.

the 75-GHz local oscillator is used. The received signal is mixed with the local oscillator signal, amplified by an IF amplifier chain, and detected. The IF amplifier response is maximum and approximately constant in a 100-MHz interval about the IF frequency of 250 MHz. The receiver incorporates an externally biased mixer so that small changes in the local oscillator power level do not affect the receiver sensitivity. A backward wave oscillator is used as the transmitter. The oscillator is repetitively swept over the frequency interval of ~ 74.5 to ~ 75.0 GHz in ~ 17 ms. By sweeping the transmitter relative to the receiver, small frequency drifts of the receiver local oscillator cannot affect the absorption measurements. Along with the received signal, the transmitter power is sampled and monitored; however, after a suitable warmup period, the backward wave oscillator output power level will remain stable over the duration of the experiment. The received signal for a typical ISX-B discharge is shown in Fig. 2.20(a). The transmitter performs approximately 15 to 20 sweeps during the discharge. Careful adjustment ensures that the plasma parameters in the latter ~ 100 ms of the discharge are maintained at approximately constant values, and four sweeps during this interval are selected for analysis. A typical sweep is shown in Fig. 2.20(b). For convenience, a frequency axis is also shown, giving the transmitter frequency as a function of time. The overall shape of the signal is determined by the response of the IF amplifier chain. The signal intensity is obtained by averaging over a ~ 100 -MHz interval at the peak of the IF amplifier response. Such averaging tends to minimize the contributions from the sharp fluctuations in the signal associated with standing waves in the system. By including several such shots, an accurate value for the signal intensity is obtained.

One of the difficulties associated with the measurement is that of separating the effect of refraction from that of absorption. The index

Fig. 2.20. Typical received signals during the $\omega = 2\omega_{ce}$ absorption measurement: (a) a view covering the entire discharge and (b) a detailed view of a single sweep. In (b) the transmitter frequency is indicated on the second horizontal axis.

of refraction for the extraordinary mode is given by

$$n_{\perp}^2 = \frac{(1 - \omega_{pe}^2/\omega^2)^2 - \omega_{ce}^2/\omega^2}{1 - \omega_{pe}^2/\omega^2 - \omega_{ce}^2/\omega^2}, \quad (2.1)$$

so that the plasma acts as a medium with a spatially varying index of refraction. The consequent refraction, or bending, of the transmitted beam out of the field of view of the receiving antenna has the same effect on the received single intensity as the presence of an absorbing layer. The effect of refraction can be partially compensated for by assuming the density to be the primary cause of the ray bending. Two

measurements of the received signal intensity are then made. The intensity (I_w) is measured at a magnetic field where the $\omega = 2\omega_{ce}$ layer exists in the plasma volume in Fig. 2.18. The intensity (I_0) is measured at a lower value of the magnetic field but with the same density profile, where the $\omega = 2\omega_{ce}$ layer is not present in the plasma. The difference in the two intensities is attributed to absorption of $\omega = 2\omega_{ce}$. To be sure, as the index of refraction is also a function of the ratio ω_{ce}/ω , the procedure is only approximately correct. However, the approximation is useful, particularly for monitoring the results of the measurement during the course of the experiment. Finally, a set of detailed numerical simulations is under way to model the effect of refraction. In these simulations, ray trajectories from a large number of rays will be computed. The calculated spread in the wave trajectories will serve as a second estimate of the effect of refraction.

The absorption of a wave passing through the $\omega = 2\omega_{ce}$ resonance can be expressed as

$$\frac{I_w}{I_0} = e^{-\tau}, \quad (2.2)$$

where

τ is the optical depth, defined formally as

$$\tau = 2 \int_s k_{im} \cdot ds, \quad (2.3)$$

ds is the group velocity vector,

k_{im} is the imaginary part of the wave vector,

s is the ray trajectory, defined as the path of energy flow.

The optical depth has been calculated analytically²² for perpendicular propagation of the extraordinary mode at $\omega = 2\omega_{ce}$ as

$$\tau = 2\pi R \frac{\omega}{c} \left(\frac{T_e}{m_e c^2} \right) (1 - 2\alpha)^{1/2} \alpha \left(\frac{3 - 2\alpha}{3 - 4\alpha} \right)^{5/2}, \quad (2.4)$$

where

$$\alpha = \omega_{pe}^2 / \omega^2,$$

$$\omega_{pe}^2 = 4\pi n e^2 / m_e,$$

$$\omega = 2\omega_{ce} = \text{wave frequency} \\ (\omega/2\pi = \text{GHz}),$$

$$n_e = \text{electron density},$$

$$T_e = \text{electron temperature},$$

$$m_e = \text{electron rest mass},$$

$$e = \text{charge on the electron},$$

$$c = \text{velocity of light},$$

$$R = \text{position of the } \omega = 2\omega_{ce} \text{ resonance} \\ \text{layer}.$$

The signal intensity in the absence of absorption (I_0) is measured at a toroidal field of $B_0 = 8.75$ kG. At $B_0 = 12.0$ kG, the absorptive $\omega = 2\omega_{ce}$ layer is present in the plasma at $R = 83.3$ cm, and the intensity I_w is determined. The electron density and temperature profiles are measured by laser Thomson scattering. The experimental values of the optical depth τ_{exp} are obtained from the measured I_w , I_0 , and Eq. (2.2).

To date, the Thomson scattering data have not been analyzed in detail, and only a preliminary estimate of n_e and T_e has been made (to

which an uncertainty of 25% has been arbitrarily assigned). The values of τ_{exp} are compared to the predictions of the analytic calculation τ_{anl} obtained when the experimental values of density and temperature are substituted into Eq. (2.4). Detailed numerical simulations of the absorption have also been performed. The simulation calculates the wave trajectory in full toroidal geometry, is fully relativistic, and includes all orders of the finite Larmor radius expansion. The simulation results typically agree with the predictions of Eq. (2.4) to within a few percentage points. The experimental values of the optical depth and those calculated from Eq. (2.4) are nevertheless in fair agreement even with the preliminary estimates of n_e and T_e (without the detailed numerical simulation of the effect of refraction).

Note that the expression for τ given in Eq. (2.4) has a linear dependence on the electron temperature T_e . This is actually an artifact from the derivation of Eq. (2.4), where only the first-order finite Larmor radius term was included.²² However, the numerical simulations confirm that this is a good approximation over the temperature range of interest ($T_e \leq 1$ keV). For fixed R and ω then, the quantity τ/T_e is to a good approximation only a function of the electron density n_e . In Fig. 2.21, τ/T_e obtained by dividing Eq. (2.4) through by T_e is plotted along with the experimental values of the optical depth τ_{exp} divided by their respective measured T_e values. Two groups of τ/T_e values obtained from the numerical simulation are also shown. In the first group, τ/T_e values are calculated using a single Maxwellian electron distribution with density n_e and temperature T_e at the $\omega = 2\omega_{ce}$ layer. This is the same assumption from which Eq. (2.4) was derived, and good agreement between the numerical calculation and Eq. (2.4) is found. In the second group, the τ/T_e values are calculated from a superposition of two Maxwellian distributions; the first (or bulk distribution) at n_{e-b} , T_{e-b} and the second (or tail distribution) at n_{e-t} , T_{e-t} .

(where $n_{e-b} = 1 \times 10^{11} \text{ cm}^{-3}$ and $T_{e-t} = 100 \text{ keV}$ at the $\omega = 2\omega_{ce}$ layer) and the density and temperature profiles for the two distributions are assumed identical. In this case, τ/T_e is calculated using $n_e = n_{e-b} + n_{e-t} \approx n_{e-b}$ and $T_e = T_{e-b}$, where $T_{e-b} = 500 \text{ eV}$ at the $\omega = 2\omega_{ce}$ layer. It is

Fig. 2.21. The optical depth τ normalized to the electron temperature T_e plotted as a function of the electron density n_e , where n_e , T_e are measured at the $\omega = 2\omega_{ce}$ layer. The solid line is derived from Eq. (2.4) of the text.

evident from Fig. 2.21 that at these values of n_{e-t} , T_{e-t} , and T_{e-b} , the contribution from the tail distribution is not large, except at the very lowest densities, and is generally within the uncertainty of the experimental measurements. At lower values of T_{e-b} , where the absorption by the bulk distribution is small, the tail distribution is responsible for a larger share of the absorbed wave energy. For example, at $T_{e-b} \approx 200 \text{ eV}$, the tail can account for more than 50% of the absorbed wave energy at the lowest densities. The simulations predict, however, that at moderate bulk densities ($n_{e-b} \gtrsim 1 \times 10^{13} \text{ cm}^{-3}$) and temperatures ($T_{e-b} \approx 1 \text{ keV}$) the addition of a small, nonthermal component to the electron distribution has a negligible effect on the absorption at $\omega = 2\omega_{ce}$.

2.1.12.3 Extraordinary mode emission

For studies of extraordinary mode emission at $\omega = 2\omega_{ce}$, the backward wave oscillator is shut off, and the gain of the receiver is increased by approximately 30 dB. All three local oscillators in the receiver (Fig. 2.19) are

used in the emission measurements at local oscillator frequencies of 64, 69, and 75 GHz. Because of the magnetic field gradient $B \propto R^{-1}$, the three different local oscillator frequencies correspond to three spatially distinct $\omega = 2\omega_{ce}$ resonance layers. The intensity I of $\omega = 2\omega_{ce}$ emission is again related to the optical depth τ as

$$I = T_e(r, t) \beta (1 - e^{-\tau}) , \quad (2.5)$$

where β is a constant determined separately for each of the three local oscillator frequencies by calibration with a noise source of known temperature. Equations (2.2) and (2.5) comprise, in effect, a statement of Kirchhoff's radiation law.²⁴ In practice, for $\tau \gtrsim 2$, the plasma is optically thick and the $\omega = 2\omega_{ce}$ emission is approximately at the blackbody level. Thus, the receiver shown in Fig. 2.19 can measure the time history of the electron temperature simultaneously at three spatial locations on the electron temperature profile. At $B_0 = 13 \text{ kG}$, the three local oscillator frequencies (64, 69, and 75 GHz) correspond to $\omega = 2\omega_{ce}$ resonance layers at $R = 107, 99.5$, and 91 cm , respectively (i.e., at $r \approx 14, 6.5$, and 2 cm , respectively). The observed signal is an average over a plasma volume of width $\delta R \approx \pm 0.5 \text{ cm}$ and cross-sectional extent of $\pm 5 \text{ cm}$. This latter is due to the beam spread associated with the horn antenna. In general, Thomson-scattering electron temperature measurements are in good agreement with the results of the $2\omega_{ce}$ emission measurements. Figure 2.22 shows the $2\omega_{ce}$ emission from a typical neutral-beam-heated ISX-B discharge plotted in terms of the radiation temperature calculated from Eq. (2.5), assuming the plasma to be optically thick. Also shown are the plasma current and line-averaged density. In Fig. 2.23, an estimate of the optical depth τ is made for each of the three frequencies (64, 69, and 75 GHz). The optical depth shown in Fig. 2.23(a), (b), and (c) is calculated using the measurement of T_e shown in Fig. 2.22(a),

Fig. 2.22. The radiation temperature T_e derived from electron cyclotron emission at $\omega = 2\omega_{ce}$ where $\omega/2\pi$ is (a) 64 GHz, (b) 69 GHz, and (c) 75 GHz for a typical neutral-beam-heated ISX-B discharge at $B_0 = 13.1$ kG. Also shown are (d) the plasma current I_p and (e) the line-averaged electron density $\bar{n}_e$.

(b), and (c), respectively, along with the density shown in Fig. 2.22(e) and an assumed density profile. Also shown in Fig. 2.23 are the neutral beam power and resistive loop voltage for the discharge of Fig. 2.22. It is evident that the $2\omega_{ce}$ emission of Fig. 2.22 is at the blackbody level during most of the course of the discharge. However, the emission from the edge of the plasma is not at the blackbody level before the neutral beam injection ($t < 100$ ms). The high radiation temperature shown in Fig. 2.22(a) early in the discharge ($t \lesssim 50$ ms) of the plasma is apparently due to runaway electron formation associated with the startup of the plasma. In any case, the

Fig. 2.23. Estimates of the optical depth τ at $\omega = 2\omega_{ce}$ where $\omega/2\pi$ is (a) 64 GHz, (b) 69 GHz, and (c) 75 GHz for the discharge of Fig. 2.22. Also shown are (d) the neutral beam power P_b and (e) the resistive component of the loop voltage V_L for the discharge of Fig. 2.22.

optical depth in the center is very large ($\tau \approx 8$), and ECH at $\omega = 2\omega_{ce}$ should be very efficient in such a plasma.

The fluctuations in the $2\omega_{ce}$ emission of Fig. 2.22 are due to the sawtooth oscillation²⁵ and are shown in an expanded view in Fig. 2.24. The emission shows the characteristic sharp drop in the electron temperature near the plasma center [Fig. 2.24(c)], with an associated increase in the temperature at the plasma periphery [Fig. 2.24(a)]. The $\omega = 2\omega_{ce}$ resonance layer for $\omega/2\pi = 69$ GHz is apparently near the inversion radius, since the $2\omega_{ce}$ emission of Fig. 2.24(b)

Fig. 2.24. Expanded view of the $\omega = 2\omega_{ce}$ emission measurements of Fig. 2.22, showing the sawtooth oscillation again, where $\omega/2\pi$ is (a) 64 GHz, (b) 69 GHz, and (c) 75 GHz.

shows little or no fluctuation. In principle, it should be possible to estimate the electron thermal conductivity from the $2\omega_{ce}$ emission signals by monitoring the heat-pulse propagation²⁵ outward from the inversion radius.

2.1.12.4 Conclusions

Measurements of the extraordinary mode absorption at the second harmonic of the electron cyclotron frequency $\omega = 2\omega_{ce}$ in a hot tokamak plasma are in agreement with the analytic calculation of ref. 22 and with the prediction of a fully relativistic numerical simulation. Electron cyclotron emission measurements at $\omega = 2\omega_{ce}$ are also reported. The absorption and emission measurements are in good agreement with Kirchhoff's radiation law. The presence of a nonthermal electron distribution, modeled here by the inclusion of a hot, diffuse, second electron distribution in the numerical simulation, has a negligible effect on the absorption at $\omega = 2\omega_{ce}$, except at very low bulk densities ($n_e \ll 1 \times 10^{13} \text{ cm}^{-3}$) or temperature ($T_e \ll 1 \text{ keV}$). The use of ECII at

$\omega = 2\omega_{ce}$ in existing and future devices is supported by these results.

2.1.13 Diagnostics

2.1.13.1 Magnetic measurements

G. H. Neilson

Magnetic measurements of bulk equilibrium quantities have been a powerful tool in ISX-B experiments. Through between-shots, on-line analysis, they have contributed to the optimum operation of the device, because they provide rapid feedback on the plasma position, shape, beta, and confinement time, enabling the operators to adjust for desired conditions. Off line, they provide a detailed description of the magnetic boundary conditions, which is incorporated into an MHD equilibrium-consistent profile and transport analysis.²⁶ These advantages were recognized during the high-beta phase of the ISX-B program, and, since then, the techniques have come into use on other tokamaks, for example, Alcator-C, Doublet-III, and the Poloidal Beam Experiment (PBX).

Two techniques have been employed. One is based on poloidal field measurements from an array of magnetic probes. A fast analysis technique developed here²⁷ is used to infer the shape of the plasma cross section, as well as the corrected safety factor q and the equilibrium parameter $\lambda = \beta_{I\Delta} + \ell_i/2$. The other technique uses a diamagnetic loop with a compensating loop to correct for drift in the toroidal field during a shot. Corrections for other parasitic effects are made within an automated computer analysis code, which determines the quantity $\beta_{I\perp}$ from the diamagnetic flux signal. As a result of efforts made during 1983, the diamagnetic measurement was made a routine, almost completely automatic, diagnostic.

It is interesting to compare equilibrium parameters inferred by these magnetic techniques with those inferred from analysis of Thomson scattering profiles and other "kinetic" measurements using the ZORNO code. In

Fig. 2.25 are plotted values of Λ from ZORNOC versus those obtained magnetically; in Fig. 2.26 are plotted values of $\beta_{I\perp}$ from ZORNOC versus those from the diamagnetic loop.

Fig. 2.25. Plot of the equilibrium parameter $\Lambda = \beta_{I\Delta} + \ell_i/2$ inferred from ZORNOC profile analysis versus that inferred from equilibrium poloidal field measurements.

Fig. 2.26. Plot of $\beta_{I\perp}$ from ZORNOC versus that inferred from the diamagnetic loop.

With both measurements, there is generally good agreement, although there is a consistent tendency for ZORNOC to give slightly higher values, especially in $\beta_{I\perp}$. Historically, we have used a simple function²¹ dependence on q to estimate the normalized internal inductance ℓ_i and so to obtain $\beta_{I\Delta}$ from Λ . However, comparisons with ℓ_i from ZORNOC indicate that the estimate is too low, and, therefore, $\beta_{I\Delta}$ inferred in this manner is overestimated by about 15%. Since the global magnetic confinement time τ_E^* used in scaling experiments, and from which the ISX-B empirical scaling was derived, is based on $\beta_{I\Delta}$, it too is subject to this 15% error.

2.1.13.2 Diamagnetic Measurements on ISX-B: Method and Results²⁸—abstract

G. H. Neilson

A diamagnetic loop is used on the ISX-B tokamak to measure the change in toroidal magnetic flux, $\delta\Phi$, caused by finite plasma current and perpendicular pressure. From this measurement, the perpendicular poloidal beta $\beta_{I\perp}$ is determined. The principal difficulty encountered is in identifying and making corrections for various noise components that appear in the measured flux. These result from coupling between the measuring loops and the toroidal and poloidal field windings, both directly and through currents induced in the vacuum vessel and coils themselves. An analysis of these couplings is made and techniques for correcting them developed. Results from the diamagnetic measurement, employing some of these correction techniques, are presented and compared with other data. The obtained values of $\beta_{I\perp}$ agree with those obtained from the "equilibrium" magnetic analysis ($\beta_{I\Delta}$) in OH plasmas, indicating no anisotropy. However, with 0.3–2.0 MW of tangential neutral beam injection, $\beta_{I\Delta}$ is consistently greater than $\beta_{I\perp}$ and qualitatively consistent with the formation of an anisotropic ion velocity distribution and with toroidal rotation. Quantitatively, the difference between

$\beta_{\perp}$ and $\beta_{\parallel}$ is more than can be accounted for on the basis of the usual classical fast-ion calculations and spectroscopic rotation measurements.

2.1.13.3 Heavy ion beam probe

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A heavy ion beam probe has been installed on the ISX-B tokamak and initial results

obtained. The major objective of this diagnostic is to measure the radial electric fields within the plasma during OH and neutral-beam-heated discharges. Secondary objectives are (1) to determine the electric fields, electron temperature, and density at the edge of the plasma and (2) to investigate fluctuations in both density and space potential.

The beam probe is based on a 150-keV ion accelerator used to produce Cs^+ or Tl^+ probing beams, as shown in Fig. 2.27. Beam characteristics are 30–150 keV, full width at half maximum (FWHM) about 3 mm at

Fig. 2.27. Schematic of the ISX-B heavy ion beam probe.

1.7 m from the source. The accelerator and beamline are mounted on ISX sector 13 at $\sim 34^\circ$ to vertical. This allows probing the "upper-outside" of the plasma, as shown in Fig. 2.28. An electrostatic energy analyzer

Fig. 2.28. Energy/angle detection grid indicating the accessible region of the ISX-B plasma.

with 12 detector plates is used to detect and measure the energy of Cs^{2+} or Tl^{2+} ions formed by electron impact ionization. The analyzer is mounted in a separate vacuum chamber, connected to ISX through bellows and a transition tank (Fig. 2.27). The analyzer tank can be tilted, and the analyzer itself translated, to intercept the secondary (doubly charged) ions that are toroidally deflected by the poloidal magnetic field.

The accelerator, ion optics, and analyzer are all under digital control using CAMAC-based equipment interfaced to one of the ISX diagnostic VAX computers. All data are digitized close to the machine, stored in local memory, and then transferred to the VAX for processing. A diagram of the control and data acquisition system is shown in Fig. 2.29.

Our initial measurements have indicated good qualitative agreement between radial

space potential profiles and the expected potential from particle momentum balance.²⁹ Our uncertainties are large, however (about ± 200 V over a full radial scan). This is primarily due to two factors—the change in toroidal angle of the secondary ions during a radial scan and nonuniformities in the energy analyzer response as the beam moves across the entrance slit. Improvements to the energy analyzer are planned to increase the electric field accuracy and to tighten mechanical tolerances. During future data runs, the analyzer will be scanned in toroidal position and angle to map out the beam trajectory effects. We expect to obtain measurements to an accuracy of ± 50 V.

Figure 2.30 indicates the radial potential profiles obtained during ohmic and counter neutral beam injection for $I_p = 150$ kA, $n_e = 1.6 \times 10^{13} \text{ cm}^{-3}$ (ohmic), $n_e = 2.8 \times 10^{13} \text{ cm}^{-3}$ (NBI), and $B_T = 12.4$ kG. A thallium probing beam was used. The space potential during the ohmic discharge is measured to increase in the negative direction toward the plasma center, with $E_r \sim -30$ V/cm. During counter neutral beam injection, the negative well increases significantly, with $E_r \sim -100$ V/cm in the outer half of the plasma. Beam attenuation limits the measurements to $r > 10$ cm during neutral beam injection, as shown in Fig. 2.30.

Our main objective during the remaining ISX operations is full documentation of the potential profiles (coinjection, counterinjection, and coinjection plus counter neutral beam injection, ohmic discharges, and scans of plasma current, density, and neutral beam power). Operation with cesium at higher beam energy should allow measurements during neutral beam injection close to the plasma center.

2.1.13.4 Langmuir probe

A. J. Wootton

K. E. Yokoyama

The method of Fourier decomposition of double probe characteristics has been improved

Fig. 2.29. Outline of the control and data acquisition system.

to incorporate both higher-order terms in the expansion parameter V_{applied}/T_e and finite circuit resistance. A 10-kHz driving voltage is used, which, together with analog filtering of the current, allows measurements of temperature ($1 \text{ eV} \leq T_e \leq 40 \text{ eV}$), density ($4 \times 10^9 \text{ cm}^{-3} \leq n_e \leq 8 \times 10^{12} \text{ cm}^{-3}$), and fluctuation levels. Density calculations include corrections for magnetic field effects, probe potential, and finite sheath thickness. Fluctuations of potential, temperature, and density can be deduced from the frequency structure away from the harmonics of the driving frequency. It has proven necessary to correct for these fluctuation levels in the calculation of both T_e and n_e . Perpendicular diffusion coefficients are estimated from the decay lengths measured behind the limiter face, considering both the perpen-

dicular flux to the wall and the parallel flux to the limiter.

Experimental results have been obtained, characterizing the differences in the edge parameters when neutral beam heating is initiated. In particular, the perpendicular particle diffusion increases dramatically in beam-heated discharges. Differences between high and low energy confinement regimes are also evident at the plasma edge. For instance, the reduction in the global energy confinement observed in gettered discharges in which neutral beam injection is used is reflected in the edge plasma. The gettered discharges, characterized by a low τ_E^* , show much larger edge densities than the higher confinement regime of ungettered discharges. A decrease in edge density is seen when neon is injected into a gettered

Fig. 2.30. Radial space potential profiles obtained during ohmic and counter neutral beam injection.

discharge. Finally, edge densities measured at the limiter are significantly lower than the densities measured far down field.

Langmuir probe density profiles have been compared with the FIR data and agreement is consistently within 20%. Excellent agreement has also been seen in comparison with the expected ion flux due to sputtering of the working gas and the ionization lengths of the

sputtering atoms calculated by the laser-induced fluorescence (LIF) diagnostic.

2.1.13.5 "A Comment on the Calculation of T_e from Thomson Scattering Data"³⁰—summary

E. A. Lazarus

Most Thomson scattering data are analyzed to obtain the electron temperature by finding the best fit to a straight line on a log-linear plot of intensity versus the square of the wavelength shift. An error is inherent in this linearization of the regression problem, with corresponding magnitude of the effect with typical Thomson scattering data from the ISX-B tokamak. The spectrum of light scattered by electrons has the form

$$f(x) = I/I_0 = C_1 \frac{n_e}{\sqrt{T_e}} e^{-x/C_2 T_e}, \quad (2.6)$$

where

I and I_0 are the scattered and incident intensities, respectively,

n_e is electron density,

T_e is electron temperature,

x is the square of the shift in wavelength of the scattered light,

$C_{1,2}$ are constants that depend on the scattering angle and the wavelength of the source.

One wishes to determine T_e and n_e by performing a regression to minimize χ^2 :

$$\chi^2 = \sum_{i=1}^N \frac{[f(x_i) - y_i]^2}{\sigma_i^2}. \quad (2.7)$$

Here, the y_i are the measured intensities and σ^2 are the associated errors determined from photon statistics. Usually the regression is

linearized by taking the logarithms of y_i and $f(x_i)$ and making the corresponding transformation of the errors (i.e., $\sigma_i \rightarrow \sigma_i/y_i$). However, such a regression minimizes the quantity

$$\chi'^2 = \sum_{i=1}^N \frac{[\ln f(x_i) - \ln y_i]^2 y_i^2}{\sigma_i^2} \quad (2.8)$$

but not χ^2 . Denoting $[f(x_i) - y_i]$ as ϵ_i and assuming $\epsilon_i \sim \sigma_i$, then to lowest order

$$\chi'^2 = \chi^2 + \sum_{i=1}^N \frac{\epsilon_i}{y_i} \quad (2.9)$$

Equation (2.9) states that the χ^2 minimization will be performed subject to a constraint on the absolute size of $\sum \epsilon_i$ with a weighting that accentuates the smallest y_i (i.e., the datum with the poorest signal-to-noise ratio). If N is sufficiently large and the errors are random, the second term in Eq. (2.9) will average to zero. However, Thomson scattering measurements are typically performed with values of N ranging from 2 to 10. Furthermore, since the spectral channels are fixed and meant to be appropriate for a large range of T_e values, the last channel with signal is likely to detect few photons, even when the overall signal-to-noise ratio is satisfactory. The problem is the unintended weighting given to the low-intensity data points by linearizing the calculation. In summary, there may be significant differences in T_e values deduced from regression fits to Thomson scattering data using the two methods discussed here. Where such differences are found, values deduced by the non-linear regression should be more reliable, since it has been shown that the logarithmic approach gives more weight to the less accurate data points.

2.1.14 Tokamak Operations and Technology

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C. R. Stewart
D. J. Webster
R. B. Wysor
J. E. Warwick
V. P. Lickliter
J. J. Schmidt
J. L. Ping

2.1.14.1 Overview

Table 2.1 presents the operating statistics for 1983 in the same form as in previous years in order to allow comparison. Tables 2.2 and 2.3 summarize the salient features of the year's operation and a breakdown of the machine-time allocation.

After initial operation of the outer power supply late in 1982, the experiment was shut down for installation of additional protective

Table 2.1. ISX-B operating history

	Achieved		Planned
	CY 82	CY 83	CY 83
Days available ^a	201	202	200
No scheduled operation ^b	75	40	42
Days lost ^c	55	13	38
Days of operation	71	49	122
Number of shots	4787	10830	9000
Shots per day	67	73	75

^aFour working days per week and ten official holidays.

^bDays allocated to improvements and modifications.

^c"Lost days" represents days when there was no operation for unscheduled reasons, and the days were not recovered by rescheduling outages or working extra days.

Table 2.2. ISX-B operations summary for 1983

Operation	Month accomplished
South (third) beamline commissioned	January
Protected outer power supply operational	January
Langmuir probe and drive system installed	January
Balanced-beam experiments commenced	February
Detailed Z-mode studies commenced	March
Pump-limiter experiment with neutral injection	June
Heavy ion beam probe operational	July
Density profiles from FIR interferometer	August
Computer (VAX)-controlled gas puff implemented	August
Beryllium limiter experiment proposal completed	August
VAX data and display system operational	September
Full charge-exchange and diagnostic neutral beam (DNB) system operational	September
Laser-induced fluorescence experiment operational	September
Microwave scatter results for poloidal rotation	October
Heavy ion beam probe (HIBP) full-voltage operation	November
Second-harmonic electron cyclotron experiments	November

Table 2.3. ISX-B program element allocation^a

	Days	Percentage
Rotation and potential studies		
HIBP potential measurements	27	18
Rotation measurements	13	9
Particle-control studies		
Pump-limiter studies	19	13
Pellet injection	5	3
Confinement improvement		
Z-mode studies	22	15
Position-dependence experiments	4	2
Other studies		
Microwave propagation	3	2
Langmuir probe	2	1
Laser-induced fluorescence	2	2
Unassigned		
Diagnostic and machine tests	52	35
Setup and exploration		
Total operation	149	100

^aBecause of program overlap and assignment uncertainties, these allocations should be taken as estimates only.

circuitry. A characteristic of solid-state systems is their vulnerability to transient overloads. With a high-power, wide-bandwidth power supply, this problem becomes acute, and the outer power supply was initially installed with inadequate protection against internal faults. The additional protection circuitry included a current-fault monitor that monitors the current into the supply and detects excessive current rise rates and overcurrents and a high-speed state monitor that monitors the on and off resistances of the switch arrays during each switch cycle. Since the completion of these modifications and after a few faults caused by infant component mortality, the power supply has run to full power with high reliability.

Also early in 1983, a third beamline injecting counter to the existing two beamlines became operational. This beamline shares a power supply with one of the existing beamlines (the east beamline), and no problems were experienced in the power supply sharing.

Because of leaks in the available standard cryopumps, the third (south) beamline has been run with a single "short" cryopump. These "short" pumps were originally purchased for the front-end location for the east and west beamlines and are the most advanced pumps available, but they were not used. The beamline performance with the reduced pumping speed associated with the "short" pump was entirely satisfactory, and pressure measurements made in the calorimeter chamber showed similar values during operation as with the full-size pumps. With the completion of installation of the opposed beamline, balanced-beam-injection experiments were begun to resolve concerns with beam-specific effects on plasma confinement.

A continuing program to develop remotely controlled Langmuir probe drive assemblies was finally completed with the installation of a system that also included an air lock to allow probe repair and replacement without venting the entire machine. In addition, a new set of electronics was developed for the diagnostic. This system, which extracts the harmonic

information from a high-frequency carrier and automatically displays time-resolved temperature and density values for the edge plasma, is described in detail by A. J. Wootton and K. E. Yokoyama (Sect. 2.1.13.4).

A continuing element of the main program has been the pump-limiter experiments. Considerable technical difficulty has been experienced with this apparatus. A necessary feature of the design is the inclusion of zirconium-aluminum getter pump modules directly behind the limiter head and topologically within the main vacuum system. These pumps have experienced spontaneous activation and have then pumped background hydrogen to their embrittlement point and contaminated the main tokamak vessel with pump material. In spite of this problem, a number of experiments were made with the pump limiters with neutral-injection-heated plasmas.

In a cooperative experiment with the Rensselaer Polytechnic Institute, a heavy ion beam probe diagnostic to measure internal potentials was installed on the machine. The diagnostic became operational on schedule, although some problems were experienced during the installation and testing phases of this unique and major tokamak experiment.

During the course of the year, the new VAX data acquisition and diagnostic control system was brought on-line and progressively replaced the existing PDP-8 and PDP-11/34 computer systems. Tests of the final data acquisition and display configuration were satisfactorily completed. However, data transmission to the main analytic computer system, the PDP-10, is unacceptably slow, and so final transfer to the VAX system has been delayed until the data analysis software has been restructured for the VAX system.

Late in the year, a proposal was written for an end-of-life experiment to evaluate beryllium as a limiter material. This experiment is described in detail in Sect. 2.1.17.

2.1.14.2 Optimized feedback control of plasma current and position

G. H. Neilson
G. R. Dyer

P. H. Edmonds
J. L. Yarber

One of the problems encountered in the design and operation of tokamak fusion research devices is that of plasma current and position feedback control. In traditional tokamak designs, whether air- or iron-core devices, a "decoupled" system of poloidal windings is used. Usually, this consists of an OH, or primary, winding that controls the cored flux and thus the plasma current I_p ; a vertical field winding that controls the plasma's horizontal position Δ_R ; a horizontal field winding to control the vertical position; and, often, multipole field windings to control the shape. However, more complex systems, such as the Tokamak Fusion Core Experiment (TFCX), may be constrained in their design by engineering considerations: the need to minimize the number of costly, superconducting coils, restrictions on where coil can be located on the device, and practical power supply limitations. Such constraints make it inevitable that the poloidal field (PF) windings will exhibit a high degree of functional coupling.

The ISX-B poloidal winding system was designed with these issues in mind. A "shell-like" poloidal coil design, in which the poloidal coils are grouped in winding sets roughly approximating the currents that would be carried in a conducting shell, was chosen because it could provide the necessary control currents, as determined by MHD equilibrium calculations, in the limited space available for locating coils. The power supplies used to energize the windings were chosen, of economic necessity, on the basis of available equipment, rather than on what might have been optimum for control requirements. Thus, ISX-B embodies many of the constraints on equilibrium control

that will be found in more advanced systems and therefore serves as a useful vehicle for testing models and implementing schemes that might be used in their design.

We have developed a model for horizontal position and plasma current ($\Delta_R - I_p$) control that has served as a useful tool for optimizing the adjustable elements (the error amplifier gains and time constants) in the ISX-B control system. Specifically, we find that the best behavior is obtained when overall Δ_R and I_p control are electronically decoupled using these adjustments. The model shows that, in fact, Δ_R and I_p are coupled in *any* tokamak, even one which uses a "traditional" PF system. Thus, the decoupling principle is applicable quite generally.

In 1983, a new power supply having faster response was installed on one of the poloidal windings. This provided an opportunity to apply the feedback model as a means of optimizing the error amplifier settings to take advantage of the improved capability. The result was a significant reduction in fluctuations in Δ_R (by a factor of ~ 2 to 3) and in I_p ; the latter led to reduced fluctuations in the loop voltage signal, making it a more reliable and useful diagnostic.

2.1.15 The ISX Data System

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Data system highlights from 1983 include

- complete conversion of the Thomson scattering on-line data system to the VAX, including the control, data acquisition, and a VAX version of the LZ832 analysis package;
- conversion of the charge-exchange diagnostic(s) to the VAX, with both the velocity-filter and mass-energy analyzer systems added to the VAX for data acquisition and analysis (the associated diagnostic neutral beam was also VAX-converted);

- development of all necessary software to support the heavy ion beam probe for both data acquisition and analysis on the VAX;
- development of codes (based on DECnet) that support binary file transmission between the PDP-10 and the VAX systems, with an extension of these codes to support remote binary file access (at the record level) of files on the PDP-10 from the VAX systems;
- development of a VAX-based gas feed system (which includes a very sophisticated user interface and an internal data base such as all operations-support software will eventually use);
- conversion of the laser fluorescence system to the VAX (in turn allowing the PDP-11/34 that previously had supported this diagnostic to be converted to a DN-20 terminal port on the PDP-10);
- conversion of the infrared camera diagnostic system to the VAX in order to support extended data acquisition for the pumped limiter;
- completion of the SAMS synchronization software that allows user-written (i.e., time-sharing mode) software to synchronize itself with the real-time environment of the experiment cycle;
- development of a VAX-based software package for the residual gas analysis (RGA) diagnostic; and
- completion of a normalization of all the operations-related software on the toroidal power supply PDP-11/10, including bringing all operating system software up to current revision levels, identifying all current source codes, and demonstrating that the system was completely self-supporting (i.e., that it could edit, compile, link, and load) for all operations software.

As seen from this list of highlights, 1983 was the year of the VAX systems for ISX. In fact, if it had not been for an unforeseen development, ISX would have completely converted from PDP-11 to VAX computers during the year. This unforeseen development was the discovery that DECnet (at least in its present

form) is not fast enough to allow the transmission of a complete ISX data set to the PDP-10 in the time available between shots. That is, if all the data acquisition were to be converted to the VAX systems, including the transient recorders now handled by the PDP-11s, data flow to the PDP-10 would fall out of phase with current operation. Since many of the data analysis programs needed for ISX operation still exist only on the PDP-10, this would be an unacceptable situation. Thus, until the source of the bottleneck in DECnet is found, ISX is running a mixed system. The VAXs handle data from sophisticated diagnostics that require large amounts of control or preliminary analysis, such as Thomson scattering and charge exchange. Meanwhile, the PDP-11/34s continue to handle the transient recorder data for display and transmission to the PDP-10 via the locally written FEDnet software. Despite the disappointment created by our inability (at present) to complete the conversion, 1983 has been a very successful year.

The successes can be grouped into three broad areas. First, for the diagnostics that were converted to the VAXs for analysis, the VAXs have provided a dramatic improvement in the ability to analyze data between shots and thus guide machine operation. Second, the new systems like the heavy ion beam probe represent significant new levels of diagnostic sophistication that could not have been supported prior to the VAX systems. The heavy ion beam probe (for example) acquires and analyzes over 200,000 words of data on every shot. This data volume may appear small compared with the X-ray array, which acquires over 1.5 million words, but it is significant because the beam probe must function on every shot, whereas the X-ray array only acquires a very selected subset of shots. Third, the advent of the VAX-based gas puff system represents a first venture into a new area. It allows the "Responsible Physicist" to set up and control the operation of the tokamak from an on-line time-sharing terminal. The system allows either tabular or graphical manipulation of the control waveforms that, in turn, drive the gas feed system. It maintains an

internal data base of remembered waveforms and can recall any such previous waveform for reuse or to serve as the basis for creation of a new waveform. This power to directly specify the waveforms that drive experiments, store and cross-reference waveforms, and create new waveforms interactively represents the first example of a capability that we expect to use extensively on ATF.

However, probably the most significant development for the future of the data system was one that took place almost incidentally to the "VAX-ination" of the Charge-Exchange diagnostic. The data that the charge exchange system generates involve a wide variety of data types and arrays. To decouple the data from the many analysis programs that need access to them (on both the PDP-10 and the VAXs), it was necessary to define a data-descriptor system that would allow data to be completely self-describing to any analysis program on any host system. This system, which prefaces each data array with a compact (6-byte) header, represents the model that will form the basis for all data handling for the ATF device.

2.1.16 TFTR Collaboration

J. L. Dunlap

An ORNL collaboration on TFTR was conceived roughly a year ago. It was then recognized that the ISX-B facility would cease experimental operations in FY 84, but its replacement, the ATF, would not come on-line until the end of FY 86. This gap in the experimental program here would free up experienced tokamak physicists who could assist toward the $Q \sim 1$ objective on TFTR.

The primary vehicle for this collaboration will be the temporary relocation of ORNL personnel to Princeton (PPPL). The anticipated level of participation in FY 85 is 17 personnel years (PY), most of whom will be on assignment at PPPL by the end of next summer. This represents about a one-third increase over the present scientific staff on TFTR. The level reduces to approximately one-half that for FY

86, as more of the personnel are required at ORNL for preparations for ATF.

The collaboration has already begun. One off-site assignment is in place, and 15 other ORNL personnel have made working visits, mostly ranging from 5 to 15 d in duration. To date, about 400 working days at PPPL have been accumulated under these arrangements. The collaborative efforts have involved pre-operational testing of magnetic windings and diagnostics, testing and implementation of diagnostics (e.g., bolometers, FIR polarimeters, SXR diodes, charge exchange, and neutrons), development of data acquisition and analysis codes, analysis of experimental data, and experimental planning. As a result of these visits and warm receptions by our colleagues at PPPL, the integration of ORNL personnel into the TFTR research efforts is proceeding well.

2.1.17 The Joint JET-ISX-B Beryllium Limiter Experiment

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J. B. Roberto	M. F. Smith
D. J. Webster	

The aim of this experiment is to perform a test of beryllium metal as a plasma limiter material in a tokamak. A large number of materials have been tested for this application, and none has met all the requirements. Beryllium is an attractive candidate for a limiter material because of its low atomic number, relatively high melting point, and desirable thermal properties. Other properties that impact the suitability of beryllium for this application include the hydrogen (tritium) inventory, material deterioration under hydrogen ion fluence, and the mechanical and thermal shock resistance.

Although single properties such as thermal shock resistance or tritium retention can be investigated in laboratory experiments, syn-

ergistic effects cannot be predicted and can only be studied in the proper plasma environment. Therefore, a necessary test prior to application in a large device like JET has to be in a tokamak.

The experiment is divided into three parts:

1. the design, procurement, and fabrication of a beryllium limiter assembly and the material tests before and after the limiter has been exposed to the tokamak plasma;
2. the setup and characterization of the test plasma; and,
3. the operation of the ISX-B tokamak until the limiter has accumulated an estimated total dose of 10^{22} hydrogen atoms/cm².

The limiter design is similar to the existing TiC-coated carbon limiters and has the specifications listed here.

Configurations	One top rail limiter
Dimensions	~10 × 10 × 20 cm
Stroke	10–15 cm
Design	Tessellated blade
Heat load	2.5 kW/cm ² (design load)
Temperature control	Bulk temperature to be controlled between room temperature and 250°C
Instrumentation	Four or more thermocouples

In addition, a simple mushroom-shaped beryllium limiter will be fabricated as a backup.

Materials tests will be conducted before installation and after completion of plasma operation. These tests will include measurements of thermal conductivity, yield strength, tensile strength, surface hardness, and surface topology. In addition, after completion of plasma operation, hydrogen and deuterium depth profiling measurements will be made.

The experiment will be conducted using a plasma with the approximate parameters $I_p = 120$ kA, $B_T = 14$ kG, 1-MW NBI, and

$n_e = 4 \times 10^{13} \text{ cm}^{-3}$. The diagnostics to be used to characterize the plasma are listed in the following table.

Plasma and wall ^a	
I_p, B_T, V_L, B_p position	Magnetics
$\bar{n}_e$	FIR interferometer
$n_e(r), T_e(r)$	Thomson scattering
T_i	Charge-exchange analyzer
Impurities	Spectrometer
MHD activity	Mirnov coils
Scrape-off layer	Langmuir probe
H_α radiation	H_α monitors
P_{rad}	Radiometer
Surface composition ^b	Surface analysis station
Limiter ^a	
Surface temperature	IR thermography
Bulk temperature	Thermocouples
Surface phenomena	Optical observation

^aAll parameters except $n_e(r)$, $T_e(r)$, T_i , and surface composition are monitored through the experiment.

^bAverage weekly composition.

On completion of the characterization of the plasma, the beryllium limiter will be exposed to approximately 3000 discharges with the aim of accumulating a hydrogen dose of 10^{22} atoms/cm².

It is estimated that the achievement of this integrated dose can be accomplished with approximately 3000 discharges of the ISX-B tokamak plasma. This estimate is based upon existing measurements in ISX-B of a reference discharge for which the estimated hydrogen ion density flux is 10^{19} atoms/cm²·s at the plasma boundary and the discharge duration is approximately 300 ms. The proposed schedule includes a total operating time of 3 months in which to set up the reference plasma and to achieve this number of discharges. The schedule for accomplishing the 3000 reference discharges is based upon typical operating experience with ISX-B obtained during the past 4 years. It allows for the normal scheduled and minor unscheduled downtime expected in this research apparatus and its auxiliary equipment,

and it allows for additional discharges for setting up the plasma and for discharges that terminate prematurely. The total time span in which these tests may be undertaken is approximately 5 months (May through September).

Some diagnostics will be used throughout the test to monitor the reproducibility of the discharge and the ion flux from the plasma. Additional diagnostics will be used during the initial period of more detailed studies in the reference experiment. Although these additional diagnostics are not planned for the final load test, they will not be disconnected and will be available to recalibrate the plasma if a serious question of its reproducibility arises.

2.2 THE ATF PROGRAM

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2.2.1 Introduction

With the planned shutdown of ISX-B in 1984, ATF (Advanced Toroidal Facility) will

ORNL-DWG 84-2564A FED

Fig. 2.33. Finite-beta ATF equilibria for different values of poloidal shaping field.

(≈ 40 kA) can supplement the externally applied transform; success with such configurations could lead to the development of more compact stellarator-tokamak hybrids.

Previous ORNL studies³³ of particle energy transport in stellarators showed that electric fields play an important role in sealing collisionless loss cones and in reducing transport coefficients at low collisionality. Figure 2.34 shows a plot of the helical-ripple (Shaing-Houlberg) contribution to the ion heat diffusivity, together with the axisymmetric (Hinton-Hazeltine) contribution. The total χ_i

Fig. 2.34. Helical-ripple and axisymmetric components of the neoclassical ion heat diffusivity as a function of normalized collision frequency ν^* .

is the sum of the axisymmetric contribution (which must be multiplied by a factor to account for the reduced number of banana-trapped particles in the stellarator) and the helical-ripple contribution. The corresponding curves for the electrons are qualitatively similar. The helical-ripple contribution is plotted for three different values of radial electric field ($E_r = -\phi'$) normalized to the ion temperature gradient (T'), where the prime signifies the radial derivative. As the magnitude of E_r

increases, the transition of the favorable dependence $\chi \propto \nu$ moves to high collisionality because the $E_r \times B$ drift increases the poloidal precession frequency of the trapped particles that dominate the helical-ripple component of χ . For potential values of the order of the temperature, the helical-ripple contribution is of the same magnitude as the axisymmetric contribution. Similar results are obtained for positive potentials. The analytical model used for Fig. 2.34 has been found to be in reasonable agreement with the results of a Monte-Carlo calculation.

The WHIST code has been used to simulate the performance of ATF for various transport models. Figure 2.35 shows the results of one such simulation. For this case, the transport coefficients were taken to be equal to twice the axisymmetric terms, plus the Shaing-Houlberg helical-ripple terms, plus anomalous terms for both the particle diffusion and electron heat

Fig. 2.35. Results of WHIST simulation for ATF. Transport model: twice the axisymmetric neoclassical, helical-ripple, and anomalous χ_e and D , chosen to match Heliotron-E data.

diffusivity coefficients. The radial electric field was calculated self-consistently throughout the simulation by requiring that the particle fluxes be ambipolar. The anomalous terms were adjusted to match experimental results obtained on the Heliotron-E device, which is the largest operating stellarator-type device with magnetic-field characteristics generally similar to those of ATF. Good agreement could be obtained for low-density currentless operation with ECH and neutral beam heating. The ATF simulation shows (1) that with a low initial electron density (typical of that obtainable with ECH) and subsequent injection of 3 MW of neutral beam power kilovolt temperatures and beta values of $\sim 5\%$ can be reached and (2) that electric potentials of several times the species temperatures can be expected to develop.

Studies of particle orbits and field lines outside the last closed magnetic surface of the ATF plasma have been used to modify the original helical field (HF) coil cross section and vacuum vessel design to increase the plasma-wall distance and eliminate the collisionless loss cone. Figure 2.36 shows orbit puncture plots for 500-eV deuterium ions launched just inside the last closed flux surface (at $\bar{r}/\bar{a} = 0.95$). The ions can go far outside the plasma but do not strike the wall directly; when charge

exchange is included in the calculations, the resulting charge-exchange neutral flux is spread approximately uniformly over the wall. Thus, the configuration can be operated without a material limiter. A number of magnetic or pumped limiter schemes may also be possible. Various schemes for particle and impurity control for ATF are being investigated both at ORNL and in collaboration with the University of Wisconsin. The improvements in the vacuum vessel design also simplified the ATF assembly procedure (described in Sect. 2.2.4).

Recent results from foreign stellarators have also increased our confidence in ATF performance. The Heliotron-E experiment (20-cm plasma radius) at the Kyoto University Plasma Physics Laboratory has obtained (1) $\langle\beta\rangle = 2\%$ at $B = 0.94$ T and $\bar{n}_e = 8 \times 10^{13} \text{ cm}^{-3}$ with 1.2 MW of absorbed neutral-beam-injection power; (2) $T_i = 1$ keV at $B = 1.9$ T and $\bar{n}_e = 2 \times 10^{13} \text{ cm}^{-3}$ with 0.7 MW of absorbed neutral-beam-injection power; and (3) $T_e = 1$ keV at $\bar{n}_e = 1 \times 10^{13} \text{ cm}^{-3}$, both at the electron cyclotron fundamental ($B = 1.9$ T) and at the second harmonic ($B = 0.94$ T), with 150 kW of 53.2-GHz ECH power. The Wendelstein VII-A experiment (10-cm plasma radius) at the Max-Planck Institute for Plasma Physics (IPP) has obtained $T_e < T_i \approx 1$ keV, $\langle\beta\rangle = 0.5\%$ at $B = 3$ T, and $\bar{n}_e \approx 10^{14} \text{ cm}^{-3}$ with 0.4 MW of absorbed neutral-beam-injection power. These results, obtained with small-radius plasmas and low absorbed power, are comparable to tokamak results. With its larger size (30-cm plasma radius) and greatly increased heating power (>3 MW of absorbed power), ATF should be capable of achieving $T_i = 1\text{--}3$ keV and $\langle\beta\rangle = 5\%$ to 10% .

Interaction with and support of the U.S. and international stellarator communities have increased this past year. ORNL hosted three stellarator workshops, actively participated in the research programs of the Kyoto University and the Max-Planck Institute groups by means of extended foreign research assignments, and

Fig. 2.36. Puncture plots of 500-eV D^+ orbits at two poloidal cross sections of an ATF field period. Particles launched at $\bar{r}/\bar{a} = 0.95$.

supported torsatron research at the University of Wisconsin. These collaborative activities will be expanded in preparation for ATF operation.

2.2.4 ATF Construction

2.2.4.1 Description

As shown in Fig. 2.37, the ATF device consists of an HF coil set, a set of inner and outer VF coils, an exterior shell structure to support the coils, and a thin, helically contoured vacuum vessel closely conforming to the HF coils for maximum volume.

ATF will be located in the present ISX-B enclosure and will make use of many of the existing ISX-B power supplies, utility systems, diagnostics, and heating systems. The device is

scheduled to begin operation at the end of 1986, and the total estimated cost is \$19.3 million.

The primary ATF parameters are listed in Table 2.4. Table 2.5 lists the coil-design parameters for ATF. The values listed are for a 5-s flattop pulse. In addition, the coils are steady-state rated at one-half the currents listed in Table 2.5. This corresponds to steady operation at a magnetic field of 1 T.

2.2.4.2 Helical field coils

The HF coil set consists of a pair of coils that form an ($m = 12$, $\ell = 2$) constant-ratio torsatron helix with the design parameters shown in Tables 2.4 and 2.5. In addition to these requirements, the coils must be constructed so that the actual current path is

Fig. 2.37. The Advanced Toroidal Facility.

Table 2.4. ATF parameters

Major radius R_0 , m	2.10
Average plasma minor radius $\langle a \rangle$, m	0.30
Average coil minor radius a_c , m	0.46
Toroidal field on-axis B_0 , T	2.0 (for 5 s) 1.0 (continuous)
Ion and electron temperatures ($T_i = T_e$), keV	1-3
Plasma density n_e , cm^{-3}	$1-10 \times 10^{13}$
Average plasma beta β , %	5-10

within 1 mm of the theoretical current path. Other torsatron and stellarator coils have been successfully constructed by carefully winding hollow copper conductor onto the vacuum vessel, but this puts the manufacturing steps in series and requires that the vacuum vessel be completed before any winding can begin. In addition, problems or mistakes can interrupt the winding process and must be corrected before the winding can proceed. To allow for parallel assembly operations, the HF coils for ATF will be manufactured as a set of 24 identical upper and lower segments (Fig. 2.38). The segments are joined in the field to form the continuous coils. Each segment consists of 14 copper conductors separated with fiberglass insulation, bolted to a T-shaped structural support member, and vacuum impregnated with epoxy. The epoxy and glass form a compressive load path to transfer the magnetic forces on the conductors into the structural member.

Fig. 2.38. Segmented HF coil concept.

As shown in Fig. 2.39, the conductors are made by machining flat developments from CDA 101 copper plate, brazing a cooling tube into a milled groove, and rough forming to shape. A complete set of conductors with suitable spacers is clamped to a precision die and stress relieved to obtain the final form tolerance. The structural "T" is fabricated as either a 304 stainless steel weldment or a casting and is machine finished. During segment assembly, each conductor is positioned on the stack relative to reference points machined in the structural "T" with the aid of a coordinate measuring machine. By retaining the measured location of each conductor, a "best-fit" position for the completed segment relative to

Table 2.5. ATF coil parameters at maximum field

Coil set	Current per coil (MA-turns)	Current per turn (kA)	Current density (A/cm^2)	Voltage per coil set (V)		Water flow rate (L/s)
				Peak	Flattop	
HF	1.750	125.0	3350	1000	500	178
VF (inner)	0.263	16.4	2540	650	121	6
VF (outer)						
Main 1	0.375	125.0	2600	1000	63	23
Main 2	0.375	125.0	2600	1000	63	23
Trim	0.159	15.9	2420	650	166	5

Fig. 2.39. HF coil segment assembly.

the theoretical helical current path can be calculated. The "best-fit" position is also used to locate the segment during device assembly.

After the segment is assembled and epoxy impregnated, the joint details are machined at the ends. Obviously, the joints are the most critical HF-coil design problem. The baseline concept is a bolted splice joint that is acceptable for pulsed operation but that requires additional cooling for continuous operation. Welded and electroformed concepts are also being considered. A special joint on the outside of each coil will provide for the crossover and current leads. Magnetic-field calculations have demonstrated that simple dipole current leads have acceptably small effects on the magnetic-flux surfaces.

To verify the segmented-coil design concept, a full-scale prototype segment is being built. Chicago Bridge and Iron in Birmingham, Alabama, will supply the conductor and structure piece parts, and the segment will be assembled at ORNL. A special facility—the Verification,

Assembly, and Test Facility (VATF)—is being prepared for this task. In addition to the assembly facility, the VATF program is in the process of testing prototype joint designs.

2.2.4.3 Vertical field coils

Two sets of VF coils are required—an inner pair and an outer pair (Fig. 2.40). The coils are all wound from hollow copper conductor, insulated with glass cloth, and epoxy impregnated in a stainless steel case. In addition to the design parameters listed in Table 2.5, the windings must be accurate to within ± 5 mm of the theoretical current path.

Fig. 2.40. Radial section of ATF showing VF coils.

The inner VF coils provide shaping and trim functions and are operated in series from a single power supply. The outer VF coils each have three independently connected windings, including two main sections and a trim section. The main sections are connected in series with the HF coils and provide the field that offsets the vertical field from the helix. Two main sections are required in each outer VF coil to maintain symmetry during helical-axis operation, when one of the HF coils is operated at a

reduced current. The trim section is powered from a separate power supply and can be energized with full current in either direction. PPPL will design and fabricate the VF coils for the ATF.

2.2.4.4 Vacuum vessel

The vacuum vessel is a stainless steel shell, closely fitting the inner bore and sidewall of the HF coils to maximize the plasma-wall separation. As shown in Figs. 2.41 and 2.42, the vessel is slightly relieved in the area above and below the HF-coil joint to allow clearance for installation of the HF-coil segments. Twelve large outer ports (1.0 by 0.6 m), 12 inner ports (0.15 m diam), and 12 upper and lower ports (0.4 m diam) provide access for diagnostics and tangential neutral beams.

Because the vessel carries only atmospheric pressure and a slight (0.3-atm) induced electromagnetic load, the wall thickness is only 6.4 mm. This provides sufficient toroidal resistance (0.5 m Ω) to avoid the need for bellows or insulating breaks. Although there is no active cooling initially, space is provided for water-cooled panels inside the vacuum vessel to permit high-duty-cycle or continuous operation. Metallic seals on the port flanges permit temperatures of up 150°C for discharge cleaning and initial operation. Limiters will be used to prevent deposition of high plasma heat flux on

Fig. 2.41. Plan view of vacuum vessel and HF coil set.

Fig. 2.42. Overall assembly concept.

the vessel wall. The design of the vacuum vessel is nearly complete. A contract for fabrication of the vessel is scheduled to be placed by September 1984.

2.2.4.5 Machine support structure

The machine support structure is designed to accurately position the HF and VF coil sets and support them against the electromagnetic and gravity forces. The principal loads on the HF coils are radially outward hoop loads and overturning or side loads. The principal VF coil loads include a radial hoop force and a vertical force of interaction between the HF and VF coils and between VF coils in a pair.

The structural concept for supporting the HF coil is an external shell composed of identical upper and lower toroidal shell segments and intermediate shell panels. The shell forms a compact structure that allows maximum access for diagnostics and neutral beams. As shown in Fig. 2.42, the shell segments are joined at insulated, bolted flanges to prevent circulating eddy currents. The shell also acts as the support for the VF coils.

2.2.4.6 Assembly sequence

The overall assembly sequence for ATF is shown in Fig. 2.42. The lower shell is assembled and aligned. Next, the lower HF segments are installed and accurately aligned with an optical alignment system. The vacuum vessel is then lowered into position. Next, the upper HF segments are attached to the lower HF segments. The intermediate panels and the upper shell are then installed. As the last step, the VF coils are attached to the support shell and aligned.

2.2.5 ATF Studies—Abstracts

2.2.5.1 "Equilibrium and Stability Properties of High-Beta Torsatrons"³¹

B. A. Carreras	L. Garcia
H. R. Hicks	J. H. Harris
J. A. Holmes	T. C. Hender
V. E. Lynch	B. F. Masden

Equilibrium and stability properties of high-beta torsatrons are investigated using numerical and semianalytical techniques based on the method of toroidal averaging. The averaged equilibria are compared with those obtained using full three-dimensional (3-D) codes. Good agreement is obtained, thus validating the averaged-method approach. The stability of plasmas for configurations with different aspect ratios and numbers of field periods is studied. The role of the vertical field is also studied in detail. The main conclusion is that for moderate-aspect-ratio torsatrons ($A_p \leq 8$) the self-stabilizing effect of the magnetic axis shift is large enough to open a direct path to the second stability region.

2.2.5.2 "Design of the Advanced Toroidal Facility (ATF-1)"³⁴

R. L. Johnson	B. E. Nelson
O. B. Adams	J. F. Lyon
T. C. Jernigan	P. B. Thompson

The ATF-1 is a torsatron being designed at ORNL as a replacement for the ISX-B

tokamak. The concept for the device includes two continuous HF coils and a set of 12 TF coils. The vacuum vessel is placed inside the HF coils, and an external toroidal shell support structure is provided to react all coil and vacuum vessel loads. The present design status for all systems is discussed.

2.2.5.3 "Equilibrium Studies for Low-Aspect-Ratio Torsatrons"³²

L. Garcia	H. R. Hicks
B. A. Carreras	V. E. Lynch
J. H. Harris	

Three-dimensional MHD equilibrium studies have been done for low-aspect-ratio torsatrons. These studies cover continuous-coil and modular torsatrons. The equilibrium properties improve with aspect ratio, as is expected. The role played by the vertical field has also been investigated. Outward shifts cause the flux surfaces to deteriorate. Inward shifts improve the flux surfaces at the expense of stability properties.

2.2.5.4 "Ion Cyclotron Resonant Heating for the Advanced Toroidal Facility"³⁵

D. J. Hoffman	J. H. Harris
A. C. England	T. C. Jernigan
O. C. Eldridge	J. F. Lyon
R. H. Fowler	N. S. Ponte

Ion cyclotron resonant heating (ICRH) is being considered as a heating method for the ATF torsatron. The expected magnetic and plasma properties of the device were used to specify power levels, antenna configuration, and frequency range. With these parameters, we examined the resulting wave impedance coupling. The impact of heating ions in perpendicular velocity space for torsatron confinement was also studied. We conclude that ICRH is a reasonable method for heating or generating the ATF plasma.

2.2.5.5 "ATF-1 Torsatron Studies"³³

J. F. Lyon	S. P. Hirshman
B. A. Carreras	J. A. Holmes
L. A. Charlton	W. A. Houlberg
W. A. Cooper	T. C. Jernigan
R. A. Dory	V. E. Lynch
R. H. Fowler	B. F. Masden
L. Garcia	J. A. Rome
J. H. Harris	K. C. Shaing
T. C. Hender	J. Sheffield
H. R. Hicks	

The main advances in the ORNL Stellarator Program since the 1982 IAEA Conference have been: (1) engineering design of the ATF-1 torsatron, (2) extension of 3-D MHD equilibrium and stability studies and calculations of helical-axis configurations, (3) study of stable equilibria with $\langle\beta\rangle \geq 8\%$ and direct access to the second stability regime, (4) 3-D Monte-Carlo and analytic transport calculations that show a large reduction in transport at low collisionality for $|e\phi'/T| \geq 1$, (5) calculation of ambipolar electric fields, and (6) calculation of well-confined ion drift surfaces in the ergodic field region outside the last closed flux surface.

2.2.5.6 "Design Description of the Helical Field Coils for the Advanced Toroidal Facility"³⁶

M. J. Cole	L. M. Vinyard
B. E. Nelson	D. E. Williamson
R. L. Johnson	T. C. Jernigan
P. B. Thompson	

The HF coil for the ATF will consist of two coils, which wrap around the plasma six times. The major radius of the coils will be 2.1 m with minor radius of 45.75 cm to the coil-current center. The coils will be positioned at assembly to within a 2-mm diam around the winding law, $\theta = 1/6\phi$.

The coils will be fabricated as a set of 24 identical segments—12 upper segments and 12 lower segments. These segments will be joined into continuous coils at the installation site by means of field-assembled joints at the horizon-

tal centerline of the machine. One special joint on each coil will contain the coil leads.

The HF coils will consist of 14 copper turns and a structural member of stainless steel that has a cross section in the shape of a "T." These pieces will be fabricated in accordance with the winding law $\theta = 1/6\phi$. The copper turns will be water cooled and formed from CDA 101 or 102 copper. The 14 copper turns will be positioned such that 7 turns will be placed on each side of the structural "T". The structural "T" will be fabricated from stainless steel (44.45 mm thick) with a minimum strength of 205 MPa and a tensile strength of 485 MPa.

2.2.5.7 "Design Description of the Advanced Toroidal Facility"³⁷

B. E. Nelson	R. L. Johnson
W. D. Cain	J. F. Monday
K. K. Chipley	P. B. Thompson
M. J. Cole	L. M. Vinyard
J. W. Forseman	D. E. Williamson
T. C. Jernigan	

The ATF is a large torsatron being designed at ORNL to replace the ISX-B tokamak. ATF will have a major radius of 2.1 m and an average plasma minor radius of 0.3 m. Major components of the device include the coil sets, structure, and vacuum vessel. The coil sets are designed for broad operating envelopes, including the capability to drive up to 100 kA of plasma current, to produce helical-axis configurations, and to operate continuously at one-half the baseline currents. The ATF structure consists of a 40-mm-thick stainless steel toroidal shell encasing the helical coil set. The shell is constructed from 24 identical upper and lower segments, with 12 pairs of intermediate panels to provide access to the HF coil joints. The lower portion of the shell also serves as an assembly fixture for the HF coil set. The vacuum vessel is a highly contoured 6-mm-thick stainless steel shell closely fitting the bore and sidewalls of the HF coil winding to provide maximum volume for the plasma. Forty-eight large ports allow good access for diagnostics and neutral beam injection.

2.2.5.8 "Design Description of the Vacuum Vessel for the Advanced Toroidal Facility"³⁸

K. K. Chipley
B. E. Nelson

L. M. Vinyard
D. E. Williamson

ATF will be a stellarator experiment to investigate improvements in toroidal confinement. The vacuum vessel for this facility will provide the appropriate evacuated region for plasma containment within the HF coils. The vessel is designed to provide the maximum reasonable volume inside the HF coils and to provide the maximum reasonable access for future diagnostics.

The vacuum vessel design is in an early phase, and all of the details have not been completed. The heat-transfer analysis and stress analysis completed during the conceptual design indicate that the vessel will not change drastically.

2.2.5.9 "Particles and Field Lines Outside the ATF-1 Plasma"³⁹

J. F. Lyon
V. E. Lynch

J. A. Rome

A careful examination of particle orbits and field lines outside the ATF-1 torsatron plasma

was part of the ATF-1 design process. There is no evidence of a separatrix in the flux-surface topology outside the last, nested closed flux surface. Plasma particles go far outside the bulk of the plasma but are mirrored off the HF coils and return to the plasma. When the current density in the HF coils is increased, direct collisionless orbit losses to the wall are almost entirely eliminated. Most ions reach the wall via charge exchange. The resulting flux is spread uniformly over the wall. The base ATF-1 configuration can probably operate without a material limiter, and a divertor or pumped limiter is also a possibility.

2.2.5.10 A Novel Method of Aligning ATF-1 Coils⁴⁰

J. A. Rome
J. H. Harris

G. H. Neilson
T. C. Jernigan

The coils for the ATF-1 torsatron may be easily aligned before the machine is placed under vacuum. This is done by creating nulls in the magnetic field by energizing the coils in various configurations. All of the nulls in B occur on the z-axis. When the nulls coincide, the coils are properly aligned.

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Chapter 3

Atomic Physics and Plasma Diagnostics Development

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3. ATOMIC PHYSICS AND PLASMA DIAGNOSTICS DEVELOPMENT

Summary of Activities

The activities within this program are divided between atomic collisions research and plasma diagnostics development. The majority of this research is supported through the ORNL Fusion Program but is carried out within the Physics Division.

The experimental atomic collisions research focuses on inelastic processes that are important in determining the energy balance and impurity transport in high-temperature plasmas and also in diagnostic measurements. This activity is not directed toward a particular fusion device but concentrates, rather, on developing a better basic understanding of collision processes involving highly ionized atoms at the relatively low kinetic energies characteristic of fusion plasmas. During the past year, the majority of this research has concerned inelastic collisions of multiply charged ions with both electrons and neutral atoms. Strong interaction with theoretical atomic physics activities has guided the selection of experiments and has provided new challenges for theory. Significant progress has been made in our understanding of electron-impact ionization of ions and particularly of the important role of indirect ionization mechanisms. The characterization of electron capture by partially stripped ions at low energies remains a difficult theoretical problem, and our experiments have provided a basis for the evaluation of various approximations. Experiments have continued to address the lower kinetic energies that are appropriate to the edge or scrape-off plasma. A new electron cyclotron resonance (ECR) source of low-energy, highly charged ions has been designed and constructed and will soon become available for atomic collision experiments. This facility will expand our experimental capabilities to considerably more highly ionized systems than have been previously accessible to us. The capability to considerably expand our measurements along isoelectronic and isoionic sequences will permit tests of various scaling laws and will challenge the limits of our understanding of atomic collision processes. The atomic physics group also operates the Controlled Fusion Atomic Data Center, which categorizes publications on atomic collisions, providing bibliographies and compilations of recommended atomic data to the fusion research community.

The plasma diagnostics program has concentrated on the development of optically pumped, continuous wave (cw) far-infrared (FIR) laser systems during the past year. In addition to density measurements via interferometry, Faraday rotation of the polarization of submillimeter-wavelength laser radiation has been developed as a probe of plasma magnetic fields. The lasers and detection systems have been improved toward the goal of a viable multichannel Faraday rotation diagnostic. We hope to demonstrate the potential for determining the spatial current distribution in a plasma from chordal magnetic field data. To date, single-channel Faraday rotation measurements have been made on the Impurity Study Experiment (ISX-B) tokamak at ORNL, and simultaneous five-channel interferometric data have yielded time-dependent plasma density profiles. During this reporting period, a study of the feasibility of pulsed CO₂ laser Thomson scattering as a diagnostic for fusion-product alpha particles in ignited plasmas was initiated. The Diagnostics Development Center has continued to identify and evaluate both the need and the potential for particular new plasma diagnostics and to participate in selecting them and initiating their development in universities and industry.

3.1 EXPERIMENTAL ATOMIC COLLISIONS

3.1.1 New ECR Multicharged Ion Source

F. W. Meyer
C. R. Mahon

N. B. Nescovic

Construction of the new ECR multicharged ion source has been completed on schedule, and testing has been initiated. The ion source (Fig. 3.1) is a two-stage design—the first stage producing a cold, dense plasma, either by ECR or by nonresonant wave conversion, while the second stage strips the ions as they diffuse from the first stage through a magnetically confined plasma containing fast electrons that are ECR heated. Confinement is provided by a minimum- B configuration produced by a superposition of axial mirror and radial hexapole magnetic fields. The mirror field is pro-

duced by three conventional coils (Fig. 3.2), while the hexapole field is produced by a compact assembly of SmCo_5 permanent magnets. Figure 3.3 is a cross-sectional view of the 12-piece hexapole magnet assembly, superimposed on a calculated magnetic field-line plot.

Initial testing of the source was begun using 2.45-GHz microwave generators for both the first and second stages. Stable neon plasmas have been obtained at microwave power levels in the range of 100 to 400 W. Figure 3.4 is a photograph of such a plasma viewed from the extraction chamber and shows the expected six-fold symmetry produced by the electron-confining fields. Evidence of ECR heating of electrons in the second stage was provided by use of a calibrated Si-Li X-ray detector, which indicated electron energies up to 160 keV. For power levels in the range of 100 to 200 W,

ORNL PHOTO 0966-84

Fig. 3.1. The ORNL ECR multicharged ion source.

ORNL-DWG 83-17376

Fig. 3.2. Magnetic field on-axis versus axial position. Locations of solenoidal coils and ECR regions are indicated. Axial position Z and radial position R are in centimeters.

Fig. 3.3. Calculated radial cross section of hexapole magnetic field lines, showing position and orientation of SmCo_5 magnet bars.

ORNL PHOTO 0662-84

Fig. 3.4. Photograph of second-stage ECR plasma, viewed from ion-extraction chamber.

readily shieldable X-ray intensities of 1 to 2 R/h were measured at the extraction chamber end flange, with second-stage pressure in the mid- 10^{-6} torr range. In addition, overdense plasma generation was achieved in the first (injector) stage using a tapered helical antenna as a slow-wave launcher. Stable plasmas were produced at magnetic fields up to three times larger than the resonance value of 0.088 T at 2.45 GHz. Operation in this non-resonant mode will permit tailoring of the axial magnetic field for optimum ion injection into the second stage, without having to satisfy the constraint of the electron resonance condition in the first stage.

Following an initial design study, the decision was made to duplicate the mass/charge analyzer recently built for the ECR source under construction at Lawrence Berkeley Laboratory (LBL). This will result in substantial savings in time and engineering costs. Fabrication of this magnet has begun and is expected to be completed early in March 1984. Construction and assembly of the beam line up to the user port is also proceeding on schedule and will be completed at about the same time. Measurements of charge-state distributions in extracted ion beams will then begin using 2.45-GHz microwave generator. The first atomic collisions experiments using the new ion source are planned for April 1984. These will parallel the source shakedown phase and will involve total electron-capture cross-section measurements for highly stripped ions colliding with atomic hydrogen. Operation of the ion source at the design frequency is expected to commence in June 1984, when delivery of the 10.6-GHz microwave system is scheduled.

3.1.2 Electron-Ion Collisions: Ionization of Doubly Charged Ions

D. H. Crandall
D. C. Gregory
G. H. Dunn

T. J. Morgan
D. W. Mueller

Electron-impact ionization is one of the critical atomic physics processes affecting power

balance, impurity transport, and edge-plasma characteristics. The present study was undertaken as part of a continuing collaboration with the Joint Institute for Laboratory Astrophysics (JILA) in order to provide data on electron-impact single ionization for a number of ions of charge +2.

The following doubly charged ions, in increasing atomic number, have been studied in this reporting period: B^{2+} , N^{2+} , F^{2+} , Cl^{2+} , Ar^{2+} , Ti^{2+} , Fe^{2+} , Cu^{2+} , Kr^{2+} , and Xe^{2+} . Boron is of particular interest because it lies along the lithium isoelectronic sequence, where experiment appears to contradict theoretical predictions of indirect ionization trends.¹ Nitrogen data were compared to previous measurements² as a check of the cross-section absolute magnitude. Previous measurements on Ar^{2+} (refs. 3 and 4), Kr^{2+} (ref. 4), and Xe^{2+} (ref. 5) compare well with the present results, which are considered to be either of higher precision or more accurate than existing data. The Xe^{2+} measurement was also important in our study of the Xenon isonuclear sequence.⁶ Iron is considered a likely contaminant in any fusion scheme currently proposed and is the highest priority for impurity studies. Although each of the measurements is of interest to the physics community and each reveals challenges for theory, only two of the cross-section experiments will be discussed in detail here.

The cross section for electron-impact single ionization of Ti^{2+} is shown in Fig. 3.5. Uncertainties at each point are relative only at the 1 standard deviation (s.d.) level, with the absolute uncertainty at the 2 s.d. level also plotted on the 200-eV point. The dashed curve of Fig. 3.5 is an upper-limit estimate of direct ionization from the Lotz semi-empirical formula.

The experimental curve rises sharply from threshold and reaches its peak, which is a factor of 2.5 larger than the Lotz estimate commonly used in plasma-modeling studies. The difference is attributed primarily to excitation-autoionization effects (excitation of an inner electron in Ti^{2+} to an excited state that decays

Fig. 3.5. Experimental cross sections for electron-impact ionization of Ti^{2+} . Dashed curve is the Lotz prediction of direct ionization. Indirect ionization effects cause a factor of 2.5 enhancement of the measured cross section.

by autoionization, leaving Ti^{3+}). Effects of dominant excitation-autoionization were first observed by Peart and Dolder,⁷ and the present measurement extends our recent study that included ionization of Ti^{3+} (ref. 8). Indirect effects in the Ti^{3+} measurement exceed direct ionization by up to a factor of 10, making it one of the largest enhancements ever observed. The observation of cross sections that are a factor of 2 to 10 larger than predicted for a series of charge states in a given element should be a cause for concern among those who base models of plasma behavior on knowledge of these cross sections to 20% accuracy.

There are obviously a number of separate features contributing to the enhancement of the Ti^{2+} cross section. Most notable and interesting is the small bump at about 50 eV and the sudden sharp increases in cross section at about 32 and 42 eV. Theoretical studies are under way to explore the physics underlying these features and to explain the overall

enhancement of the cross section over a broad energy range.

The cross section for ionization of Fe^{2+} is shown in Fig. 3.6. Relative uncertainties are approximately the size of the plotted points, and the absolute uncertainty at good confidence is plotted at 250 eV. The dashed curve is a distorted-wave calculation due to Younger⁹ and is thought to be a good estimate of the direct ionization cross section.

Theory and experiment are in good agreement in both magnitude and shape over the entire energy range. There are several energies (e.g., near 33 eV) at which the measured cross section may show some structure due to indirect effects, but these are minor contributions to the total ionization. The experimental onset is observed to occur at about 25 eV (10 eV below the predicted ground-state ionization energy). This early onset is indicative of a metastable component in the incident ion beam, which is expected due to the complex level structure in the ground-state electronic configuration.

The most interesting feature of this curve is the one we do *not* observe near 57 eV. A

Fig. 3.6. Electron-impact ionization of Fe^{2+} . Good agreement is seen between experiment and direct-ionization theory (dashed curve, from ref. 9). Theoretical prediction (ref. 10) of a strong indirect ionization feature at 57 eV is not substantiated by the measurements.

predicted¹⁰ factor of 2 cross-section enhancement due to a sharp isolated excitation-autoionization feature at 57 eV has not materialized. In fact, we see no significant enhancement anywhere in this energy range. More elaborate calculations are under way to investigate the possibility of canceling effects due to interference in this cross section.

The two measurements shown illustrate two major problems that face the atomic physics community concerning electron-impact ionization. Ti^{2+} illustrates how simple scaling laws may prove to be inaccurate in a specific case. Indirect effects must be taken into account if we are to predict ionization cross sections reliably. The greatest difficulty is seen in ions with unfilled d-subshells. A second problem is illustrated by the Fe^{2+} measurement and calculation. First-approximation calculations of indirect effects may also be inaccurate due to competing or canceling processes. Continued cooperative experimental-theoretical benchmark studies are our best prospect for unraveling the physics of ionization.

3.1.3 Electron-Ion Collisions: Multiple Ionization

D. H. Crandall
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A. M. Howald
R. A. Phaneuf

Absolute cross sections for electron-impact double ionization of Ar^{4+} , Kr^{4+} , and Xe^{4+} have been measured at collision energies ranging from the double-ionization threshold to 1500 eV (ref. 11). The experiments were performed by crossing a quadruply ionized beam from the ORNL Penning ionization gage (PIG) ion source with a magnetically confined electron beam.¹² The apparatus and experimental technique are identical to those employed for single-ionization measurements on doubly charged ions (Sect. 3.1.2). Advantage was taken here of the identical initial-to-final charge ratios for $2 \rightarrow 3$ and $4 \rightarrow 6$, which permitted use of the same electrostatic charge analyzer for both series of experiments.

The only cross-section data of which we are aware for direct comparison are those of

Achenbach et al.¹³ for $e + \text{Xe}^{4+} \rightarrow \text{Xe}^{6+}$. Our measurements average 13% smaller than theirs, but the level of agreement falls within the combined experimental absolute uncertainties. The peak magnitudes of the cross sections and the approximate energies at which the peaks occur are: Ar^{4+} ($\sigma_{46} = 1.4 \times 10^{-18} \text{ cm}^2$ at 800 eV), Kr^{4+} ($\sigma_{46} = 6.8 \times 10^{-18} \text{ cm}^2$ at 700 eV), and Xe^{4+} ($\sigma_{46} = 9.2 \times 10^{-18} \text{ cm}^2$ at 225 eV). Near the peak in the cross section, total uncertainties at good-confidence level are $\pm 8\%$.

In all of the cases investigated, the multiple-ionization cross section appears to be dominated by ionization of an inner-shell electron followed by autoionization. For example, in Ar^{4+} the threshold energy for direct ionization of two 3p electrons (165 eV) is well separated energetically from the 2p ionization threshold (≈ 324 eV). From the double-ionization measurements for argon ions (Fig. 3.7), the direct double ionization is estimated to contribute less than 10% of the peak double-ionization cross section that is instead dominated by ejection of

Fig. 3.7. Comparison of electron-impact double-ionization cross sections for argon isomeric sequence. $\circ$ = experimental measurements for Ar^{2+} and $\triangle$ = experimental measurements for Ar^{3+} (ref. 14). $\bullet$ = present measurements for Ar^{4+} with absolute uncertainty shown only on the point near 1200 eV. Solid curve is a distorted-wave calculation for the 2p ionization of Ar^{4+} . Arrows designate double-ionization thresholds and 2p inner-shell ionization thresholds.

a single 2p electron, followed by autoionization, giving net double ionization. The Ar^{4+} results extend the results of Müller and Frodl,¹⁴ who found a similar but less dramatic contribution to double ionization by 2p ejection-autoionization for argon ions of initial charge +2 and +3. Their data are also plotted in Fig. 3.7 for comparison, along with a distorted-wave calculation for 2p inner-shell ionization.¹¹ In fact, for all three of these argon ions, the double-ionization cross section has nearly the same peak value of just over $1 \times 10^{-18} \text{ cm}^2$ near 800 eV, and this is believed to be simply the cross section for direct ejection of a 2p electron.

The situation is qualitatively similar for Kr^{4+} and Xe^{4+} in that the double-ionization cross section is believed to be dominated by single inner-electron ejection and subsequent autoionization. However, for these heavier ions, the thresholds for direct double ionization and for inner-shell ionization followed by autoionization are not sufficiently separated to produce distinct features. Interpretation of the data is therefore less straightforward than for Ar^{4+} . For Kr^{4+} a well-resolved structure is observed beginning near 600 eV, which enhances the cross section by about 10%. We are aware of no simple processes with thresholds in this energy region and thus are unable to identify the origin of this feature.

Another systematic approach to the study of collisional electron-ejection mechanisms was explored in a recent series of measurements of cross sections for single, double, and triple ionization of Xe^{6+} . It was observed in the case of double ionization of Ar^{q+} ions that direct single ionization of an inner-shell electron may result in net double ionization. Similarly, in some cases, triple or higher ionization may be the result of ejection of a single, inner-shell electron followed by autoionization as the excited ionic core relaxes. Such a study of the final charge-state distribution for electron impact on Xe^{6+} will reveal additional details about indirect ionization channels and the branching ratios to different ionization stages for these processes. Detailed theoretical analysis of the measurements has not been

completed, but double and triple ionization both have measured peak cross sections near 10^{-18} cm^2 , considerably larger than would be expected on the basis of existing scaling laws or simple theories. It is becoming apparent that for complex ions, the relative importance of multiple ionization increases significantly with increasing ionic charge. This process is generally not considered in the modeling of plasma ionization balance and could be important in some situations.

3.1.4 Ion-Atom Collisions: Electron Capture

R. A. Phaneuf

C. C. Havener

In a continuing program to address atomic collision processes relevant to the edge or scrape-off plasma, the pulsed laser ion source and associated time-of-flight collision apparatus¹⁵ have been applied to measurements of total cross sections for electron capture by a number of multiply charged ions colliding with hydrogen atoms and molecules at energies in the range of 10 to 1000 eV/amu. Ions studied during this period include $\text{B}^{(2-5)+}$ and $\text{Al}^{(2-10)+}$. Aluminum ions were chosen for study because of their importance as impurities in ELMO Bumpy Torus-Scale (EBT-S). At these energies, where the nuclear motion is slow compared to that of the hydrogenic electron, such collisions are best characterized in terms of a quasi-molecular model, in which the capture is represented as a transition between stationary states of the system. Predicted cross sections depend strongly on the internuclear distance at which the relevant molecular potential energy curves cross and on the dynamics of the coupling between them. The wide range of ions and charges investigated to date allows some characteristics of the variation of the capture cross sections with ion species, charge, and collision velocity to be interpreted within the context of the molecular model.

Collisions between nearly or fully stripped ions and hydrogen atoms (*one- or few-electron systems*) are characterized by one or, at most, a few curve-crossings that are important for capture, and detailed coupled-state calculations

are usually necessary for reliable predictions of the cross sections at low energies. Cross sections can be strongly velocity and species dependent and do not scale with ionic charge in any predictable way. Detailed theoretical methods for treating such systems are outlined in Sect. 3.2.2 of this report, where comparisons are drawn between experiment and theory at low energies.

For ions of a fixed charge q , the degree of degeneracy of levels within a given principal shell is reduced as the number of core electrons becomes larger, and an increasing number of curve-crossings may occur at internuclear separations that are favorable for capture. Total capture cross sections for such multiply ionized *many-electron systems* at low energies tend to scale more or less linearly with ionic charge, to be rather insensitive to collision velocity, and to reach a saturation value for a given q that becomes independent of species as the number of core electrons becomes large. For these many-electron systems, empirical scaling laws, such as the recently proposed $\sigma(\text{cm}^2) = q \times 10^{-15}$ (ref. 16), can give reasonable representations of the cross sections at low energies.

Several theoretical methods have been applied to account for the influence of ionic core structure in a simplified manner. Bottcher and Heil¹⁷ have developed a "screened potential" method in which the capture is treated in a one-electron approximation and the role of the core electrons is to relax the molecular symmetries and selection rules for transitions in the quasi molecule. Recently, Larsen and Taulbjerg¹⁸ have used simple quantum-defect functions to describe the removal of degeneracy of levels within a principal shell caused by the presence of ionic core electrons. Their predicted variation of the total capture cross section with atomic number Z for ions of ionic charge $q = 6$ is compared in Fig. 3.8 to low-energy experimental data^{15,16,19} for a number of different ion species. The remarkable agreement suggests that such approximate methods will prove valuable in representing the electron-capture process in complex collision systems.

Fig. 3.8. Variation of total electron capture cross sections with atomic number Z for ions with ionic charge $q = 6$ colliding with hydrogen atoms at a fixed velocity of 2×10^7 cm/s. Carbon and oxygen data are from ref. 15; argon and xenon data are from ref. 19; iron datum is from ref. 16; aluminum datum is unpublished; and theory (solid curve) is from ref. 18. The dashed curve is an extrapolation of the theoretical result.

An ion-atom, merged-beam experiment is also in final stages of development.* This approach will allow total electron-capture cross sections to be precisely measured for collisions between multiply charged ions and hydrogen atoms down to center-of-mass collision energies as low as a few electron-volts. At such energies, an orbiting mechanism is predicted to give very large electron-capture cross sections with a $1/v$ velocity dependence in some multiply ionized systems.²⁰ Experimental and theoretical results suggestive of this phenomenon are presented in Sect. 3.2.2 of this report, where measurements¹⁵ obtained with the laser ion source at energies as low as 69 eV/amu are compared to fully quantal close-coupling calculations¹⁷ for $O^{5+} + H$ collisions. Precise measurements on this and other systems at still lower energies are needed to verify this interpretation and to provide a basis for evaluation of theoretical methods in this difficult low-energy regime.

*This research is being supported by the U.S. Department of Energy, Division of Chemical Sciences.

3.2 ATOMIC THEORY

3.2.1 Electron-Ion Collisions: Ionization, Excitation, and Recombination

C. Bottcher
D. C. Griffin

M. S. Pindzola

During the past few years, we have performed calculations that established the important role of excitation-autoionization in the ionization of complex ions by electron impact at energies near threshold; for example, in Ti^{3+} the cross section is enhanced by a factor of 10, and this is typical rather than exceptional. In direct ionization the interaction between a bound electron and the projectile causes the former to make a transition into the continuum in a single step. In excitation-autoionization an inner-shell electron is excited to another bound orbit in which it has enough energy to eject a valence electron. To interpret ionization measurements, we have had to calculate precise energies (within 1 eV) for the intermediate states and the cross sections to excite them. Our early calculations identified many autoionizing levels in Al^{2+} and Si^{3+} (ref. 21), in Ga^+ (ref. 22), and in Ti^{3+} , Zr^{3+} , and Hf^{3+} (ref. 23) and, in most cases, explained the magnitudes of the observed cross sections reasonably well. However, in studying the transition elements, we had to make rather drastic approximations in the cross sections and, in the end, divide by 2.5 to agree with experiment (in some cases).

We thus undertook the major project of writing a set of codes to calculate unitarized distorted-wave excitation cross sections (with exchange) for systems that have any number of open shells and intermediate coupling. The only limitation is to single-configuration Hartree-Fock wave functions. Using these codes, we have greatly reduced the disagreement with experiment for Ti^{3+} , Zr^{3+} , Hf^{3+} (ref. 24); for example, in the least favorable of these cases, theory needs to be divided by 1.6. We have made studies of the very complex structures of Fe^{4+} and Ti^{2+} that suggest that full distorted-wave calculations for such cases

can be well reproduced by a simpler statistical model. However, the magnitude of the Ti^{2+} cross section is 2.2 times experiment, though its shape agrees well (Fig. 3.5). The disagreements for Ti^{2+} and Ti^{3+} are almost certainly due to pairing correlations in the target wave functions, and we are now extending our codes to accommodate multiconfiguration wave functions.

We have now performed calculations for the entire isonuclear sequence of Xe^{q+} ($1 \leq q \leq 5$), mostly using a "spectator" model in which the 5p shell was assumed to take no part in the transition. Where it could be checked (the $4d \rightarrow 4f$ excitation for $q = 1$ and $q = 5$), this model is astonishingly successful. Our particular concern was to qualitatively explain the humplike structure²⁵ observed in Xe^{3+} . Figure 3.9 indicates that we have succeeded; the structure is due to excitations that violate dipole selection rules. The residual disagreement is in the region below the thresholds for excitation-autoionization. The cross section in this case is almost certainly due to the

Fig. 3.9. Excitation-autoionization of Xe^{3+} . The full curve is our calculated total ionization cross section. Ranges of thresholds for the transition $4d \rightarrow n l$, where $n l = 5p, 5d, 4f$, and $5f$, are indicated by arrows. The dotted curve is the result of convoluting the theory with a 2-eV Gaussian to simulate experimental resolution. The dashed curve is a distorted-wave calculation of the direct-ionization cross section. The experimental points are from ref. 25.

recombination-double-Auger mechanism postulated by LaGattuta and Hahn²⁶ for Fe^{15+} . Though a complete calculation is prohibitively complicated for Xe^{3+} , we can explain the systematic trends of this process in the xenon sequence.⁶

One significant recent development in electron-impact ionization is the recognition that double and multiple-ionization cross sections can be almost as large as the single, particularly for heavy targets. It was natural for us to investigate the sequence of targets Xe^{q+} ($q = 1, 2, 3, 4$) for which double-ionization cross sections have been measured by a group at Giessen.¹³ Since direct double ejection is rather improbable, we considered the mechanism of "ionization-autoionization," in which an inner-shell electron (in xenon, the 3d) is ejected, leaving an autoionizing "hole" state that can eject the second electron. We showed that this mechanism gives reasonably good agreement with experiment for $\text{Xe}^+ \rightarrow \text{Xe}^{3+}$, if we allow for term dependence in the final state and correlation in the initial state.²⁷ The theory has now been applied to higher members of the sequence¹¹; for example, Fig. 3.10 compares experiment with different theories for $\text{Xe}^{2+} \rightarrow \text{Xe}^{4+}$.

In Ca^+ and Ba^+ we have identified a new source of disagreement between conventional theories (including close-coupling) and experiments, with respect to pronounced narrow peaks just above the excitation thresholds, $3p \rightarrow 3d$ in calcium and $5p \rightarrow 5d$ in barium. These peaks are due to shape resonances in the scattered f-wave, which may be sensitive to correlation in the target wave functions.

We are now proceeding to extend our codes to calculate *dielectronic recombination* to the same level of sophistication.

3.2.2. Ion-Atom Collisions: Low-Energy Charge Exchange

C. Bottcher

T. G. Heil

We are making systematic studies of electron capture from hydrogen atoms by ions

Fig. 3.10. Ionization-autoionization of Xe^{3+} . Experimental points (pertaining to double ionization, $\text{Xe}^{3+} \rightarrow \text{Xe}^{4+}$) are from ref. 13. The dotted curve labeled "BEA" is a crude binary-encounter estimate of direct double ejection. The dashed curve is our calculation (ref. 11) of ionization of the 4d electron with configuration-averaged wave functions; the full curve is our calculation with term dependence in the final state and correlation in the initial target state.

more highly charged than 3+ at energies below 250 eV/amu. Our method is to expand the wave function of the active electron in two-center Coulomb eigenfunctions and then to solve the fully quantal close-coupling equations.¹⁷ This approach enables us to attack two goals:

1. For projectiles that are bare nuclei, these electronic wave functions are exact. Thus, disagreements with experiment must lie in the scattering theory, and we can gain fundamental insight into the Coulomb three-body problem. The simplest system that has a large cross section at low energies is $\text{B}^{5+} + \text{H}$, so we are concentrating our efforts here in parallel with experiments by Phaneuf and coworkers.^{15,16}
2. Modeling impurity transport near the edge of a fusion plasma demands low-energy

charge-exchange cross sections for *all* stages of each impurity; this requires some method of calculating cross sections that is simpler than generating all-electron wave functions by quantum-chemistry techniques. We have shown that good results are obtained with the two-center Coulomb basis when the multielectron aspects of the process are relegated to a "screened potential." The physics is governed by the off-diagonal elements of this potential. We have used the model to explain systematics in the 4+ and 5+ isoionic sequences.^{15,28}

In our fundamental studies, we have to examine convergence with respect to the basis set. To handle large numbers of channels (up to 50), we have developed a vectorized code to run on the National Magnetic Fusion Energy Computing Center (NMFECC) Cray computers. Using the code, we have now included π orbitals in calculations on C^{6+} , B^{5+} , C^{5+} , and O^{5+} . In the O^{5+} case, small basis-set cross sections have pathological oscillations that disappear when π orbitals are added. Figure 3.11 illustrates the effect of increasing the basis set in the 5+ sequence and, in particular, the improved agreement with experiment for O^{5+} . We are extending these calculations to much larger basis sets and including the effects of translation factors, to which end we are developing some new approaches.

As far as applications are concerned, we believe that calculations with a small number of σ orbitals suffice for many purposes. In this spirit, we are looking into Al^{3+} and the sequence O^{8+} , Ne^{8+} , Fe^{8+} .

The most striking low-energy phenomenon is the rising cross section at very low energies, as seen in the 5+ sequences, which we attribute to orbiting resonances. In a new development, we are investigating differential cross sections to see if a transition to orbiting behavior (redistribution of the forward peak to larger angles) can be discerned.

Fig. 3.11. Electron capture from $H(1s)$ by the ions B^{5+} , C^{5+} , and O^{5+} . Experimental data are from ref. 15. The solid curves are fully quantal calculations with three σ states (ref. 17), and the dashed curves with an additional 3 π states (ref. 28). We also show the classical orbiting cross section (dotted) and the absorbing-sphere cross section $1/2\pi R_x^2$, where R_x is the internuclear separation at the dominant curve crossing ($R_x \approx 13 a_0$).

3.3 CONTROLLED-FUSION ATOMIC DATA CENTER

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The data center continues to maintain a current, categorized, annotated bibliography of atomic and molecular collision processes. Yearly bibliographies are published as ORNL reports. At the beginning of 1982, the bibliographical scheme was revised to eliminate those papers not of direct relevance to the fusion program. Papers involving molecules other than those found in plasma peripheries or

ion sources are no longer considered as part of the input. This action has resulted in a 47% decrease in the number of citations entered into the computer file.

Cooperative efforts have continued to exist with the Atomic Data Center for Fusion at the Institute of Plasma Physics (IPP), Nagoya, Japan, and with the International Atomic Energy Agency (IAEA) in Vienna. During this reporting period, *Recommended Data on Excitation of Carbon and Oxygen Ions by Electron Collisions*²⁹ was published as a collaborative effort between IPP and ORNL. ORNL's staff continues to meet with and advise the IAEA's Coordinated Research Program.

Progress has been made on the revision of Vols. 1 and 2 of *Atomic Data for Controlled Fusion Research*, commonly referred to as the "Redbooks."³⁰ The revisions of both volumes (and the future volumes) will contain tabular and graphic data of the reaction cross sections. In addition, reaction-rate coefficients will be included for interactions of both beam-Maxwellian and Maxwellian-Maxwellian velocity distributions. Computer programs have been written to indicate uncertainties in these rates that are of importance where rates are needed at the extreme low or high energy ranges of the cross-section data. Seven-parameter polynomial fits are being made to all reaction-rate data. The revision of Vol. 1 on heavy-particle collisions is being conducted in-house. A subcontract with JILA has been initiated to revise Vol. 2 for electron collisions. Data are being assembled for both volumes. Volume 3 of the series, *Collisions of Atomic Particles with Surfaces*, has been completed by E. W. Thomas of the Georgia Institute of Technology and is now in the final stages of publication. We are still unable to characterize in a quantitative manner the trapping and desorption of particles from surfaces. The scope and outline for Vol. 4, *Collision of Impurity Ions: C and O*, have been finalized and data collection has commenced. Future volumes of the series will be devoted principally to collisions of other impurities found in high-temperature plasmas.

In the summer of 1983 the data center organized a workshop on electron collision theory with discussions concentrated on the effects of intermediate states (excitation-autoionization and recombination resonances) on all inelastic collisions.³¹

An intense effort has been made during the past year to update our computer facilities and programs. Prior to 1983 our bibliographical files were stored off-line. Some of these files have been transferred to an IBM 3033 computer for on-line retrieval. Since 1960 we have gone through five generations of computer-storage programs. Now on-line retrieval for only the period 1978 to present is practical. A stand-alone computer with digitizer, graphical display, and printout has been installed to aid in the retrieval, evaluation, and compiling of numerical data. We expect greater efficiency and accuracy in the production of the compilations of evaluated numerical data.

3.4 PLASMA DIAGNOSTICS DEVELOPMENT

3.4.1 Diagnostics Development Center

C. F. Barnett

The Diagnostics Development Center's activities are concentrated in three areas: (1) support of the national effort in the development of new diagnostics, (2) support of innovative and speculative developments through a feasibility stage by in-house efforts and by small contracts with universities, and (3) initiation of studies and research for diagnostics applicable to reactor-like experiments. Our efforts during 1983 have gone into programs to carry out these objectives.

High-speed (4000-fps) framing camera studies have been completed on the TEXT tokamak (University of Texas, Austin) during stable and turbulent operation. Photographs were taken at three viewing ports: perpendicular to the plasma at the limiter port, longitudinal to the plasma viewing the inside of the toroidal limiter, and perpendicular to the plasma 180° from limiter. Semiquantitative

data from the films were obtained by visual observation and frame-by-frame scanning with an optical densitometer. The observations are summarized as follows:

- Striations or particle density channels are always present at the beginning or termination of the discharge and during turbulent operation.
- During stable periods of operation, no fluctuations were observed.
- Spallation of macro-size particles or molten pieces of metal were observed during the formation of the discharge, at disruption or with unstable operation, and at the end of discharge.
- Macro-particles were observed at 180° from the limiter, apparently coming from the wall.
- Particles coming from the wall or limiter usually flowed in the direction of the plasma current with a luminous plume extending in front of and behind the particles.

Work on the development of a diagnostic using liquid-oxygen absorption of 2.35-MeV deuterium-deuterium (D-D) neutrons to measure plasma ion temperature continued in 1983. Preliminary calculations had shown the experiment to be feasible for a 2-keV plasma ion temperature using an available liquid-nitrogen cell. More precise calculations by the ORNL Engineering Physics Division for a global neutron source from a 6-keV D-D plasma indicated that the overall efficiency of the neutron detector at the rear of the absorption cell would be 4×10^{-11} neutrons per source neutron. This is to be compared to a source strength on ISX-B of 2×10^{10} neutrons per second. Since the calculations are believed to be accurate to within 20%, the technique does not appear to be feasible; thus, the activity has been terminated.

A collaborative effort has been initiated with E. W. Thomas (Georgia Institute of Technology) and P. Bakshi (Boston College) to make a feasibility study of the electric fields in tokamaks. Fast-response diode arrays with H_α filters are being constructed to observe time correlations of optical emission from adjacent locations in the plasma edge using similar tech-

niques to those of Zweben et al. at the California Institute of Technology.³² First measurements on TEXT tokamak will establish the physical extent of coherent emission regions, both poloidally and toroidally. These activities will be preliminary to electric-field measurements using Stark-broadened profiles or shifts of the H_α line originating in the turbulent edge plasma. Since the conventional analysis of Stark effect in plasmas is in terms of the static Holtsmark fields, it will be necessary to also include the line shape and shifts due to quasi-static and high-frequency fields. Line-shape modeling will be done to include the effect of these fields.

Studies are continuing on the role of diagnostics in fusion-reactor-like experiments. Diagnostic techniques involving nuclear, atomic, orbit-loss, plasma-phenomena, and laser-scattering processes as applied to fusion-product alpha particles were to be discussed at a workshop in February 1984. In future experiments such as the Mirror Fusion Test Facility expansion (MFTF-B) or the tandem mirror machine (TARA) at the Massachusetts Institute of Technology (MIT), it is imperative that an unambiguous diagnostic method be developed to measure the plasma potential at different spatial positions along the magnetic field. Heavy-ion-beam probes have been used successfully in tokamaks and other plasmas. In the mirror machines, however, the data may be difficult to interpret due to (1) high plasma beta (as much as 50%), (2) necessity of beam projection across a long distance (~ 10 m) in the magnetic field, and (3) the complex magnetic field shape in the barrier region. Preliminary plans were made to organize a workshop in early 1984 to discuss methods for measurement of plasma potentials.

3.4.2 Far-Infrared Laser Development

D. P. Hutchinson
C. H. Ma

P. A. Staats
K. L. Vander Sluis

During the past two years, we have continued to improve the characteristics of FIR sources for plasma diagnostics applications. These efforts have resulted in a considerable

increase in both power level and stability of our FIR systems. The power level in our cw CO₂ pump lasers was increased from 30–40 W to approximately 70–80 W by using a new, larger-bore, longer, split-electrode discharge tube. The split-electrode design was used to minimize the high voltage required to energize these longer tubes. The mode structure of the CO₂ lasers is controlled by an aperture consisting of a spiral of 0.508-mm (20-mil) wire placed near one end of the laser tube. The spiral aperture prevents off-axis, higher-order modes from oscillating. To improve the overall stability of the laser system, the entire system of two CO₂ lasers and two submillimeter (SMM)-wave lasers has been packaged into a single invar-stabilized structure. A closed-cycle freon cooling system using a liquid-air heat-exchanger loop was designed to cool the CO₂ pump lasers. The freon coolant was necessary because several parts of the laser tubes float at high voltage. A liquid-air heat-exchanger loop was employed to cool the system to ambient room temperature, thereby inhibiting water condensation during humid summer months.

In addition to improvements in pump laser design, changes were made in the optics system coupling the pump and SMM-wave lasers, as well as to the SMM-wave cavity itself. A Gaussian beam-propagation computer code was developed to optimize injection of pump power into the SMM-wave cavity. Also a new SMM output coupler recently developed at Laser Power Optics, Inc., was installed in the FIR lasers. The combination of improvements has resulted in a maximum SMM-wave power level of approximately 100 mW at a wavelength of 0.447 mm using methyl iodide as a lasing vapor.

3.4.3 Multichannel Interferometry

D. P. Hutchinson
C. H. Ma
P. A. Staats

K. L. Vander Sluis
N. G. Demas

The FIR interferometer/polarimeter has been modified during the past year to provide

more accurate density data. In addition an Abel-inversion routine has been developed to convert the multichannel measurements into radial density profiles. The replacement of the cumbersome liquid-helium-cooled detectors has allowed us to combine the Schottky diode mixer, bias supply, and first low-noise amplifier into a single shielded enclosure. This design has considerably reduced spurious noise pickup during the plasma discharges. The interferometer has been expanded to five simultaneous channels. Having five channels available on the majority of plasma discharges has allowed us to develop a method of converting the line-averaged measurements from five different chords through the plasma to radial electron-density profiles. Some results of this inversion code are shown in Fig. 3.12. The solid curves are density profiles calculated for several times during the shot. The density profile information derived from the pulsed ruby laser Thomson scattering measurements (taken at only one point in time for each discharge) is represented by the solid circles on the FIR-derived profile at 280 ms. The agreement between the two

Fig. 3.12. ISX-B tokamak density profiles calculated from the line-averaged chordal measurements plotted vs minor radius. The solid circles represent the point measurements of the density profile as determined by the pulsed Thomson scattering diagnostic.

diagnostics is excellent. Since FIR density measurements are made continuously during the plasma discharges, a time-evolved picture of the density profile may be made. Work is continuing on the inversion technique to make such data available on virtually every discharge. In addition to making measurements on neutral-beam-heated discharges, the interferometer has been used to study experiments in which several solid hydrogen pellets were injected to determine the best way in which to refuel a fusion reactor. Figure 3.13 contains line-averaged density measurements of a tokamak plasma shot in which two pellets were injected. An inversion of the data was not possible in this case because the form of the mathematical expression used to calculate the profile has difficulty with the apparently flat profiles produced by pellet injection. Other formulations are being investigated that will better fit the pellet-induced profiles.

In addition to the line-averaged density measurements, the interferometer has also been used to study plasma density fluctuations. When using a heterodyne interferometer, den-

sity fluctuations appear as sidebands on the 1-MHz heterodyne beat signal. The ability to observe density fluctuations was realized due to our efforts to make improvements in the interferometer signal-to-noise ratio. The data obtained thus far are preliminary, and we expect to spend a portion of our time during next year studying fluctuations and correlating them with other diagnostic measurements to glean whatever plasma information is available from these measurements.

3.4.4 Faraday-Rotation Measurements

D. P. Hutchinson
C. H. Ma

P. A. Staats

During the past year, we have continued our efforts to integrate the high-speed Faraday-rotation modulator into our Faraday-rotation measurements on ISX-B. Several improvements were made in the areas of detector optics, detector shielding, and calibration to improve the heterodyne signal containing the Faraday-rotation information. The result of these improvements was the observation of scattering from plasma density fluctuations. The frequency spectrum from the fluctuation scattering overlaps the Faraday-rotation signals and increases the apparent receiver noise for the Faraday experiment. It appears that the scattering from fluctuations will set the minimum "noise" level for the Faraday-rotation experiment. Although the density fluctuations complicate the Faraday-rotation measurements, we have been able to make Faraday measurements on ISX-B. A single-channel measurement of line-averaged electron density and Faraday rotation is shown in Fig. 3.14. The third curve, labeled I_p , represents the time profile of the plasma current. Since the Faraday signal should be roughly proportional to density times plasma current, we attribute the rapid variations on the polarization signal to density fluctuations. We are presently exploring operating regimes in which we will be able to separate these two effects.

Fig. 3.13. The injection of two solid hydrogen pellets into the ISX-B tokamak produces an abrupt density increase in all channels of the interferometer, corresponding to different chords through the plasma. The time resolution of the interferometer is less than 1 ms.

Fig. 3.14. Single-channel, line-averaged, electron density (n_e) and Faraday rotation (θ_p) signals for a neutral-beam-injected discharge on ISX-B. The plasma current I_p is also included for reference.

3.4.5 Alpha-Particle Diagnostic Using CO_2 Laser Thomson Scattering

D. P. Hutchinson

K. L. Vander Sluis

The feasibility of CO_2 laser Thomson scattering from a multicomponent burning plasma has been evaluated for the measurement of the velocity distribution of deuterium-tritium (D-T)-produced alpha particles. The density and velocity distribution of the alpha particles from their initial energy of 3.5 MeV down to near-thermal energies may be measured by small-angle ($<1^\circ$) Thomson scattering from the

Debye sphere of electrons associated with the alpha particles. A computer simulation of the experiment indicates that a 100-MW pulsed laser, combined with a bank of heterodyne receivers, will be able to measure a scattered signal from the alpha particles in a number of velocity intervals with a post-detection signal-to-noise ratio of greater than 100 for an assumed alpha-particle line-averaged density of $5 \times 10^{11} \text{ cm}^{-3}$. More detailed studies of the experimental parameters will continue during 1984, and laboratory testing of the proposed optical heterodyne detection scheme will be initiated.

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Chapter 4

Plasma Theory

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4. PLASMA THEORY

Summary of Activities

There has been continued convergence in the efforts of tokamak, stellarator, and bumpy torus theorists into the physics of plasma confinement in nonsymmetric systems. The key issues have outgrown the realm of heuristic simplifying assumptions to incorporate more experimental realities. Specialization to given geometries has waned, and there emerge several broad themes that integrate our efforts.

The already predominant capabilities within the magnetohydrodynamics (MHD) group have been extended substantially through the addition of kinetic corrections. These gain increasing importance when plasma temperatures approach the thermonuclear regime and physics familiar from ELMO Bumpy Torus (EBT) stability theory begins to be important for the helical systems. Equilibrium and stability codes developed under the impetus of the stellarator design effort have important applications to bumpy tori and to real tokamaks in which the toroidal symmetry is imperfect. The key technical advance in this area has been development of scenarios by which the Advanced Toroidal Facility (ATF) stellarator torsatron can access its high-beta ($>6\%$), second stability regime without encountering zones of instability from internal and external ideal MHD modes. Important to experimental verification of stability predictions is the flexibility to violate stability limits at will in order to assess the importance of specific modes. This can be done by adjusting currents in the helical field (H_z) and vertical field (VF) coils to modify the well and rotational transform.

The second major theme results from theoretical demonstration of the critical roles played by the ambipolar electric fields in the confinement for all three systems. Monte Carlo orbit studies of confinement have been carried out for a rearranged EBT called ELMO Bumpy Square (EBS). These suggest that more symmetric equipotential surfaces would provide about two orders of magnitude improvement in particle lifetimes. In stellarators, it has been shown that the condition of balanced radial particle flows predicts a branch of operation with long energy confinement time. In this, the electric field is in the direction opposite that associated with dominantly lossy electrons. Transport simulation studies predict that control of plasma density and of heating profiles would permit access to both branches, as well as permit study of transition between them. For tokamak devices, the relation of impurity flows to ambipolar potential and toroidal rotation caused by momentum input from neutral injection has been determined theoretically, with substantial confirmation from experiments in the Impurity Study Experiment (ISX) and the Princeton Large Torus (PLT). The nature of the observed anomalous radial transport of toroidal momentum is still under investigation and appears to be related to the enhanced electron transport. Looking to the future, the design of a national Tokamak Fusion Core Experiment (TFCX) will form a focus as we assess the effects of plasma heating mechanisms and field ripple on the ambipolar potential and on the particle and impurity confinement.

Implicit in the preceding discussion is the third theme: a substantial and successful effort has been carried out in improvement of the confinement concepts available for experiments. Having developed new theories, models, and codes well beyond the former state of the art, we have found superior forms of both helical systems and bumpy tori. While the ATF device and the EBS

represent major improvements over earlier devices, the search continues for more advanced configurations and improved methods to control plasma behavior.

The past year's work is discussed in more detail in summaries for the EBT, tokamak, stellarator, and computing support areas in Sects. 4.1, 4.2, 4.3, and 4.4, respectively. Results of applications to EBT and ISX-B experimental observations and to the design and planning for the ATF-1 experiment may also be found in Chaps. 1 and 2 of this report.

4.1 ELMO BUMPY TORUS THEORY

In the past year, the EBT Theory group has concentrated in two main areas: formulating advanced-concept EBTs (see Chap. 1, Sect. 1.3) and understanding the present experiment. Although the initial advanced-concept studies involved a wide class of ideas, a focusing on the square configuration of EBT (the EBS) occurred toward the end of the year. The early single-particle orbit calculations, which provoked the initial interest in the square configuration (much better single-particle orbits than in circular EBT), have been extended to include collective effects such as equilibrium, stability, heating, and transport.

The theory of magnetic equilibrium for both circular and square EBT configurations draws from the theory of closed-line toroidal systems (closely related to mirror equilibrium theory). The major difference between the square and circular EBT configurations is that in the square configuration pressure surfaces are much better centered in the device. This came as no surprise, since in closed-line systems the pressure surfaces are "average drift surfaces" and the individual particle orbits are much better centered in the square than in the circular configuration.

An early concern was that high-field corners might lead to overly restrictive beta limitations due to ballooning modes. The original argument that the high B in corners should reduce this type of instability drive (small local β) is being borne out by MHD and kinetic models. The MHD calculation (rigid ring) indicates

that the limitation imposed by ballooning modes is no more restrictive than for other EBT configurations, provided the ring beta does not become excessively large. These calculations are just now being supplemented by more detailed kinetic ballooning calculations that indicate the same qualitative behavior. Other drives for instability have been examined; none have been identified as uniquely restrictive to the square configuration.

A major contribution of EBT heating theory is that Doppler shifts can strongly influence the location at which microwave power is absorbed. For the circular configuration of EBT, this leads to the conclusion that this form of heating tends to pump low-energy passing, transitional, and weakly trapped particles into the region of poor orbit confinement at high energy. Fokker-Planck calculations indicate that this is highly deleterious for the circular EBT configuration but not for the square configuration.

Increasingly, the importance of including microwave scattering in addition to Coulomb scattering in calculating losses associated with drift orbits (diffusive and direct) is being recognized. An important subtheme for the future will be the closely coupled calculation of heating and transport and of heating and stability.

A new picture has emerged for the potential formation in the present EBT. Radially resolved transport calculations indicate that a potential peaked in the radial vicinity of the second harmonic will occur provided that second harmonic heating sustains a warm group of electrons (e.g., 0.5 to 10 eV), which

are lossy. The potential forms to retard the flow of this group. For purely diffusive behavior, this leads to

$$|e|\nabla\phi \approx \alpha\nabla T_w + T_w\nabla n_w/n_w,$$

where T_w and n_w are the temperature and density of this warm component (localized in radius about the second harmonic).

Relatively simple arguments based on the asymmetry of orbits indicate that n_w and T_w should be higher on the inside of the torus (asymmetric). From the preceding equation, one sees that this would lead to similarly asymmetric potentials (as observed experimentally). Preliminary Monte Carlo results indicate that symmetrizing the potentials would lead to an increase of two orders of magnitude in the lifetime. This makes the square configuration very attractive, since its highly symmetric orbits should lead to much more symmetric potentials and, hence, a much longer lifetime for the cooler components.

4.1.1 Magnetics and Orbits—Abstracts

4.1.1.1 "Calculation of Diamagnetic Loop Signals from 2-D Magnetic Equilibrium Solutions for EBT"¹

E. F. Jaeger

C. L. Hedrick

The induced emf in a diamagnetic loop surrounding the EBT plasma is calculated from a two-dimensional (2-D) solution to the Grad-Shafranov equation with tensor pressure. This allows direct comparison between calculated and measured diamagnetic loop signals for different values of stored energy ($W_\perp$) in the hot electron ring. In particular, we calculate the diamagnetic loop signal required for a local minimum in $\oint d\ell/B$ to occur and compare to the signal observed experimentally at the C-T transition between stable and unstable operation. Sensitivity to parameters of the ring model will be discussed.

4.1.1.2 "Reflection-Symmetry Effects in the Perturbation Series of an Action Integral for the Field-Line Displacement in an ELMO Bumpy Torus"²

D. K. Lee

C. L. Hedrick

Deviations from the ideal geometry and less-than-perfect alignment of the field coils in an ELMO Bumpy Torus generate perturbations to the ideal magnetic field configuration, resulting generally in failure of the field lines to close on themselves and thereby causing degradation in plasma confinement. The sensitivity of the field-line displacement to certain types of errors in coil parameters is studied by means of a perturbation formalism developed for an action integral representing the longitudinal adiabatic invariant. Reflection-symmetry properties satisfied by the magnetic field and the vector potential are employed, and it is demonstrated both analytically and numerically that the leading term of the field-line displacement per period of 2π around the major axis is second order in the perturbation parameter if the field coils are planar loops and if the coil planes remain invariant under the perturbation. Numerical analyses for the field-line displacement also reveal some more useful properties for the first- and second-order terms in the perturbation series.

4.1.1.3 "Particle Orbits and Nonresonant Electron Transport Coefficients for the ELMO Bumpy Square"³

L. W. Owen

D. K. Lee

New magnetics configurations based on the EBT confinement concept have been developed and are shown to give greatly improved single-particle confinement. The EBS is formed by four linear arrays of simple magnetic mirrors linked by sections of a high-field toroidal solenoid of elliptical cross section. Improved confinement results from localizing the unavoidable toroidal curvature in regions in which the magnetic field is much stronger than

the average field in the mirror sections. Magnetic field geometry, single-particle orbits, and plasma pressure surfaces for EBS are displayed and discussed. Nonresonant electron transport coefficients are evaluated for EBS, EBT, and toroidal arrays of shifted Andreoletti coils. Preliminary results indicate that electron confinement in EBS and in the Andreoletti configurations is improved by a factor of 10 to 15 when compared to the basic EBT configuration of toroidally linked circular mirror coils.

4.1.1.4 "ELMO Bumpy Square"⁴

L. W. Owen

D. K. Lee

A new magnetics configuration based on the EBT confinement concept has been developed. The EBS or ELMO Bumpy Racetrack (EBR) is formed by four or two bumpy cylinder sections (multiple magnetic mirrors) linked by sections of a high-field toroidal solenoid of elliptical cross section. The EBS configuration (which is the focus of this work) localizes the unavoidable toroidal curvature in the corners of the square, where its effects can be minimized by a magnetic field that is much stronger than the average field in the mirror sections. As in EBT, the central core plasma in EBS is stabilized by the presence of hot electron rings in the bumpy sections.

Detailed vacuum magnetic field and orbit calculations indicate that the single-particle confinement, plasma centering in the magnetic field, and neoclassical lifetime in EBS are distinctly superior to those in a bumpy torus of comparable size. The hot electron rings, which are formed in sections of a bumpy cylinder, are exceedingly well centered about the magnetic axis. The core plasma pressure surfaces and the ambipolar potential should be better centered because toroidal effects in $\int d\ell/B$ occur in regions of high magnetic field. The fraction of transitional and passing particles (whose drift orbits are the least well confined at high energies) is reduced by high "global" mirror ratio. In addition, these orbits are better centered than those in toroidal geometry.

A number of interesting heating techniques may be more practical in an EBS than in an EBT. Access at the corners permits a long path length for neutral beam injection, and lack of magnetic moment conservation at high beam energies should isotropize the hot ion distribution rather quickly. In an EBS that utilizes an EBT-S-like magnetic field (≈ 1 T) in the bumpy cylinder sections, slow wave ion cyclotron resonance heating (ICRH) and 60-GHz electron cyclotron heating (ECH) can be launched from the corners with the rings sustained by 28-GHz second-harmonic heating. Also, one is encouraged to speculate that launching localized electromagnetic waves (e.g., lower hybrid) in the corners might reduce neoclassical losses by scattering particles off poorly confined drift orbits and might reduce nonlinear effects of some types of instabilities as well.

4.1.2 Heating—Abstracts

4.1.2.1 "Absorption of Obliquely Propagating Waves in Fully Relativistic Plasmas"⁵

K. Audenaerde*

R. C. Goldfinger

D. B. Batchelor

Analytic and numerical calculations of electromagnetic wave properties in fully relativistic plasmas are extended to the case of oblique propagation. Acceptable approximations to reduce computing time are explored, and the results are applied to actual designs of reactors and experimental devices. Special attention is paid to the investigation of the predicted decrease of absorption above 80 to 100 keV.

*University of Wisconsin, Madison.

4.1.2.2 "Electron Cyclotron Heating and Ion Cyclotron Heating in the ELMO Bumpy Torus Device"⁶

D. B. Batchelor

The ELMO Bumpy Torus is a steady-state fusion experiment consisting of 24 toroidally linked simple mirrors. High-frequency rf heating is used in each of the simple mirrors to

produce the plasma and to provide all plasma heating. High-power gyrotrons (200 kW at 28 GHz) are used to heat electrons by the electron cyclotron resonance interaction. A unique feature of EBT is that in each mirror sector a high-beta, relativistic electron ring is formed. The magnetic well produced by the hot electron stabilizes the bumpy torus against MHD modes to which a simple bumpy torus is susceptible. Radio-frequency waves in the range of 15 to 30 MHz with power up to 20 kW have been used to heat ions. Substantial ion heating is obtained in deuterium plasmas above 25 MHz, although at this frequency only the third through tenth ion cyclotron harmonics are present in the plasma. The stored energy of the relativistic electron annuli is observed to increase with the application of the wave power.

4.1.2.3 "Propagation and Absorption of Electromagnetic Waves in Fully Relativistic Plasmas"⁷

D. B. Batchelor
R. C. Goldfinger

H. Weitzner

The broadening of electron cyclotron harmonic resonances by the relativistic mass variation can have important effects on wave propagation and absorption even in low temperature plasma for which $T_e \ll m_e c^2$. As an example, for a wave near cyclotron resonance ($\omega \approx \Omega_e$) propagating perpendicular to the magnetic field in a uniform plasma, nonrelativistic theory predicts the local damping rate, $\text{Im}\{k\}$, to be infinite for the ordinary mode and zero for the extraordinary mode. On the other hand, a relativistic treatment gives a finite value for both of these numbers. The relativistic broadening affects the amount of wave absorption, the spatial location of wave absorption, and details of mode conversion processes. Higher temperature plasmas such as the relativistic electron rings in EBT, the end cells of the Tandem Mirror Experiment Upgrade (TMX-U), and Mirror Fusion Test Facility (MFTF-B) have T_e of order $m_e c^2$. Relativistic effects therefore modify the gross

properties of wave propagation and absorption. For example, the locations of the extraordinary mode cutoff and the upper hybrid resonance are relativistically shifted. Also, the absorption of cyclotron harmonic waves is found to be a peaked function of temperature (for waves at the second harmonic resonance, this peak occurs at about $T_e = 120$ keV).

4.1.2.4 "Finite-Element Computation of ICRF Fields in EBT Devices"⁸

D. B. Batchelor
C. W. Nestor, Jr.

H. Weitzner

We have continued the development of a computer code to calculate the wave fields in a bumpy-cylinder model of an EBT device. Simulation of a single cylindrical cavity has yielded resonant frequencies and field component shapes in satisfactory agreement with analytical results for the first few TE modes; there is also the expected improvement in agreement with decreasing mesh size. We have used slightly different dependent variables (rather than the electric field components) to eliminate the apparent singularities in the differential equations on the axis of the cylinder.

4.1.2.5 Detailed Modeling of Microwave Energy Deposition in EBT Devices⁹

D. B. Batchelor
D. A. Rasmussen*

R. C. Goldfinger

Ray-tracing studies have been combined with a simple wave power-balance model to provide a complete, albeit approximate, description of microwave power deposition in the EBT-I, EBT-Scale (EBT-S), and EBT Proof-of-Principle (EBT-P) devices. Electron cyclotron absorption of ordinary and extraordinary waves by the combined core plasma and relativistic annuli is calculated using a fully relativistic damping package developed for the RAYS geometrical optics code. The rays are traced in finite-beta bumpy cylinder plasma

*EBT Experimental Section.

equilibria that are obtained from the Oak Ridge National Laboratory (ORNL) 2-D equilibrium code. These results for direct, single-pass absorption are combined with results from a statistical model for the deposition of multiply reflected and mode-converted waves to obtain estimates of the power deposited in the core, surface, and annulus plasma components. Wave absorption by the annuli and by the core components at the fundamental and second harmonic resonances, reflection and Budden tunneling of the extraordinary mode at the right-hand cutoff, and conversion between ordinary and extraordinary modes upon wall reflection are the processes included in the power-balance model. Experimental measurements of wave power flux on the cavity wall in EBT-S made with a simple microwave calorimeter are in good agreement with predictions of the model for a variety of operating configurations.

4.1.2.6 "Theoretical Aspects of Throat Launch Microwave Heating in EBT-S"¹⁰

D. B. Batchelor
R. C. Goldfinger

D. A. Rassmussen*
D. W. Swain*

A simple radiation power-balance model is used to gain insight into the role of antenna directivity and polarization control when throat launch is used to improve core heating efficiency and to separate ring heating from core heating. Ray-tracing calculations are used to illustrate energy flow and absorption behavior for various throat launch positions and angles.

*EBT Experimental Section.

4.1.2.7 "Monte Carlo Analysis of Electron Ring Formation in EBT"¹¹

M. D. Carter*
D. B. Batchelor

R. C. Goldfinger
J. D. Callen

A Monte Carlo approach is used to analyze electrons subjected to second harmonic cyclotron

resonance in EBT. Theory predicts a very small coupling of second harmonic electron cyclotron resonance heating (ECRH) to low-energy electrons, while experiments indicate electron energies greater than 1 MeV. Integration of the relativistically correct Lorentz equations indicates substantial energy oscillations due to second harmonic ECRH. The effects of collisions and more complicated geometry are considered. Superadiabatic barriers are investigated.

4.1.2.8 "Stochastic Electron Heating Due to ICRH in EBT-S"¹²

G. L. Chen

D. B. Batchelor

In the EBT geometry, the annular electrons are classified into trapped and passing particles. Motion near the boundary between trapped and passing orbits is studied both numerically and theoretically for the appropriate parameters of ICRH experiments on EBT-S. Stochastic electron motion is observed within the ranges of these experimental parameters, resulting in wave power being transferred to the electrons by stochastic diffusion. The temperature increase of the electron annuli found on the recent ICRH experiments on EBT-S could be explained from this heating mechanism. The details of calculation and comparison with experimental results are discussed.

4.1.2.9 "Fokker-Planck Calculations of Hot Electrons in EBT"¹³

G. L. Chen
D. B. Batchelor

Y. Matsuda*

We have used a bounce-averaged relativistic Fokker-Planck code to study the hot electron ring formation in EBT. Quasi-linear rf diffusion coefficients and relativistic collision

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*Lawrence Livermore National Laboratory, Livermore, Calif.

coefficients are used. However, random gyrophase is assumed and superadiabaticity is neglected. High-energy electron direct loss due to the open drift surface is considered. Both trapped and untrapped electron distribution functions in the medium-temperature range (2–200 keV) are calculated. The electron density, energy, moment flux, and ECRH required power are obtained from the steady-state distribution function.

4.1.2.10 "RAYS: A Geometrical Optics Code for ELMO Bumpy Torus"¹⁴

R. C. Goldfinger

D. B. Batchelor

A geometrical optics computer code RAYS has been developed to numerically simulate the propagation and absorption of electromagnetic waves in an arbitrary, three-dimensional (3-D), magnetized plasma configuration. The RAYS code integrates the Hamiltonian form of the geometrical optics equations for position $\mathbf{r}$ and wave vector $\mathbf{k}$ from initial conditions $\mathbf{r}_0$, $\mathbf{k}_0$ with arc length along the ray S or with time as the ray parameter. In addition, the local electric field polarization is evaluated, and quantities such as the wave damping rate or the phase path length can be integrated along the ray. The code is written in modular form, with subroutines specifying the plasma equilibrium magnetic field and density and with subroutines specifying the wave dispersion relation as independent. In this way, various models for the plasma geometry and for the wave physics can be easily interchanged without disturbing the bulk of the program. The RAYS code has been used extensively in the theoretical study of microwave heating of the EBT device at ORNL. The theory, structure, and operation of the code are described. Mathematical details of equilibrium subroutines for slab, bumpy torus, and tokamak plasma geometry are presented. Wave dispersion and absorption subroutines are presented for frequencies ranging from ion cyclotron to electron cyclotron frequencies. Graphics postprocessors for RAYS output data are also described.

4.1.2.11 "Ray-Tracing Calculations of Core Electron Heating in EBT-S at Lower Hybrid Frequencies"¹⁵

R. C. Goldfinger
T. L. Owens*

D. B. Batchelor

A proposal has been made to use lower hybrid heating (LHH) in EBT-S as a means of heating core electrons. There are a number of theoretical and experimental benefits that could be derived from such an experiment. These include a study of how LHH affects $n_{\text{hot}}/n_{\text{cold}}$ and ring stability near the T-M transition and desirable modifications of the distribution function for certain particles. In addition, if LHH is successful, it could become a low-cost way to supplement ECH gyrotron power. This work describes the application of the RAYS code to predict electron heating near the lower hybrid frequency as a result of varying the wave frequency, parallel refractive index ($n_{\parallel}$), launch location (midplane versus throat launch), and ion species (hydrogen or deuterium). We find that, with a careful choice of parameters, the lower hybrid waves will be absorbed by the core electrons at intermediate radii (5–9 cm) in the coil throats.

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4.1.2.12 "Absorption of Second Harmonic X-Mode in a Weakly Relativistic Inhomogeneous Plasma due to the Mode Coupling with the Quasi-Electrostatic Mode"¹⁶

K. Imre*
H. Weitzner

D. B. Batchelor

It is known that when the wave propagation is perpendicular (or nearly so) to the external field, the geometrical optics method (thus the associated WKB method) fails in a narrow boundary layer near the resonance region, when the plasma density is within a critical

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range. We apply a full-wave analysis on this boundary layer by making use of the consistent set of differential equations that are derived by rescaling and solving the linearized relativistic Vlasov equation. Absorption and reflection of the incident wave due to the mode coupling of the extraordinary and the quasi-electrostatic modes, and also due to the relativistic broadening, are evaluated by numerically solving the full-wave equations and matching the asymptotic values in the low- and high-field sides. The energy flow is calculated by making use of the appropriate Poynting theorem. The results are compatible with those obtained by the geometrical optics, wherever the latter is valid. In the critical region, a strong mode coupling is found. The results are expressed in terms of the parameters $X = (\omega_p/\omega)^2$, $\eta = v_{th}/c$, and $L = dx/d(\log B_0)$, for the special case of $B_0 = B_0(x)z$ and $n_{||} = 0$.

4.1.2.13 *Ray-Tracing Study of Electron Cyclotron Heating in Toroidal Geometry*¹⁷

A. H. Kritz^{*}
H. Hsuan[†]

R. C. Goldfinger
D. B. Batchelor

TORAY, a ray-tracing code, has been developed to study ECH and current drive in toroidal geometry. Ray patterns are initiated similar to those of an actual antenna, and a full graphics package has been developed for displaying the behavior of the rays. We study the interplay of the plasma and wave parameters in order to establish which parameters are most important in determining the energy deposition.

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4.1.2.14 "Electron Ring Heating in EBT"¹⁸

H. Weitzner

D. B. Batchelor

It is observed experimentally that the hot electron rings in EBT are strongly heated by

applied electromagnetic radiation at frequencies on the order of a few times the ion cyclotron frequency but well below lower hybrid frequencies. A simple model for this phenomenon is proposed to start quantitative estimates of this ring heating. A slab geometry is chosen with constant magnetic field in the z direction. The hot electron component has an equilibrium distribution determined by the Vlasov equation, and the electrons are localized to a slab one or two Larmor radii wide in the x direction. The cold ions and electrons generate the charge and current necessary to maintain equilibrium. An electromagnetic wave is applied at a frequency on the order of the ion cyclotron frequency and with small wave numbers in the y and z directions. It is easy to show that the solution of the linearized Vlasov equation for the hot component generates an effective conductivity tensor operator with significant Hermitian—that is, dissipative—components. The associated wave-scattering problem is formulated, properties of the resultant equations are given, and numerical solution techniques are discussed.

4.1.3 Transport—Abstracts

4.1.3.1 *S3C: EBT Steady-State Shooting Code Description and User's Guide*¹⁹

W. B. Downum

The ORNL one-dimensional (1-D) steady-state shooting code (S3C) for EBT plasmas is described. Benchmark calculations finding the steady-state density and electron and ion temperature profiles for a known neutral density profile and known external energy sources are carried out. Good agreement is obtained with results from the ORNL radially resolved time-dependent 1-D transport code for an EBT-Q-type reactor. The program logic is described, along with the physics models in each code block and the variable names used. Sample input and output files are listed, along with the main code.

4.1.3.2 *The Oak Ridge National Laboratory ELMO Bumpy Torus Radially Resolved, Time-Dependent, One-Dimensional Transport Code—User's Guide*²⁰

W. B. Downum

E. F. Jaeger

The ORNL radially resolved time-dependent 1-D transport code is described. The physical models and numerical techniques incorporated to follow the time evolution of EBT plasmas ranging in size from the present experiment to power reactors are discussed. Sample input/output files are presented, and instructions for use on the Oak Ridge DEC-10 and the National Magnetic Fusion Energy Computing Center (NMFECC) Cray systems are given.

4.1.3.3 "Electron Transport in EBT in the Low-Collision-Frequency Limit"²¹

D. E. Hastings

A variational principle formulation is used to calculate the electron neoclassical transport coefficients in a bumpy torus for the low collisionality regime. The electron radial drift is calculated as a function of the plasma position and the poloidal electric field, which is determined self-consistently. A bounce-averaged differential collision operator is used, and the results are compared to previous treatments using a BGK operator.

4.1.3.4 "Fat Bananas in EBT"²²

D. E. Hastings

In an asymmetric device like the EBT, the radial width of the collision orbits is not determined fully until the self-consistent ambipolar potential is known. There is a class of potentials for which the orbit width is not small compared with the equilibrium scale lengths, thus calling into question standard linear diffu-

sion theory. A diffusion equation is derived in the constants of motion space for a hot minority species undergoing large orbits in a cold dense species. This equation is solved to all orders in the step-size parameter, and the solution is examined in various limits. In particular, it is found that only odd derivatives of the hot-species bulk Maxwellian drive diffusion, making the corrections to linear diffusion theory second order in the step-size parameter.

4.1.3.5 "Neoclassical Transport Associated with Collisionless Detrapping in a Bumpy Torus"²³

D. E. Hastings

In the low collisionality nonresonant regime in a bumpy torus, the transitional particles can make a large contribution to neoclassical transport. This contribution can be moderated by the toroidally induced radial drift, which causes transitional particles to detrapp and retrapp in the mirror sectors. This effect leads to diffusion coefficients that are linear in the collision frequency and scale with the inverse aspect ratio instead of the more usual square of the inverse aspect ratio.

4.1.3.6 "Neoclassical Transport Due to Large Orbit Effects in Bumpy Tori"²⁴

D. E. Hastings

In an asymmetric device like the EBT, the radial width of the collision orbits is not determined fully until the self-consistent ambipolar potential is known. There is a class of potentials for which the orbit width is not small compared with the equilibrium scale lengths, thus calling into question standard linear diffusion theory. A diffusion equation is derived in the constants of motion space for a hot minority, nearly Maxwellian species undergoing large orbits in a cold dense species. This equation is solved to all orders in the step-size parameter, and the solution is examined in various limits.

4.1.3.7 "Nonresonant Electron Transport in the ELMO Bumpy Torus (EBT) for Multitemperature Maxwellians"²⁵

D. E. Hastings

For the experimental conditions in the EBT, it appears that the electron distribution function may not be a single-temperature Maxwellian. Neoclassical transport coefficients have been developed for the nonresonant electron species in a bumpy torus with the assumption that the lowest-order distribution function is the sum of l different Maxwellians. These show that there can be significant coupling between the different electron species. For comparison, the diffusion coefficients are contrasted to single-temperature diffusion coefficients.

4.1.3.8 "Nonresonant Particle Transport for Bumpy Field-Line Devices with Arbitrary Shaped Flux Surfaces"²⁶

D. E. Hastings

In a bumpy closed-field-line device, the radial drift through the pressure surfaces is the sum of the ∇B , curvature, and poloidal electric field drifts. Since the ∇B and curvature drifts are determined by the magnetic field geometry, which is independent of the plasma for low-beta plasmas, then the radial drift is a function of plasma position. This may enhance the vertical drift that a particle sees and, hence, neoclassical diffusion. Another way the vertical drift may be enhanced is if the magnetic field has a poloidal structure beyond that caused by the toroidal effects—for example, if the mod- B surfaces are slightly elliptical in shape. We explore the changes in the diffusion coefficients caused by both of these effects.

4.1.3.9 "Transport of a Multiple-Ion-Species Plasma in the Collisionless Regime in a Bumpy Torus"²⁷

D. E. Hastings

The ion neoclassical transport coefficients in a multiple-ion-species plasma in a bumpy torus

are calculated in the low collisionality regime. The poloidal electric field is calculated self-consistently with collisional electrons. Both pitch-angle and energy scattering are included in the collision operator.

4.1.3.10 "Transport Studies of ECH-Heated Bumpy Torus Plasmas"²⁸

D. E. Hastings

T. Kamimura*

A model of the measured potential profile in an ECH-heated bumpy torus is used in the radial transport equations for bumpy tori. The particle and energy confinement times are predicted along with the ECH power, ion temperature, and neutral density necessary for a steady state to be maintained.

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4.1.3.11 "Nonresonant ELMO Bumpy Torus Transport Coefficients in the Small-Electric-Field Regime"²⁹

D. E. Hastings

C. L. Hedrick

J. S. Tolliver

A conservative BGK collision operator is used to obtain nonresonant neoclassical transport coefficients for a bumpy torus when the ∇B drift dominates over the $E \times B$ drift. Previous nonresonant coefficients have considered the opposite limit. For large collisionalities, the diffusion coefficients are only weakly dependent on the $E \times B$ drift, while for small collisionalities, plateau diffusion coefficients are obtained that have an exponential dependence on the $E \times B$ drift.

4.1.3.12 WHISTBT— $1\frac{1}{2}$ -D Radial Transport Code for Bumpy Tori³⁰

D. E. Hastings

S. E. Attenberger

W. A. Houlberg

D. K. Lee

The computer code WHISTBT has been developed from the ORNL WHIST code to

study radial transport in bumpy tori. The code can handle both positive and negative ad hoc electric fields for devices ranging from the size of EBT-S to a reactor-type device, EBT-R. Fueling can be by gas puffing or pellets; heating can be by injection of rf power or neutral beams.

4.1.3.13 "Sensitivity of Global Confinement Properties in EBT to the Existence of an Ambipolar Potential Well"³¹

E. F. Jaeger

Recent radial transport calculations for EBT-S suggest that global confinement properties are less sensitive to the existence of an ambipolar potential well than previously thought. We consider an ad hoc ambipolar potential profile in which the well depth can be varied continuously while maintaining a constant positive radial electric field at the plasma edge. Radial transport calculations with this potential show modest variation in global energy containment time as the potential well depth $\Delta\phi$ is varied from $\Delta\phi \sim 0$ to $\Delta\phi \sim kT_d/e$.

4.1.3.14 *Ambipolarity and Transport with Resonant Ion Diffusion in EBT*³²

E. F. Jaeger
C. L. Hedrick

D. E. Hastings
J. S. Tolliver

Using recently derived analytic expressions for resonant and nonresonant neoclassical transport coefficients in EBT, we calculate the ambipolar potential required to maintain quasi-charge neutrality in the presence of a high-energy ion tail produced by nonclassical heating. The electric field obeys a differential rather than an algebraic equation. Solution of this equation gives a potential proportional to the local magnetic field strength and thus a rigid rotation of low-energy ions near the magnetic axis. Radial transport calculations using this potential give improved agreement with experimental data for neutral density and particle lifetime. However, high-energy ion orbits

in the calculated potential exhibit banana widths larger than assumed in the resonant transport theory. The required density of high-energy ions is therefore larger than would be expected if realistic banana widths could be included.

4.1.3.15 "Bounce-Averaged Energy and Pitch-Angle Scattering Operators and Monte Carlo Transport Code for EBT"³³

J. S. Tolliver

A bounce-averaged Monte Carlo code has been developed to study particle and energy transport in an EBT device. Since the drift and transport motion in EBT occur on a much slower time scale than the parallel streaming motion, the plasma transport properties are accurately represented by a bounce-averaged description, leaving two space coordinates (α, β) and two velocity dimensions (ϵ, λ), where α is a flux function, $\nabla_\alpha \times \nabla_\beta = \mathbf{B}$, ϵ = total energy, and $\lambda = \mu B_m / (\epsilon - Ze\phi)$. For use in a Monte Carlo calculation, bounce averaging eliminates the need to follow the detailed parallel motion (thus saving much time) but requires a bounce-averaged collision operator that is derived and presented in Monte Carlo form in terms of ϵ and λ . Transport calculations are made by solving the bounce-averaged, guiding-center equations of motion, $\langle \dot{\alpha} \rangle = (\partial J / \partial \beta) / Ze\tau$ and $\langle \dot{\beta} \rangle = -(\partial J / \partial \alpha) / Ze\tau$, while introducing ϵ - and λ -scattering. Diffusion coefficient results are presented for EBT-I/S parameters.

4.1.3.16 "Extensions of the ORNL EBT Monte Carlo Diffusion Code"³⁴

J. S. Tolliver
E. F. Jaeger

D. E. Hastings
C. L. Hedrick

The recently developed EBT Monte Carlo Resonant Diffusion code has been extended to examine the effects of nonzero poloidal electric field and finite-width, crescent-shaped orbits. Numerical results are compared with recent

analytic results. Extensions to include pitch-angle effects through bounce averaging of the Monte Carlo collision operator will be presented. Using a bounce-averaged collision operator retains the advantage of a 2-D code while including 3-D effects. Inclusion of pitch-angle scattering allows examination of nonresonant diffusion.

4.1.4 Stability—Abstracts

4.1.4.1 "EBT Stability Theory"³⁵

H. L. Berk*
J. W. Van Dam*
M. N. Rosenbluth*

D. A. Spong
C. Z. Cheng†

The theory of unfavorable curvature-driven instabilities is developed for a plasma interacting with a hot electron ring whose drift frequencies are larger than the growth rates predicted from conventional MHD theory. A Z-pinch model is used to emphasize the radial structure of the problem. Stability criteria are obtained for the five possible modes of instability: the conventional hot electron interchange, a high-frequency hot electron interchange (at frequencies larger than the ion cyclotron frequency), a magnetic compressional instability, a background pressure-driven interchange, and an interacting pressure-driven interchange. The effect of finite Larmor radius (FLR) stabilization on the low-frequency modes (less than the ion cyclotron frequency) will be discussed.

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†Princeton Plasma Physics Laboratory, Princeton, N.J.

4.1.4.2 "Is a Diamagnetic Well Necessary for Stable EBT Operation?"³⁶

A. M. El Nadi

Recent experimental and theoretical studies of the EBT device showed that the hot electron diamagnetism may be too small to produce an average magnetic well when the transition

toward stability occurs (the C-T transition). We can thus invoke another stabilizing mechanism, namely, plasma compressibility. Taking into account the presence of the hot electron rings, an expression for the stability threshold toward the interchange mode is derived and compared with experimental results. It appears that stabilization may occur due to the presence of local temperature peaks near the electron cyclotron second and third harmonic locations. The analysis seems to be consistent with a number of experimental results, including the density scaling and the role of profile heating.

4.1.4.3 "On the EBT Stability Problem"³⁷

A. M. El Nadi

In the first part of this work, we study the stability of an EBT plasma toward finite parallel wavelength perturbations. It is shown that the coupling of the negative energy hot electron drift wave to the modified convection and shear Alfvén waves is destabilizing. In the second part, we study both ion and hot electron FLR effects. The latter tend to stabilize the high-frequency modes when $k_{\perp} \rho_h \gtrsim 1$.

4.1.4.4 "Plasma Stability in a Bumpy Cylinder with Hot Electron Rings"³⁸

A. M. El Nadi

The plasma stability in an EBT device has been adequately studied in the cylindrical approximation where effects related to the bumpiness of the confining magnetic field were ignored. The results of such a simplified analysis cannot fully explain the experimentally observed EBT stability. In this work, we extend the analysis to allow for the finite length of the hot electron rings along the field lines. Stability criteria for both low- and high-frequency modes will be presented.

4.1.4.5 "A Numerical Analysis of the EBT Flute Modes in the Low Poloidal Mode Number Limit"³⁹

A. M. El Nadi
D. A. Spong

J. C. Whitson

We have used an EBT radial stability code to investigate the stability of low and high frequency modes in the low poloidal mode number limit. The model ignores both poloidal and toroidal variations in the equilibrium parameters but treats the radial variation properly in the straight cylindrical limit. The model also assumes a bi-Maxwellian hot electron energy distribution along and perpendicular to the magnetic field lines, thus allowing for temperature anisotropy. We generally find an improvement in the stability over the slab model and the results seem to agree with the experiment. The stability boundaries will be presented.

4.1.4.6 "Effect of Magnetic Bending on the High-Frequency Stability of the ELMO Bumpy Torus"⁴⁰

H. F. Hassan*
H. A. Kirolous*

A. M. El Nadi

It has been shown recently that both the high-frequency, cold plasma density gradient drift wave and the compressional Alfvén wave can be driven unstable through interaction with the hot electron magnetic curvature drift wave in the EBT device. In this work, we remove the flute assumption and thus allow for a finite amount of magnetic field line bending. The dispersion relation must then account for the shear Alfvén branch, together with the modification in the three waves mentioned above. In general, two types of new instabilities are found. They result from the coupling of the hot electron drift wave to both the shear Alfvén and the high-frequency drift waves. The stability conditions will be presented.

4.1.4.7 "Comparison of Magnetic Equilibria and Low-Frequency Stability for EBT and EBS"⁴¹

C. L. Hedrick

Analytic approximations are developed for the magnetic equilibria of both a standard EBT and EBS or EBR. Sufficient toroidal effects are included to distinguish the low-frequency stability properties of the two classes of devices. To illustrate the application of the equilibrium quantities, simple analytic results based on the so-called rigid-ring stability model are presented. Examination of more detailed stability theories that include effects leading to the Lee-Van Dam-Nelson limit will be presented as time permits.

4.1.4.8 "Hot Plasma Decoupling Condition in Bumpy Cylinder Geometry"⁴²

D. A. Spong
H. L. Berk*

J. W. Van Dam*

Recently, the hot plasma decoupling condition between the low-frequency hot electron interchange mode and the interacting core pressure-driven interchange has been of interest. This condition influences the critical values of β_c and $n_{\text{hot}}/n_{\text{core}}$ required for stability. Quantitative evaluations of this condition for EBT devices have been carried out both analytically and using radially dependent shooting codes only in simplified slab geometries localized near the midplane at the hot electron ring position. Decoupling criteria have also been derived for a bumpy cylinder model that involve field-line weightings of the various core and hot plasma equilibrium parameters. Evaluations of the decoupling conditions will be made in the more realistic bumpy cylinder geometry using a 2-D finite-beta equilibrium code.

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4.1.4.9 *Radial Structure of Curvature-Driven Instabilities in a Hot Electron Plasma*⁴³

D. A. Spong
H. L. Berk*

J. W. Van Dam*

A nonlocal analysis of curvature-driven instabilities for a hot electron ring interacting with a warm background plasma has been made. We have examined four different instability modes characteristic of hot electron plasmas: the high-frequency hot electron interchange (at frequencies larger than the ion cyclotron frequency), the compressional Alfvén instability, the interacting background pressure-driven interchange, and the conventional hot electron interchange (at frequencies below the ion cyclotron frequency). We have also examined the decoupling condition between core and hot electron plasmas as it influences the background and hot electron interchange stability requirements. The assumed equilibrium plasma profiles and resulting radial mode structure differ somewhat from those used in previous local analytic estimates; however, when the analysis is calibrated to the appropriate effective radial wavelength of the nonlocal calculation, reasonable agreement is obtained. Comparison with recent experimental measurements indicates that certain of these modes may play a role in establishing operating boundaries for the EBT-S experiment.

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4.1.4.10 "Profile Effects on EBT Stability Boundaries"⁴⁴

D. A. Spong
A. M. El Nadi

S. Hiroe*

Recent experimental measurements on the EBT-S device have indicated that the core

electron and hot electron density profiles may not fall off at similar rates on the outside edge of the plasma, as has been assumed in a previous EBT stability theory. This can have an important effect on predicted stability boundaries on a number of modes which are of importance in experimental operation. For example, a significant change in the topology of hot electron interchange boundary has been observed in going from a sharp drop-off in core density through the outer ring region to a more gradual drop-off, such as is indicated in the experimental measurements. The latter model shifts the range of the most unstable m numbers to $m \approx 7-10$, in better agreement with fluctuation measurements. The shift is caused by a change in the coupling condition between the hot electron drift frequency and the core convection wave. Profile effects also have an important influence on the low-frequency core interchange mode. Stability boundaries for these modes are examined for several different ring and core profiles.

*EBT Experimental Section.

4.1.4.11 "A Numerical Analysis of Alfvén and Surface Waves in the EBT"⁴⁵

J. C. Whitson

A. M. El Nadi

It is well known that a strong flute interaction can occur in an EBT plasma between the hot electron precession and background Alfvén and surface modes. Besides, it was found experimentally that significant ring heating occurs in ion rf heating experiments. In order to investigate the above coupling adequately, we have modified our cylindrical flute stability code to allow for a finite component of the wave vector along the magnetic field lines. The basic core and surface modes are studied particularly in relation to the numerically predicted efficient antenna-ring coupling. Stability boundaries are also presented.

4.2 TOKAMAK THEORY

We have continued our analyses of processes and methods for increasing beta through use of beams, rf heating, pellet injection, impurity control, and analysis of plasma confinement properties. Inclusion of nonlinear kinetic effects has been shown to introduce new possibilities for controlling disruption (tearing mode) limits. Emphasis is placed on transport effects from strong rotation due to neutral beam injection and on impurity control with beams and ambipolar fields. Work has continued in the study of ideal MHD (stability of bean-shaped plasma cross sections, ballooning stability of ISX-B) and resistive tearing modes and inclusion of kinetic effects in ballooning modes. Anomalous transport coefficients for resistive ballooning mode turbulence and effects of neutral-beam-induced rotation and impurity flow have received major attention.

Close collaboration between theorists and ISX-B experimentalists, particularly in the areas of rotation and transport simulation of tokamak discharges, has resulted in major advances in the understanding of neutral-beam-injected tokamaks.

The group has focused on six areas:

- ideal and resistive magnetohydrodynamics;
- kinetic modification of MHD instabilities;
- kinetic theory and anomalous transport;
- neoclassical theory, especially impurity control via neutral-beam-injected toroidal momentum;
- predictive and interpretive tokamak transport simulation and plasma-wall interaction; and
- tokamak reactors, especially the effects of alpha particle dynamics.

4.2.1 Ideal and Resistive Magnetohydrodynamics—Abstracts

4.2.1.1 "Dynamics of Spectra in Reduced and Helicity-Carrying MHD Turbulence"⁴⁶

Z. G. An*
P. H. Diamond
T. Chiueh*

B. A. Carreras
H. R. Hicks

The eddy-damped quasi-Markovian (EDQM) renormalization procedure is used to study the dynamics of kinetic and magnetic energy and helicity spectra in reduced and helicity-carrying MHD turbulence. In reduced MHD turbulence, attention is focused on the mechanism for generation of short-wavelength kinetic energy during the final phase of the major disruption in tokamaks. Specifically, coupling through the $\mathbf{B} \cdot \nabla J_{\parallel}$ nonlinearity of the vorticity equation offers a likely candidate for such a mechanism. The relevance of such a process to "anomalous" resistivity and viscosity is discussed. Comparisons with numerical solution of the equations are made. In helicity-carrying MHD turbulence, attention is focused on the effect of short-wavelength helicity on magnetic energy (dynamo process). Also, the relative nonlinear transfer rates of magnetic energy and helicity are examined. Implications for field-reversal processes are discussed.

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4.2.1.2 "3-D Resistive MHD Calculations for Tokamak Plasmas: Beyond the Simple Reduced Set of Equations"⁴⁷

B. A. Carreras
L. Garcia
T. C. Hender
H. R. Hicks

J. A. Holmes
V. E. Lynch
B. F. Masden

Numerical studies of the resistive stability of tokamak plasmas in cylindrical geometry have been performed using (1) the full set of resistive MHD equations and (2) an extended version of the reduced set of resistive MHD equations including diamagnetic and electron temperature effects. In particular, the nonlinear interaction of tearing modes of many helicities has been investigated. The numerical results confirm many of the features previously uncovered using the simple reduced equations.

4.2.1.3 "Equilibrium and Stability Properties of 'Bean'-Shaped Plasmas"⁴⁸

L. A. Charlton
B. A. Carreras
T. C. Hender

J. A. Holmes
B. F. Masden

Work that has shown increased stability to internal ideal MHD modes if an indentation is placed on the inside of a conventional D-shaped plasma (generating a "bean" shape) has led to experimental interest in building or modifying tokamak devices to generate such shapes. This interest has motivated a more complete study of the stability properties (both resistive and ideal) of such plasmas.

Two sequences of equilibria were generated in which the shape was characterized by $\delta_B = b/a$ (b is the distance from the major axis to the inside edge of the plasma at the midplane minus the distance from the major axis to the extreme inside edge of the plasma, with a the distance across the plasma at the midplane). Each sequence varied δ_B from zero (D shape) to 0.26 (strong bean shape). For one sequence, the safety factor at the edge was allowed to vary (from 1.6 to 2.75; $q_0 = 0.7$) with I_p (plasma current), B_T (toroidal field), V_p (plasma volume), and $\bar{\beta}$ (toroidal average β)

fixed. For the other sequence, the safety factor profile was fixed ($q = 0.7$ to 2.75) with I_p varied. Again B_T , V_p , and $\bar{\beta}$ were fixed at the above values.

Ideal MHD stability studies were done with the computer code ERATO (for low- n modes) and MBC (for large n). Initial results confirm internal mode stabilization with increasing δ_B . However, for external modes, an increase in δ_B results in significant destabilization. Both sequences had $\delta_B = 0$ equilibria that were stable to $n = 0$ axisymmetric modes. In contrast, the $\delta_B = 0.26$ equilibrium common to both sequences was unstable with an inverse growth rate of $\sim 100 \mu s$. This mode could be stabilized, however, with a perfectly conducting wall near the plasma.

For internal resistive modes, the code RST was used. Stabilization increased with δ_B for both sequences. The effect was much greater, however, when the q profile was fixed. This is due to the increase in rational surfaces in the plasma when δ_B was increased and I_p was held fixed. This increase in rational surfaces partly masks the stabilizing effects of the shaping being studied.

Details of the above and additional results are shown.

4.2.1.4 "Incompressible Resistive MHD Studies"⁴⁹

L. A. Charlton
B. A. Carreras
H. R. Hicks

J. A. Holmes
V. E. Lynch

The low-frequency MHD activity observed in high- β tokamak plasmas has successfully been interpreted for low-power injection, using a nonlinear resistive MHD model valid in the large aspect ratio limit. Recent experimental results indicate that at high beam-injection power, the internal kink mode could play an important role. This instability cannot be studied with the reduced MHD model. We use the full MHD equations in the incompressible approximation to study the stability properties of high- β tokamaks in this high beam-injection power regime. These equations have been

implemented in the FAR computer code, using a formulation similar to that of Azumi (1983). Results are presented.

4.2.1.5 "Electromagnetic Turbulence and Dissipative Pressure-Driven Modes"⁵⁰

P. H. Diamond
B. A. Carreras

T. C. Hender

Recent investigation has indicated that resistive ballooning instabilities may have significant impact on electron energy confinement in the ISX-B tokamak. The previous work utilized the reduced resistive MHD model. Here, we investigate the effect of electromagnetic turbulence on dissipative pressure-driven modes using a model which incorporates (linearly and nonlinearly) more complicated parallel electron dynamics.

Using a simplified set of moment equations, the renormalized electron fluid response is derived. In the parallel momentum balance equation (Ohm's law), the physical effect of an electron pressure gradient measured along fluttering magnetic field lines leads to the presence of an anomalous electron viscosity and *negative* anomalous resistivity in the renormalized theory. *The simultaneous presence of both these effects is necessary for conservation of energy.* The combined effect of viscosity and resistivity is an energy transfer from short to long perpendicular wavelength, which results in strong nonlinear growth at long wavelength. This growth appears in the theory as a coupling of the usual ballooning instability to a (nonlinear) electromagnetic flute mode. Numerical studies of the eigenvalue problem will be present. Also, the renormalized electron temperature response is discussed.

Using the renormalized theory, an estimate of the level of magnetic turbulence necessary for hydrodynamic electron behavior is obtained. *Preliminary* results on the self-consistent determination of the saturated turbulence level and electron thermal conductivity are presented.

4.2.1.6 "Anomalous Tearing Mode Growth and Rapid Magnetic Reconnection in Multiple-Helicity MHD Turbulence"⁵¹

P. H. Diamond
Z. G. An*
T. Chiueh*

B. A. Carreras
H. R. Hicks

Reduced resistive magnetohydrodynamics is used to study anomalous tearing mode growth and rapid magnetic reconnection in the presence of multiple-helicity turbulence. Renormalized equations for long-wavelength tearing mode perturbations in a turbulent MHD fluid are derived and solved. The various physical processes contributing to enhanced growth are discussed. When magnetic islands of different helicities overlap, a long-wavelength tearing mode in the turbulent region grows at the rate

$$\gamma\tau_A \sim (\Delta'_k)^{1/2} \left[\sum_{\mathbf{k}} k_\theta^2 \langle \phi^2 \rangle_{\mathbf{k}} \right]^{3/8}.$$

Here, ϕ is the electrostatic potential. The growth rate is *independent* of collisional resistivity. Magnetic flux expulsion, which lowers the plasma self-inductance and relaxes the current profile, proceeds at a similar rate. Numerical solutions of the nonlinear equations are consistent with analytical predictions. The mechanism for generation of the short-wavelength turbulence and applications to reconnection processes in solar flares are discussed.

4.2.1.7 "Theory of Anomalous Tearing Mode Growth and the Major Tokamak Disruption"⁵²

P. H. Diamond
R. D. Hazeltine*
Z. G. An*

B. A. Carreras
H. R. Hicks

An analytic theory of turbulence in reduced resistive magnetohydrodynamics is developed

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and applied to the major disruption in tokamaks. The renormalized equations for a long-wavelength tearing instability are derived. The theory predicts two principal nonlinear effects: an anomalous flux diffusivity due to turbulent fluid convection in Ohm's law and a vorticity damping term due to turbulent magnetic stresses in the equation of motion. In the final phase of the disruption, when fine-scale fluid turbulence has been generated, detailed considerations show that anomalous diffusivity has the dominant effect at long wavelengths.

For a low- m tearing mode, the solution of the renormalized equations during the turbulent phase yields a growth rate analogous to the classical case but increased by turbulent resistivity:

$$\gamma \sim \left(\sum_{\vec{k}} k_{\theta}^2 |\phi_{\vec{k}}|^2 \right)^{3/8} (\Delta')^{1/2}.$$

This analytical prediction is in good accord with computational results.

4.2.1.8 "Drift Rippling Modes"⁵³

L. Garcia
B. A. Carreras

H. R. Hicks

A model based on the rippling mode turbulence has been proposed to explain the edge transport of tokamak. For simplicity, only finite, parallel thermal conduction was included in the model. However, other effects must be included in the model to have a complete physical description.

A reduced system of equations, valid for low- β , cylindrical geometry, has been derived from the two fluid equations. This system includes terms such as diamagnetic drifts, viscosity, or thermal force and can be used for linear and nonlinear calculations.

We have done linear stability calculations, including the effects of ω_* . The growth rates compare favorably with the analytical dispersion relation. Calculations are in progress for

realistic tokamak parameters. Results are presented.

4.2.1.9 "Effect of Thermal Force on Tearing and Rippling Modes"⁵⁴

L. Garcia
B. A. Carreras

H. R. Hicks

Nonlinear interaction of tearing modes has been proposed as a likely mechanism for major tokamak disruptions. The ω_* effects, which modify the linear evolution of the tearing mode, have little effect on its nonlinear evolution and do not modify the basic model for tokamak disruptions. Recently, it has been shown that the temperature gradient term and thermal force can have a strong stabilizing effect on linear stability of these modes. We have studied the implications of these effects in the nonlinear regime using a reduced set of equations, valid for low- β , cylindrical geometry. Results of calculations for realistic tokamak parameters are presented.

4.2.1.10 The Mercier Criterion for Rotating Plasmas⁵⁵

E. Hameiri*

J. T. Hogan

Recent results suggest that sheared mass flow in an equilibrium state suppresses ballooning modes. However, Mercier modes are known to exist even in such cases. We derive a Mercier stability criterion for axisymmetric configurations with flow, which is stronger than an already known sufficient criterion. The instability corresponds to accumulating eigenmodes at real (stable) points $\omega = m\Omega(\psi_0)$, where ψ_0 indicates any rational magnetic surface, Ω is the toroidal-flow frequency, and m is any azimuthal mode number.

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4.2.1.11 "The Effects of Compressibility on the Resistive Ballooning Mode"⁵⁶

T. C. Hender
B. A. Carreras

W. A. Cooper
P. H. Diamond

The effects of compressibility on the resistive ballooning mode have been investigated both numerically and analytically. Detailed studies have been made for small aspect ratio, high- β_p (near marginal ideal ballooning stability), and modest temperature plasmas—the conditions relevant to ISX-B. The equilibria used in the studies are either matched directly to experimental ISX-B measurements or have parameters (q , β_p , etc.) chosen to resemble ISX-B. At high toroidal currents and modest β_p (≈ 1), it is found that the effects of compressibility can completely stabilize the resistive ballooning modes of low toroidal mode numbers. The critical toroidal mode number for instability varies between several hundred at the $q = 1$ surface and about 20 at the plasma edge. At low toroidal currents, high β_p (≥ 2), and magnetic Reynolds numbers consistent with observed temperatures, the stabilizing effects of compressibility are much less severe, even for very low n modes.

4.2.1.12 "The Effects of Compressibility on the Resistive Ballooning Mode"⁵⁷

T. C. Hender
B. A. Carreras
W. A. Cooper

J. A. Holmes
P. H. Diamond
P. L. Similon*

The linear stability of the resistive ballooning mode, as described by the resistive MHD model, is investigated both analytically and numerically. When the pressure evolution is approximated by fluid convection (reduced MHD model), an instability driven by geodesic curvature, with a growth rate $\gamma \sim \eta^{1/3} \beta_p^{2/3}$, is found. For conditions relevant to the ISX-B, it

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is shown that for modest poloidal beta ($\beta_p \approx 1$), high current, and relatively high temperatures, compressibility has a significant stabilizing influence, relative to the pressure convection model, for low toroidal mode number modes. However, at high β_p (≥ 2), low current, and lower temperatures, compressibility has much less effect.

4.2.1.13 "Resistive Ballooning Mode Studies"⁵⁸

T. C. Hender
B. A. Carreras
L. A. Charlton

J. A. Holmes
P. H. Diamond
P. L. Similon*

A set of linear resistive ballooning equations is derived including the effects of parallel dynamics and FLR terms. Anomalous resistivity and electron viscosity terms derived from a renormalized theory of the turbulent ballooning spectrum may also be included. These equations are solved as an initial value problem in ballooning space.

The transition from resistive to ideal ballooning is examined for a sequence of varying beta equilibria, derived from a reconstructed ISX-B equilibrium. The effects of parallel dynamics are shown to be in good agreement with analytic results. The stabilizing influence of diamagnetic effects, predicted analytically, is examined. Nonlinear extensions of this formulation are discussed.

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4.2.1.14 "The Effect of Diamagnetic Rotation on the Nonlinear Coupling of Tearing Modes"⁵⁹

H. R. Hicks
B. A. Carreras

J. A. Holmes

The tokamak disruption model based on the nonlinear interaction of multiple-helicity tearing modes is extended to include diamagnetic effects. This introduces mode rotation and time-varying phases during the nonlinear interaction. The basic nonlinear destabilization

mechanism associated with plasma disruptions remains unaffected by diamagnetic effects.

4.2.1.15 "Rotational Flux-Surface Shaping in Large Toruses"⁶⁰

J. T. Hogan

Significant toroidal rotation is observed in beam-heated tokamaks, even with near-perpendicular injection. We study the use of large flows to produce favorable magnetic flux-surface shaping in large toruses, where local shaping by centrifugal stress may be more effective than that provided by relatively remote vacuum-field shaping coils. Toroidal rotation directly increases the triangularity in tokamaks and will affect the magnetic well in stellarator/torsatron designs.

We present a new equilibrium equation for the case of large toroidal flow with anomalous viscosity, which incorporates the viscous stress contribution. We explore scenarios for reaching pressure-stabilized regimes by means of a transient rotation, which is then allowed to decay.

4.2.1.16 "Collisional Transport of Momentum in Axisymmetric Configurations"⁶¹

J. T. Hogan

Calculations of the cross-field transport of toroidal momentum are presented for the collision-dominated regime in devices with an axisymmetric magnetic configuration. Intended as a point of reference for more complex calculations of transport in the low-collision-frequency regime, the development treats the case of pure toroidal flow and closely parallels previous calculations of collisional thermal conductivity in tokamaks. Certain counterintuitive features of previous fluid-regime calculations of momentum diffusion are removed, and the contribution of viscous heating to the ion energy balance is discussed. A relation between internal disruptions (sawtooth oscillations) and momentum transport is proposed.

4.2.1.17 "Nonlinear Evolution of Resistive Modes in Reversed Field Pinches"⁶²

J. A. Holmes
B. A. Carreras
T. C. Hender

H. R. Hicks
V. E. Lynch

The nonlinear evolution of resistive tearing and g-modes is studied in the reversed field pinch configuration using a full set of resistive MHD equations. These equations are solved numerically using 3-D initial-value, spectral finite-difference techniques. The effects of compressibility and finite beta upon the linear stability and nonlinear single-helicity evolution of the $m = 1$ tearing mode are studied in detail, together with the extension to multiple helicities. We also examine the linear scaling of the g-mode with S , the ratio of the resistive skin time to the Alfvén time, and with Γ , the ratio of specific heats, as well as the extension of these calculations to the nonlinear regime.

4.2.1.18 "A Comparison of the Full and Reduced Sets of Magnetohydrodynamic Equations for Resistive Tearing Modes in Cylindrical Geometry"⁶³

J. A. Holmes
B. A. Carreras
T. C. Hender

H. R. Hicks
V. E. Lynch
B. F. Masden

The results of numerical calculations using a full set of resistive MHD equations are compared with the results of similar calculations using a reduced set of equations derived for tokamaks in the limits of low beta and large aspect ratio ($\beta \sim \epsilon^2 \ll 1$). The calculations, which are carried out in 3-D cylindrical geometry using initial-value techniques, allow the comparison of linear stability properties as well as detailed nonlinear studies. The results of these calculations (including linear growth rates and eigenfunctions, the nonlinear evolution of single-helicity magnetic islands, and the nonlinear evolution of multiple-helicity cases) confirm the validity of the reduced set of equations at low beta in cylindrical geometry.

4.2.1.19 "Nonlinear Evolution of 3-D MHD Instabilities for Full and Reduced Sets of Equations"⁶⁴

J. A. Holmes
B. A. Carreras
T. C. Hender

H. R. Hicks
V. E. Lynch
B. F. Masden

Initial-value calculations are being used with success to study instabilities and MHD behavior in toroidal devices. Most of this work is carried out using systems of two or three nonlinear partial differential equations solved in three spatial dimensions and time. These systems are derived from the full MHD model or eight such equations through the use of various ordering schemes, or sets of limiting assumptions, which allow simplification of the model. It is, therefore, of interest to compare the results obtained with reduced sets of MHD equations to those obtained with a more general set of equations. The solution of a full nonlinear system of MHD equations in three spatial dimensions and time requires the advancement of seven or eight equations, rather than two or three. Numerical stability dictates time-step restrictions to the Alfvén (τ_A), rather than poloidal Alfvén ($\tau_{H_p} = R\tau_A/a$), time (where R and a are the major and minor plasma radii). Even so, techniques developed for the efficient representation and solution of the reduced systems of equations can be applied to the solution of a full set, and this, together with the projected advances in computer speed, encourages the development of nonlinear 3-D, full MHD computer codes.

A mixed finite-difference spectral method has proven to be an efficient and compact approach to nonlinear initial-value MHD calculations. A (ρ, θ, ζ) coordinate system based upon the equilibrium magnetic geometry is chosen. All dynamic variables are represented using a Fourier expansion in the angle coordinates:

$$f(\rho, \theta, \zeta, t) = \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty}$$

$$\times \left\{ f_{mn}^c(\rho, t) \cos(m\theta + n\zeta) + f_{mn}^s(\rho, t) \sin(m\theta + n\zeta) \right\}.$$

This expansion, which is truncated at a finite number of terms or modes, has been shown to be a more compact representation than, for example, 3-D finite differences. While the choice of important modes is problem dependent, efficient mode-selection schemes have been devised, tested, and validated. For example, recent major disruption calculations have been carried out specifically to study the turbulent stage of the disruption. In order to properly represent such cases having magnetic Reynolds numbers R_m ranging up to 100, we have made calculations with over 100 modes and radial grid densities of more than 350. Not only do such calculations provide statistical information about the turbulent latter stages of the disruption, but comparison with similar calculations using coarse grids and as few as 11 modes confirms the validity of the latter at describing the basic interaction which leads to the turbulent stages of the disruption.

As a first step in the development of a 3-D toroidal, full MHD, initial-value code, we have written a cylindrical program, CYL, using the above techniques. Seven equations are advanced:

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{J} \times \mathbf{B} + \frac{1}{R} \nabla^2 \mathbf{v},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \mathbf{J}),$$

and

$$\frac{dp}{dt} = 0,$$

where the mass density ρ is taken to be constant, $\mathbf{v}$ is the velocity, p is the pressure, $\mathbf{B}$ is

the magnetic field, $\mathbf{J} = \nabla \times \mathbf{B}/\mu$ is the current, R is the Reynolds number, η is the resistivity, and $d/dt = \partial/\partial t + \mathbf{v} \cdot \nabla$ is the convective derivative. Calculations have been performed for a variety of linear and nonlinear cases, and results have been compared with similar calculations carried out in cylindrical geometry by the RSF code, which solves a reduced set of two equations derived in the limit of low beta ($\beta_o = 2\mu p_o/B_o^2$, where p_o and B_o are scale factors for the pressure and magnetic field) and large aspect ratio ($\epsilon = a/R \ll 1$, $\beta \sim \epsilon^2$). Defining $\epsilon_L \equiv 2\pi a/L$, where a is the radius and L the length of the cylinder, we find good agreement between results obtained using the two systems of equations for small ϵ_L and β (Fig. 4.1), but for large ϵ_L and β , the full system of equations yields faster growth and stronger nonlinear effects than are obtained using the reduced equations.

Fig. 4.1. Comparison of full system (CYL) and reduced system (RSF) results.

4.2.1.20 "Resistive Modes in Reversed Field Pinches"⁶⁵

J. A. Holmes
B. A. Carreras
T. C. Hender

H. R. Hicks
V. E. Lynch
B. F. Masden

The stability and nonlinear evolution of resistive tearing and g-modes are studied in the reversed field pinch configuration using a full set of resistive MHD equations. These equations are solved numerically in cylindrical

geometry using the 3-D, initial-value, spectral finite-difference computer code CYL. The effects of compressibility and finite beta upon the linear stability and nonlinear single-helicity evolution of the $m = 1$ tearing mode are studied in detail, together with the extension to multiple helicities. We also examine the linear scaling of the g-mode with S , the ratio of the resistive skin time to the Alfvén time, and with Γ , the ratio of specific heats, as well as the extension of these calculations to the nonlinear regime.

4.2.1.21 "Effects of Toroidal Rotation and Pressure Anisotropy on Tokamak Equilibria"⁶⁶

L. L. Lao
W. A. Cooper

R. M. Wieland
F. J. Helton

The effects on tokamak equilibria of toroidal plasma rotation and pressure anisotropy due to neutral beam injection are studied by generalizing a previous variational-moment method. The appropriate MHD equilibrium equations are reduced variationally to a few second-order nonlinear ordinary differential equations making use of the Lagrangians

$$L_T = \sqrt{g} \{ (B_p^2 - B_t^2)/8\pi - \bar{p}(\psi) \}$$

$$\exp[R^2 \omega_t^2(\psi)/2T(\psi)] \},$$

$$L_A = \sqrt{g} \{ \omega(B_p^2 - B_t^2)/8\pi - [p_{\parallel}(\psi, B) + p_{\perp}(\psi, B)]/2 \}.$$

Here, $\omega_t(\psi)$ and σ are the plasma toroidal-rotation frequency and anisotropic factor. Specific calculations using the Doublet III (DIII) and ISX-B geometries are presented. In the anisotropic pressure case, the functional forms for the beam pressures are obtained from a model beam slowing-down distribution function appropriately weighted in the perpendicular and parallel directions.

⁶⁶GA Technologies, Inc., San Diego.

4.2.1.22 "Discrete Alfvén Eigenmode Spectrum in Magnetohydrodynamics"⁶⁷

S. M. Mahajan^{*}
D. W. Ross^{*}

G. L. Chen

The conditions for the existence of global Alfvén eigenmodes below the continuum are investigated, and an analytical dispersion relation describing the modes is obtained. In cylindrical geometry, the curvature, together with gradients of the equilibrium current (magnetic shear), and finite ω/ω_{ci} effects are responsible for these modes, which could play an important part in Alfvén-wave heating of tokamak plasmas.

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4.2.1.23 "MHD Equilibria of a Tokamak with Nonsimply Connected Noncircular Plasma Cross Section"⁶⁸

E. Uchimoto^{*}
B. A. Carreras

L. Garcia
J. D. Callen

It has been conjectured that low- q (≤ 0.5) discharges in the Wisconsin Tokapole II (noncircular tokamak with four internal rings) may be due to the separatrix, which could limit the amount of helical flux outside the $q = 1$ surface available for magnetic field reconnection. In addition, a considerable amount of plasma that resides outside the separatrix of Tokapole II may modify MHD equilibrium and stability significantly. In order to properly estimate the growth rate and mode structure of the $m = n = 1$ tearing mode, MHD equilibria of such a device are studied numerically and analytically, including a plasma outside the separatrix. Plasma pressure and current-density profiles in the vicinity of the separatrix are examined.

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4.2.1.24 "Three-Dimensional MHD Equilibria Obtained Using the Inverse Spectral (Moment) Method"⁶⁹

J. C. Whitson

S. P. Hirshman

The numerical methods used to solve the MHD equilibrium equations in the inverse (moment) representation are presented. The MHD variational principle is used numerically in three respects: (1) as a means for truncating the Fourier flux-coordinate representation of X in the most convergent manner; (2) to determine the equilibrium equations in a conservative form suitable both for finite differencing and for applying fixed, as well as free, boundary conditions; and (3) to obtain an algorithm for finding the path of steepest energy descent in the phase space comprised of the Fourier moment amplitudes. The Fourier analysis in the poloidal and toroidal angles reduces the equilibrium equations to 1-D, second-order, ordinary differential equations that, with the addition of first- and second-order time derivatives, become a critically damped hyperbolic system. Several time-stepping algorithms are discussed, including a stiff-integration scheme (neglecting second-order time derivatives) and an explicit predictor-corrector (Adams) method. Although the magnetic axis is a singular point of the flux-coordinate system, it can be handled without difficulty by power series expansion of all equilibrium quantities in its vicinity. The critical importance of the renormalized poloidal angle θ is explored by considering exact 2-D inverse solutions of the Solov'ev type. Finally, examples of 2-D kidney-shaped equilibria, as well as a 3-D corrugated tokamak equilibria, are presented.

4.2.2 Kinetic Modifications of MHD Instabilities—Abstracts

4.2.2.1 "A New Long Mean Free Path Resistive MHD Instability"⁷⁰

J. D. Callen

K. C. Shaing

In the banana-plateau regime in which most tokamaks operate, the (parallel) electron

viscosity damping rate ($\mu_e \sim \epsilon^2 \omega_{be}$ in the plateau regime) of poloidal flows is larger than the growth rate or diamagnetic drift frequency of medium-mode-number ($n \sim 3-20$) resistive MHD modes. However, in the usual collisional ($\nu_e > \omega_{be}$) resistive MHD picture, pressure fluctuations induce a primarily poloidal flow, $\nabla_{\perp} = \mathbf{B} \times \nabla \tilde{p} / nqB^2$; the divergence of the corresponding perpendicular current is the primary drive for resistive-g and resistive ballooning modes. The strong electron viscous damping of poloidal flows in the banana-plateau regime causes, in analogy with neoclassical transport theory, a fluctuating "bootstrap" current, $J_{\parallel} = -(c/B_p)(\mu_d/\nu_e)(d\tilde{p}/dr)$, contribution to the perturbed parallel Ohm's law. This produces a new type of "long mean free path" resistive MHD instability that has (1) $\tilde{p}$ odd, $J_{\parallel}$ even about a rational surface—tearing mode parity; (2) $\gamma\tau_R \sim S^{2/3}n^{2/3}e^{-i\pi/6}(\beta_p q^2 \mu_d/\nu_e)^{2/3}$, similar to resistive ballooning mode scalings and magnitudes; (3) inferred anomalous transport coefficients similar to those due to resistive ballooning modes with β/ϵ replaced by $\beta_p(\mu_d/\nu_e)$; (4) parallel current fluctuations comparable to the neoclassical bootstrap current, thus vitiating the equilibrium bootstrap current. Since many features of the new mode scale as $\mu_d/\nu_e \sim 1/n_e$, there is some possibility that Alcator-like $\tau_E \sim n_e$ scalings may emerge from plasma confinement in the presence of these modes. The formal analysis proceeds by utilizing a Grad 13-moment representation for the distribution function (to include the viscosity effects) and a multiple-timescale (finite-gyroradius) expansion in a ballooning mode representation with a subsidiary expansion in $(\gamma, k_{\parallel} v_T, \leq \mu_e)/(\nu_e \omega_{be}) \sim \delta \ll 1$.

4.2.2.2 "Kinetic and Fluid Ballooning Stability in Anisotropic Ion Tokamaks"⁷¹

W. A. Cooper

We present the derivation of a kinetic ballooning mode equation for multiple anisotropic fluid ion plasmas and Maxwellian adiabatic electrons. Considering the MHD limit, we

obtain a fluid ballooning mode equation similar to that derived from the Kruskal-Oberman energy principle, except that the energetic ions do not contribute to the instability driving mechanism because they drift across the destabilizing curvature region at a rate that is faster than the oscillation of the mode. A numerical example shows that the Kruskal-Oberman critical beta, $\beta_c \approx 2.65\%$, can be increased to $\beta_c \approx 4.1\%$ when the ratio of peak energetic ion beta to peak total beta $(\beta_{H0}/\beta_0) = 0.3$. Finite Larmor radius (FLR) corrections are also evaluated.

4.2.2.3 "Kinetic Theory of Resistive Ballooning Modes"⁷²

P. H. Diamond
P. L. Similon*

T. C. Hender
B. A. Carreras

A linear and nonlinear kinetic theory of resistive ballooning modes that includes diamagnetic drifts and FLR effects is presented. The linear stability of resistive ballooning modes is examined analytically and numerically. A renormalized resistive ballooning equation is derived, and the saturation level of the instabilities is analytically calculated. Finally, a calculation of the electron thermal conductivity for the large ω_e regime is presented.

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4.2.2.4 "Stabilization of the Tearing Mode at Low Densities by Turbulent Electron Diffusion"⁷³

E. Esarey*
J. P. Freidberg
K. Molvig

C. O. Beasley, Jr.
W. I. van Rij

Experimental results on Alcator-C have indicated that a threshold in plasma density must be surpassed before the tearing mode is

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observed. In contrast, resistive MHD theory predicts that if $\Delta' > 0$, as is generally true experimentally, then instability occurs independent of density. In this work, a kinetic approach to the tearing mode is developed that predicts stability for sufficiently large turbulent electron diffusion. Provided the electron diffusion coefficient scales inversely with density ($D_e \sim 1/n_e$), a density threshold exists. This theory uses the Normal Stochastic Approximation (NSA) to obtain the turbulent electron response, and the ion response is assumed to be classical. From this, a system of coupled, self-adjoint equations is obtained for the fluctuation potentials $\tilde{A}_1$ and $\tilde{\phi}$. It is proved analytically that, for D_e above some value, the energy drive of the tearing mode goes to zero, and, hence, the tearing mode is stabilized, whereas in resistive MHD theory one has $\Delta' > 0$, which implies instability. Physically, electron diffusion prohibits the tearing region from becoming too small, whereas in resistive MHD the layer thickness is limited only by dissipation, which alters the growth rate without affecting stability. Numerical solutions to the coupled self-adjoint system for $\tilde{A}_1$ and $\tilde{\phi}$ are also presented.

4.2.2.5 "Magnetic-Flutter-Induced Transport in Resistive Interchange and Ballooning Turbulence"⁷⁴

P. T. Katt
P. H. Diamond
Z. G. An*

B. A. Carreras
T. C. Hender

A detailed theory of the nonlinear saturation of electrostatic resistive interchange modes is presented. Energy conservation is addressed and used to classify effects appearing in perturbation theory. Predictions of the mixing length theory ($\delta p/P_0 \sim 1/k_x L_p$) are recovered. Behavior of the growth rate for fluctuation levels in excess of the mixing length amplitude is discussed. The validity of transport estimates using stochastic magnetic-field diffusion

theories is discussed. In particular, it is argued that: resonance broadening releases the $D \sim \langle E^2 \rangle$ constraint of quasi-linear theory; pressure fluctuations, where $\tilde{p} \sim \tilde{n} T_0$, survive in the presence of large parallel heat conduction (hence, magnetic flutter transport does *not* feed back onto all pressure drive); maintenance of $\nabla \cdot \mathbf{J} = 0$ forces the redistribution of $\mathbf{J}$ by magnetic fluctuations to occur on *Alfvén*, rather than on *thermal*, timescales (hence, resistivity survives as the dominant dissipation mechanism).

4.2.2.6 "Kinetic Approach to Long Mean Free Path Resistive MHD Instabilities"⁷⁵

K. C. Shaing

J. D. Callen

Recently, a new long mean free path resistive-MHD-like instability in a tokamak has been proposed. The eigenmode equation for this new instability is derived from a set of fluid equations. In particular, an electron parallel viscosity term that is important in the banana-plateau regime has been included in the parallel Ohm's law. In this work we derive the eigenmode equation from the linearized drift kinetic equation. We use the ordering $\nu_e \sim \omega_{pe} \gg \omega > \omega_{de} \gg k_{\parallel} v_{te}$, and $\rho (d \ln \tilde{\phi}/dx)$ is of the order of unity to expand the kinetic equation to include the self-consistent fluctuating flows and currents. The eigenmode equation we obtain is similar to that obtained previously. The kinetic modification of the earlier fluid treatment and the form of the linearized resistive MHD equation in the long mean free path regime will be discussed.

4.2.2.7 "Spectral Properties of the Kinetic Alfvén Wave in Tokamak Geometry"⁷⁶

G. Vahala*
D. J. Sigmar

Y-T. Yan*

It is shown that for low mode numbers ℓ and m such that $\ell q > m$, the incorporation of finite-gyroradius effects to all orders in cylindrical geometry will not destroy the discrete

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spectrum of the shear Alfvén eigenmodes predicted by first-order, finite-gyroradius-effect theory.

4.2.3 Kinetic Theory, Anomalous Transport, and Neoclassical Theory—Abstracts

4.2.3.1 "A Gyrokinetic Approximation for Drift and Ballooning Modes"⁷⁷

C. O. Beasley, Jr.
K. Molvig

W. I. van Rij

A study of drift and ballooning modes makes use of a gyrokinetic formulation of the ion kinetic equation. While this is possible to do with complete accuracy numerically by employing a $V_{\perp}$ mesh, the usual problems and the initial-value code TEDIT, in particular, also employ $V_{\parallel}$ and X meshes as well, thereby making the problem less than practical numerically. On the other hand, analytic integration over $V_{\perp}$ permits only the crudest gyrokinetic approximation valid for $k_x \rho_i \ll 1$. We show here an alternative approach to incorporating gyrokinetic effects to greater accuracy and give some numerical results.

4.2.3.2 "Universal Mode with Diffusive Electrons: Linear Instability and Nonlinear Saturation"⁷⁸

C. O. Beasley, Jr.
K. Molvig

W. I. van Rij

The effects of spatial electron diffusion on the stability properties of the universal drift mode in a sheared magnetic field are studied using an initial-value code, TEDIT. In previous studies of this problem, Hirshman and Molvig relied on an approximation to the electron resonance function equivalent to making a Krook approximation for the spatial diffusion operator, $D \partial^2 / \partial x^2$. The present work treats the diffusion operator precisely and also allows the treatment of a realistic parallel-velocity dependence of the diffusion coefficient, $D = D(v_{\parallel})$. For the case of a velocity-independent diffusion coefficient, the qualitative features found by Hirshman and Molvig are observed.

The modes with $k_y \rho_i > 1$ destabilize at small values of the diffusion coefficient and saturate at higher values, corresponding to several orders of magnitude in D . There are quantitative discrepancies with the previous work that, near the saturation point, can be accounted for reasonably well by a simple asymptotic theory. However, when the code uses a more realistic form, $D = D_0(v_c/|v_{\parallel}|) \exp(-v_c^2/v^2) + D_c$, where D_c corresponds to the (small) collisional diffusion and D_0 parametrizes the turbulence level, then a quantitative difference is observed. Instability persists down to zero turbulence levels, $D_0 = 0$. This is essentially linear instability due to collisional diffusion alone.

4.2.3.3 "Turbulent Plasma Response in a Stochastic Orbit Regime"⁷⁹

K. Molvig
J. P. Freidberg
R. Potok*

S. P. Hirshman
J. C. Whitson
T. Tajima†

The theory for the nonlinear, turbulent response in a system with intrinsic stochasticity and long-lived fluctuations is considered. It is argued that perturbative Eulerian theories, such as the direct interaction approximation (DIA) are inherently unsuited to describe such a system. The exponentiation and chaotic properties that characterize stochasticity appear in the Lagrangian picture and cannot even be defined in the Eulerian (one-point) representation. An approximation for stochastic systems—the normal stochastic approximation (NSA)—is developed; it states that the perturbed orbit functions (Lagrangian fluctuations) behave as normally distributed random variables. This is independent of the Eulerian statistics, and, in fact, these Eulerian fluctuations are treated as fixed. A simple model problem (appropriate for the electro response in the drift wave) is subjected to a series of computer experiments. To within numerical noise, the results are in agreement with the

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NSA. The predictions of the DIA for this model show substantial qualitative and quantitative differences.

4.2.3.4 "Calculation of Parallel Viscosity in the Plateau Regime"⁸⁰

K. C. Shaing

J. D. Callen

A direct calculation of the parallel viscosity $\langle \mathbf{B} \cdot \mathbf{V} \cdot \vec{\pi}_a \rangle$ in the plateau regime for a large aspect ratio, axisymmetric tokamak is presented.

4.2.3.5 "Recent Developments of Neoclassical Ion Transport in Tokamaks with Strong NBI"⁸¹

D. J. Sigmar

Due to strong, parallel neutral beam injection (NBI), tokamak plasmas with toroidal rotation velocity $v_\phi \leq v_{thi}$, $v_\phi > v_{thi}$ have been produced. From $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$, this implies a new ordering for the large ensuing radial and poloidal ambipolar electric fields, in the neo-classical theory. Using this ordering, the drift kinetic equation (DKE) is solved in the plateau regime. The large toroidal rotation produces off-diagonal elements in the stress tensor $\vec{\pi}$ of the order $(\rho_i/r_n)^2$ without having to expand the DKE through $(\rho_i/r_n)^4$, as is necessary to calculate the perpendicular viscosity $\nu_\perp$ in the standard ($v_\phi \ll v_{th}$) theory. The plateau-regime result is $\nu_\perp = 0.28n_i\rho_iq^2\nu_{ii}$ (similar in appearance to the earlier banana-regime results). Particle and heat-flow transport coefficients are also calculated as a function of (v_ϕ/v_{thi}) . Besides the friction-driven particle flux Γ_1 , due to the large flow velocity v_ϕ , a perpendicular viscosity-driven flux Γ_2 arises. One finds

$$\Gamma_2/\Gamma_1 = (v_\phi/v_{thi})(\rho_{pip}/r_n) \cdot (m_i/m_e)^{1/2}(\nu_{ei}/\omega_{te}) ,$$

which for the "maximal ordering" $(m_i/m_e)^{1/2} \leq (r_n/\rho_{pip})$ can imply Γ_2 to be important for the particle balance.

4.2.3.6 "Plateau-Regime Transport for Plasmas with Strong Toroidal Rotation"⁸²

D. J. Sigmar

K. C. Shaing

Due to strong, parallel NBI, tokamak plasmas with toroidal-rotation velocity $v_\phi \leq v_{thi}$, $v_\phi > v_{thi}$ (where v_{thi} , v_{thl} are the hydrogen/impurity thermal speeds) have been produced. From $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$, this implies a new ordering for the large ensuing radial and poloidal ambipolar electric fields, in the neo-classical theory. Using this ordering, the DKE is solved in the plateau regime. The large toroidal rotation produces off-diagonal elements in the stress tensor $\vec{\pi}$ of order $(\rho_i/r_n)^2$ without having to expand the DKE through $(\rho_i/r_n)^4$, as is necessary to calculate the perpendicular viscosity $\nu_\perp$ in the standard ($v_\phi \ll v_{th}$) theory. The plateau-regime result is $\nu_\perp = 0.28n_i\rho_iq^2\nu_{ii}$ (similar in appearance to the earlier banana-regime results). Particle and heat-flow transport coefficients are also calculated as a function of (v_ϕ/v_{thi}) . For $v_\phi/v_{thi} = 1$, the enhancement of $\chi_i \approx 2$. Besides the friction-driven particle flux Γ_1 , due to the large flow velocity v_ϕ a perpendicular viscosity-driven flux Γ_2 arises. One finds

$$\Gamma_2/\Gamma_1 = (v_\phi/v_{thi})(\rho_{pip}/r_n) \cdot (m_i/m_e)^{1/2}(\nu_{ei}/\omega_{te}) ,$$

which for the "maximal ordering" $(m_i/m_e)^{1/2} \leq (r_n/\rho_{pip})$ (such that electron-ion equilibration equals ion heat conduction in the tokamak) can imply Γ_2 to be important for the particle balance. While Γ_1 is automatically ambipolar, Γ_2 is so only after a few perpendicular viscosity times $(r_n^2/\eta_\perp)$. After this transition, E_r is adjusted such that

$$\sum_a \langle R^2 \nabla \phi \cdot (\nabla \cdot \vec{\pi}_a - \vec{\kappa}_a) \rangle = 0 ,$$

where $\vec{\kappa}_a$ is the momentum input to species a from the beam.

4.2.3.7 "Particle Transport and Ambipolar Field in Strongly Rotating Tokamak Plasma"⁸³

D. J. Sigmar
K. C. Shaing

W. M. Stacey, Jr.

The theory has been worked out for toroidal-rotation velocities $v_\phi \geq v_{thi}$ (the main ion thermal speed) for pure and impurity plasmas in the plateau and the plateau-Pfirsch-Schlüter mixed regime, including simultaneously inertial and direct beam-momentum source effects. In particular, the parallel viscous force $\langle \mathbf{B} \cdot \nabla \cdot \vec{\tau} \rangle$ and the toroidal viscous force $\langle R^2 \nabla \phi \cdot \nabla \cdot \vec{\tau} \rangle$ are calculated for the neoclassical and for an electromagnetic drift turbulence model. This determines the ambipolar field in steady state. Experimental consequences for toroidal momentum confinement and for impurity transport are discussed.

4.2.3.8 "The Effects of Neutral Beam Injection on Impurity Transport in Tokamaks"⁸⁴

W. M. Stacey, Jr.

D. J. Sigmar

A self-consistent theory is presented for particle flows in the flux surface, radial particle fluxes, and the radial electric field in a tokamak. The effects of beam-impurity momentum exchange, radial transfer of toroidal momentum, and the poloidal variation in density and potential that ensue when $v_\phi \approx v_{th}$ are treated—the interaction among these effects is nonlinear. Model problem predictions based on the theory indicate enhanced inward impurity transport with strong counter-injection and outward impurity transport with strong coinjection of neutral beams.

4.2.3.9 "NBI-Driven Impurity Flow Reversal"⁸⁵

W. M. Stacey, Jr.

D. J. Sigmar

The authors' previous theory for the effect of NBI momentum input upon impurity transport

in a tokamak has been extended to include the inertial effects that become significant when the impurity rotation velocity and thermal velocity are comparable. Momentum balance, particle conservation, and charge neutrality are invoked to define a self-consistent formalism for the particle flows in the flux surface, the radial electric field, the poloidal variations of particle densities and electrostatic potential, and the radial transport fluxes. The results are similar to the authors' previous results in that the major effect of momentum injection is to create a transport flux component proportional to the radial electric field, which for impurities is outward with coinjection. The magnitudes of the transport flux components and of the radial electric field are modified by the inertial effect and by the poloidal nonuniformities.

4.2.3.10 "Neutral-Beam-Driven Impurity Flow Reversal in Tokamaks"⁸⁶

W. M. Stacey, Jr.
R. B. Bennett*

D. J. Sigmar

A theory is outlined that is capable of explaining the observed effects of NBI on impurities in tokamak plasmas. In the collisional regime, it is shown for a representative model problem that, for sufficiently strong coinjection, the outward impurity flux component produced by the radial electric field becomes larger than the inward flux components due to the density gradient, rotation, and direct beam-impurity momentum exchange, thereby producing an outward impurity flux. In the mixed regime, a preliminary version of the theory provides a reasonable interpretation of the PLT impurity flow-reversal experiments. This preliminary theory, when adjusted to match the PLT results, predicts significant impurity flow reversal in the Tokamak Fusion Test Reactor (TFTR) and in a plasma the size of a Fusion Engineering Device (FED) and an International Tokamak Reactor (INTOR) plasma.

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4.2.4 Transport Simulations and Plasma-Wall Interactions—Abstracts

4.2.4.1 "Simulation of Tritium Pellet Injection in TFTR"⁸⁷

S. E. Attenberger
W. A. Houlberg

S. L. Milora*

Preliminary studies of fusion rates and power amplification factors (Q) are reported for tritium pellet injection in deuterium beam-heated deuterium discharges in TFTR. These tritium pellet injection sequences can be performed under the conditions of a minimal tritium inventory and a restricted number of shots. Penetration of the pellets is evaluated with a computer model that includes pellet ablation in the presence of fast ions from a neutral beam. The distribution functions for fast beam ions and fusion alphas are evolved in time with a time-dependent Fokker-Planck model and coupled with evolution of the background plasma using the WHIST 1½-D transport code. Time-dependent neutron production rates and Q values are obtained. Preliminary results indicate that extended beam pulses (~ 1 s) are desirable for a $Q \approx 1$ demonstration in TFTR without compression heating.

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4.2.4.2 "Dielectronic Recombination Rate Coefficients for FeXVI-FeXIX"⁸⁸

E. C. Crume, Jr.

Highly ionized impurity ions are readily produced in tokamak discharges. If it were known independently that cross-field transport through steep temperature gradients were small enough for the ions to come into corona equilibrium distributions, then the ratios of ionization and recombination rates could be measured from spatially resolved measurements of spectral lines of adjacent ionization stages. But it is known from confinement studies of laser-injected impurities that the transport rates may be large enough to influence the ionization balance so that the atomic coefficients

cannot be determined. During counterinjection discharges in the ISX-B tokamak, however, a unique situation exists; the impurities have long confinement times and accumulate in the interior of the plasma, where T_e is reasonably uniform. Simulations of such accumulation based on theories of beam-driven neoclassical transport are in qualitative agreement with the experimental observations. The plasma cools because of increased radiation, and recombination takes place into lower ionization stages. During this recombination phase, the relative concentrations have been measured for FeXIX/FeXVIII, FeXVIII/FeXVI, and FeXVI/FeXV. The recombination coefficients are determined by assuming that theoretical calculations of ionization coefficients are accurate. The dielectronic recombination coefficients are then inferred by subtracting the contributions of radiative and charge-exchange recombination. It is found that the dielectronic recombination coefficient for FeXIX agrees well with theory, but the agreement is poorer for lower stages. For FeXVI, the rate coefficient is lower than theoretical calculations by at least a factor of 3. These results imply that the tendency of iron in some tokamaks to have a maximum abundance at temperatures much higher than implied by the rate coefficients usually employed results from transport effects and not from uncertainties in the atomic data.

4.2.4.3 *Simulation of Inertial and Beam-Driven Effects on Impurities in Tokamak Plasmas*⁸⁹

E. C. Crume, Jr.

Experiments on beam-heated tokamak plasmas in the ISX-B indicate that counterinjection leads to enhanced accumulation of impurities and coinjection leads to reduced accumulation of impurities relative to ohmically heated plasmas. According to neoclassical theory, both inertial and beam-driven effects can modify impurity distributions in beam-heated plasmas. We have implemented

treatments of these effects in our basic impurity transport simulation code, IMP-TAR, in order to investigate whether these effects could account for the observations in ISX-B. We briefly review the neoclassical theory of these effects and infer various consequences. We then present simulation results for model coinjected and counterinjected ISX-B plasmas with inertial and beam-driven effects treated both separately and together. These results indicate that for plasmas with ion density and temperature gradients comparable to those observed in ISX-B (1) impurity distributions even in ohmically heated plasmas are modified by the inertial effect; (2) the inertial effect alone qualitatively could account for the enhanced impurity accumulation observed in counterinjected plasmas; and (3) neither the inertial effect alone nor inertial and beam-driven effects in combination qualitatively can account for the reduced accumulation observed in coinjected plasmas.

4.2.4.4 "Simulation of Combined Inertial and Momentum Effects on Impurities in ISX-B"⁹⁰

E. C. Crume, Jr.
D. J. Sigmar

D. E. Arnurius

Previously, we modeled impurity transport in beam-heated ISX-B plasmas using separate theoretical treatments of the inertial and the beam momentum effects. We found that, qualitatively, the inertial effect alone predicts the strong impurity accumulation observed with counterinjection in ISX-B, but the apparent expulsion of impurities observed with coinjection was not reproduced in simulations with the inertial effect, either alone or in combination with the beam momentum effect. In fact, for the impurity drag model used, the inertial effect completely dominated the beam momentum effect. Stacey and Sigmar have recently combined the two effects in a single theoretical treatment. We use this treatment in our tokamak impurity transport code IMP-TAR along with new theoretical treatments for

the impurity drag to determine whether the combined model will give improved agreement with ISX-B data, especially for coinjection. We present results from the new simulations and compare them with experimental data and earlier simulations.

4.2.4.5 "Numerical Comparison of Classical and Ripple Diffusion in a Tokamak"⁹¹

H. Grad*
J. T. Hogan

A. Bayliss†
L. Ibanez*

A fully 3-D tokamak simulation code has been described. Results for resistive flux diffusion have been given. Results are now given concerning the numerical comparison of classical and ripple diffusion. Ripple diffusion is introduced in order to couple the diffusion and the 3-D equilibrium. As a first step, the comparison is made in the plateau regime. The ripple coefficient is calculated in a self-consistent manner from the 3-D equilibrium solver and then used in the transport part of the code. The inclusion of ripple conductivity makes the results highly dependent on the 3-D equilibrium. Results are given for values of $0 < \beta < 8\%$ and ripples up to 10%.

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4.2.4.6 "Toroidal Momentum Confinement in Beam-Heated Tokamaks"⁹²

J. T. Hogan

Several aspects bearing on momentum confinement analysis are treated. Modified Stix coefficients are derived for momentum and energy transfer from fast ions to a streaming background plasma. The incremental coefficients vary as

$$(\text{momentum}) \delta K_i \propto \frac{\left(\frac{e_i}{e_b}\right)^2 \left(\frac{m_i + m_b}{m_b}\right) \frac{v_\phi}{v_c}}{\cos \theta_0}$$

and

$$(\text{energy}) \delta G_i \propto \frac{\left(\frac{e_i}{e_b}\right)^2 \left(\frac{m_i + m_b}{m_b}\right) \frac{v_\phi}{v_c}}{\cos \theta_0},$$

where i and b refer to plasma and beam, θ_0 is the injection angle, and v_c is the critical velocity denoting transition from electron to ion slowing. The increments arise from modifications to the Rosenbluth potentials by the presence of flow; numerical results are presented both for the conventional assumptions ($v_e \gg v_b \gg v_i$) and with the unexpanded potentials. Monte Carlo (3-D) modeling of "halo" neutrals, which are produced by charge exchange of the injected neutrals with the background, show a significant enhancement of the halo neutral density when there is a toroidal flow ($v_\phi/c_s \approx 0.3$). Halo neutrals are then preferentially produced in a direction requiring long escape times. Charge-exchange losses of momentum are enhanced. An ad hoc momentum confinement model using the new Stix coefficients and charge-exchange effects, and based on previous fluid-regime diffusion calculations, is proposed to satisfy available data from 'SX-B.

4.2.4.7 "General Principles of Magnetic Confinement"⁹³

J. T. Hogan

These lectures were intended as preparation for detailed discussions at the 1982 NATO Advanced Study Institute of the role of atomic and molecular physics in confinement research. They begin with a description of the major approaches to magnetic confinement: tandem (ambipolar) mirrors, with their associated auxiliary barriers; tokamaks; and stellarators. The leading alternatives, the EBT and the reversed field pinch, are also treated. The evolution equations for particle, energy, and (where relevant) field diffusion are presented and discussed. This is the context for atomic and molecular processes relevant to confinement.

4.2.4.8 "Impurity Thermal Charge-Exchange Effects"⁹⁴

J. T. Hogan

Recent measurements of electron-capture cross sections for H^0 on ions of carbon, oxygen, and iron allow estimation of the radiative cooling rates for typical tokamak plasma conditions for these ions. The calculations extend earlier results for carbon, in which large enhancements of the radiative rates over conventional estimates were found. The effect of charge-exchange recombination in producing asymmetric radiative emission owing to non-symmetric H^0 spatial distributions is also studied.

4.2.4.9 A Model for Pneumatic Pellet Injection⁹⁵

J. T. Hogan
S. L. Milora*

D. D. Schuresko*

A hydrodynamic code has been developed to model the performance of pneumatic pellet-injection systems. The code describes 1-D, unsteady compressible gas dynamics, including gas friction and heat transfer to the walls in a system with variable area. The mass, momentum, and energy equations are solved with an iterated Lax-Wendroff scheme with additional numerical viscosity. The code is described, and comparisons with experimental data are presented.

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4.2.4.10 "Tritium-Pellet-Injection Sequences for TFTR"⁹⁶

W. A. Houlberg
S. L. Milora*
S. E. Attenberger

G. L. Schmidt†
C. E. Singer†

Tritium pellet injection into neutral deuterium beam-heated deuterium plasmas in the

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TFTR has been proposed as a means of obtaining $Q \geq 1$ conditions with reduced tritium consumption. We explore the sensitivity of instantaneous and integrated Q values to tritium pellet size, velocity, and timing in 85-cm discharges and compare with the earlier studies for compression discharges. We also compare the Q values obtained with this T-pellet mode of operation with the two-component mode of injecting deuterium beams into a tritium plasma (TCT mode). A nominal T-pellet-mode case consists of injecting a large pellet (equivalent spherical radius of ~ 2 mm) into a low-density deuterium plasma ($n \approx 3.0 \times 10^{13} \text{ cm}^{-3}$). Enhanced ablation by the fast deuterium ions is included in the improved pellet-ablation code. Comparable Q values can be obtained for the T-pellet and TCT modes, but the T-pellet mode of operation can significantly reduce the amount of tritium consumed per discharge. This observation is sensitive to particle recycle rates from the limiter and particle confinement in the plasma-edge region. The T-pellet mode is most attractive, however, because all of the plasma optimization is done with deuterium discharges before the first tritium is injected into the system. A $Q \approx 1$ demonstration is then conceivable, with very few discharges containing tritium and very low total neutron production. The greatest uncertainty in predicting attainable Q values still lies in the electron energy confinement model.

4.2.4.11 "Measurement of the Recombination Rate Coefficient of a Tokamak Vacuum Vessel Wall"⁹⁷

H. C. Howe

R. A. Langley^{*}

The recombination rate coefficient of the ISX-B vacuum vessel wall has been measured by observing the rate of decrease of gas pressure in the vessel during a glow discharge. A simple analytic expression that relates the rate of change of the pressure to the

recombination rate is derived and verified by comparison with a complete numerical simulation. Comparison of the recombination coefficient measured in ISX-B with previous laboratory measurements shows that the measured value is typical for a stainless steel surface covered with an oxide layer.

4.2.4.12 *Determination of the Equilibrium Parameters for the Tokamak de Varennes Using the WHIST Transport Code*⁹⁸

M. M. Shoucri^{*}
W. A. Houlberg
V. Fuchs^{*}

T. W. Johnston[†]
I. P. Shkarofsky[‡]

The equilibrium parameters for the Tokamak de Varennes are determined using the WHIST time-dependent transport code, which couples the 1-D flux-surface-averaged fluid transport equations to solutions of the 2-D Grad-Shafranov equation. The resulting equilibrium parameters are shown to be in very good agreement with the equilibrium parameters obtained using the VARTOK1 code.

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4.2.5 Tokamak Reactors—Abstracts

4.2.5.1 "Fast Alpha Diffusion and Thermalization in Tokamak Reactors"⁹⁹

S. E. Attenberger

W. A. Houlberg

Energy relaxation and spatial diffusion of fast alpha particles are incorporated into a multienergy group model that is coupled to a fluid transport code for the thermal plasma species. The multienergy group equations evolve the temporal- and spatial-dependent

^{*}Tokamak Experimental Section.

alpha particle distribution function and, thus, determine alpha particle heating and loss rates for arbitrary thermalization and diffusion models. The effects of deviations from classical, local thermalization on plasma performance are discussed. It is shown that spatial diffusion can lead to inversion of the fast-ion distribution function even if thermalization remains classical. This inversion may drive instabilities and lead to anomalous thermalization. Ripple-induced spatial diffusion of fast alphas is used to illustrate the importance of extending the analysis to include pitch-angle dependence.

4.2.5.2 "Multigroup Diffusion of Fast Alpha Particles in Tokamaks"¹⁰⁰

S. E. Attenberger

W. A. Houlberg

We have developed a code based on a multigroup model for the thermalization and radial diffusion of fast alphas for use in a 1½-D tokamak transport code. The model was suggested by D. Post and has been used previously for similar applications. We investigate the performance of the model for various choices of energy group widths and time steps, with $1 \leq N_G \leq 100$, where N_G is the number of energy groups.

The equation

$$\frac{\partial n_j}{\partial t} = \frac{1}{V(\rho)} \frac{\partial}{\partial \rho} \left[DV(\rho) \frac{\partial}{\partial \rho} n_j \right] + S_j - \frac{n_j}{\tau_{sj}},$$

where

n_j is the alpha density in the j th group,
 τ_{sj} is the time to slow down across group j ,
 S_j is the particle source in the j th group,
 ρ is a flux-surface label,
 V is volume within a flux surface,
 the prime denotes differentiation with respect to ρ ,

is solved for each energy group j , starting with the highest energy group. The source for the highest energy group is the fusion rate. For all other groups, the thermalization loss from one group is the source for the next group, so that the diffusion equations for the various energy groups can be solved sequentially, rather than simultaneously, while still preserving particles. The method is fast, taking only 2.5×10^{-3} minutes per call with $N_G = 100$ on an NMFECC Cray computer. While this is adequate for many applications, good accuracy may be achieved using fewer groups and less execution time. Nonuniform energy bins are considered. The sensitivity of a typical tokamak transport simulation to the number of energy groups is displayed.

The sensitivity of the time response to numerical approximations is examined in model problems in which the source is treated as a step function at $t = 0$. The effects of implicit time treatment and assumed distribution within an energy group are discussed.

4.2.5.3 "Optimal Beam Heating in Tokamaks"¹⁰¹

W. A. Houlberg

L. M. Hively*

S. E. Attenberger

While neutral beam heating seems assured of a prominent place in the tokamak reactor program, there remain important questions about beam energies and species mixes that strongly influence technological requirements. We display the sensitivity of beam power supply requirements to change in beam energy, beam species mix, and plasma energy confinement time. The results are derived from 1½-D, time-dependent calculations and include the effects of the shift of the magnetic axis and neutralization efficiency for positive ions. Plots of plasma profiles during an "optimal-path" startup are presented. It is shown that there is only a modest decrease in the power required

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by the plasma as the beam energy is increased because the improved penetration is partially offset by reduced ion heating. Power supply requirements for positive ion systems are significantly reduced by using lower beam energies.

4.2.5.4 Plasma Engineering Studies for Tennessee Tokamak (TENTOK) Fusion Power Reactor¹⁰²

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J. T. Lacatski[†]
J. B. Miller^{*}
W. E. Bryan[‡]

P. W. King^{**}
R. T. Santoro^{††}
T. E. Shannon[†]
N. A. Uckan

This paper presents the results of the plasma engineering and systems analysis studies for the Tennessee Tokamak (TENTOK) fusion power reactor. TENTOK is a 3000-MW(t) central-station power plant that uses a deuterium-tritium (D-T) fuel in a D-shaped tokamak plasma configuration (though bean-shaped configurations are also considered, and the results are discussed) with a double-null poloidal divertor. The major design parameters are $R_0 = 6.4$ m, $a = 1.6$ m, σ (elongation) = 1.65, $\langle n \rangle = 1.5 \times 10^{20}$ m⁻³, $\langle T \rangle = 15$ keV, $\langle \beta \rangle = 6\%$, B_T (on-axis) = 5.6 T, $I_p = 8.4$ MA, and wall loading = 3 MW/m². The plasma and device parameters were determined by trade-off studies with plausible plasma physics and technology and engineering constraints such as stability (beta limit), confinement scaling, toroidal field ripple limit, heating and fueling, divertor configuration, wall lifetime, and maximum field at the conductor. Specifically, detailed analyses were performed in the areas of (1) transport simulation using the 1½-D WHIST transport code, (2) equilibrium/poloidal field coil systems using a 2-D MHD equilibrium code, (3) neutral beam and rf heating, and (4) pellet fueling. Surveys of impurity control systems and diagnostics and controls were also conducted.

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Some of the major features of TENTOK include rf heating in the ion cyclotron range of frequencies, superconducting equilibrium field coils outside the superconducting toroidal field coils, a double-null poloidal divertor for impurity control and ash removal, and possible microwave plasma preheating and steady-state current drive.

4.2.6 General Tokamak Topics—Abstracts

4.2.6.1 "The Status of the Magnetic Fusion Energy Programme"¹⁰³

W. A. Cooper

Fusion-reactor-level plasma parameters have been achieved in experimental devices during the last decade. Energy breakeven is expected in the larger plasma confinement devices that have recently begun or are about to begin operation with the goal of demonstrating that magnetic fusion systems are scientifically feasible. The present status of research in toroidal and mirror systems is reviewed. Specifically, the tokamak, stellarator, and mirror programmes are described, with a concentration on the important physics issues (heating, confinement, stability, potential formation, etc.) that these programmes address. Reactor designs are undertaken to identify and address issues associated with the engineering and economic feasibility of magnetic fusion as a power source. The first-generation reactors will be based on the D-T fuel cycle and have as design goals the production of electricity, fissile fuel, and high-temperature heat.

4.2.6.2 "Technological Requisites of the Magnetic Fusion Energy Programme"¹⁰⁴

W. A. Cooper

An integral part of magnetic fusion energy research is the development of the technologies necessary for the confinement and heating of reactor-level plasmas. Heating systems based on injecting beams of energetic neutral particles or rf waves (or both) will be required to

heat plasmas to the temperatures at which fusion is self-sustaining. These systems may be used also to drive plasma currents. The magnet systems required to confine reactor-size plasmas rely on the development of effective superconductors. Safety and tritium-handling concerns become important considerations in designing reactor concepts.

4.2.6.3 "Theoretical and Experimental Progress in Confinement of Tokamak Plasmas"¹⁰⁵

D. J. Sigmar

This survey talk assesses the present trends in theoretical and experimental tokamak research, which is aimed at

1. further development of our understanding of confinement and heating processes;
2. parameter "pushing" towards reactor values in new, large machines; and
3. optimization and improvement of the tokamak confinement principle, for example, steady-state current drive.

4.3 STELLARATOR THEORY

The initial goal of the stellarator theory effort at ORNL was to find a steady-state and disruption-free configuration stable at beta values greater than 5% to be used as a basis for the design of the Advanced Toroidal Facility (ATF). A torsatron configuration was found that surpassed this criterion and is stable to beta values of 8% to 10% (limit of resolution of the codes). Since construction of the ATF device has been approved, stellarator theory efforts have focused on (1) completing the detailed analysis of subsystems for ATF, (2) improving the theoretical understanding of basic stellarator physics, and (3) exploring new stellarator configurations.

Major improvements of the design of ATF have been carried out during the year. MHD studies of the high-beta regime have shown

the importance of controlling the rotational transform when beta increases. Control has been shown to be possible in practice by programming the shape of the poloidal magnetic field. The ATF vertical field coil system has now been specified to give this extra flexibility to the device. Calculations were also performed for the design of the ATF vacuum vessel, and the very large cross-section helical coils were successfully modeled using the judicious choice of six filaments. Particle and field lines were followed with unexpected results: ion orbits previously thought to be in a loss region in fact reflect from the increasing B fields near the coils and return to the plasma. The orbit pattern in the region outside the plasma permitted a major change in vacuum vessel design. The vessel could be sectioned vertically near the joints of the coils so that the coil segments are not linked by the vessel and can be readily removed.

Improved understanding of the basic physics properties of stellarators has been achieved by combining analytical and computational methods. Computations of 3-D equilibria and stability are now routinely performed. Fast 3-D solvers have been developed that can now be coupled to transport simulations of stellarator plasmas. The transport simulations also include the proper transport coefficients for realistic nonsymmetric configurations and can incorporate, in a self-consistent manner, the effect of the ambipolar electric field. This has been made possible by developing fundamental transport theory for nonsymmetric systems using realistic magnetic fields.

Finally, with the ATF design completed, part of our efforts have turned toward alternative stellarator configurations with a helical magnetic axis, such as a heliac, a cycloidal stellarator, and a geodesic stellarator. The development of an expansion method for helical-axis configurations has improved the efficiency of the MHD studies for such configurations. While these configurations look attractive at first sight, they have yet to be optimized and work is continuing.

4.3.1 Magnetics and Orbits—Abstracts

4.3.1.1 "Monte Carlo Orbit Calculations in ATF"¹⁰⁶

J. A. Rome
R. H. Fowler

J. F. Lyon*

A state-of-the-art set of computer codes now exists to perform orbit calculations for the ATF torsatron. All calculations are performed in field-line coordinates. Fields are obtained either from the coil configuration and the Biot-Savart Law or from the Chodura-Schlüter 3-D MHD code. Collisions are introduced via the operators of Boozer and Kuo-Petravic. Heating can be introduced by suprathermal beam-injected ions or by a local ICRH operator. Vectorization of the code allows following 64 particles simultaneously, while requiring only 5% of the computer time used to follow 64 separate particles.

For typical ATF parameters ($T = 1$ keV, $n = 10^{14}$ cm⁻³), the ion tail (which dominates transport) is well into the collisionless ν regime. The presence of a radial electric field [$e\Phi \sim (1-3)kT$] has a dramatic effect on reducing ion losses. With the same parameters, the electrons are typically in the $1/\nu$ regime.

Monte Carlo calculations help to refine and verify analytic transport coefficient models and interface with the radial transport codes. They supply information about loss cones in the presence of large orbits and radial E fields. Radial ion and electron fluxes are calculated as a function of E to determine the ambipolarity conditions.

Also, a "bootstrap" estimate of energy and particle containment times may be obtained. With no E field, $\tau_E \sim 1$ ms, but with a potential, this can increase an order of magnitude or more.

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4.3.1.2 "Helical-Axis Stellarator Configurations"¹⁰⁷

J. A. Rome
J. H. Harris*

V. E. Lynch

Helical-axis stellarators induce rotational transform via torsion of the field lines. Several configurations have been explored. One is the cycloidal stellarator, which is composed of two sizes of unlinked circular coils that rotate about each other. The flux surfaces are bean shaped, similar to a heliac. Another, the ELMO bumpy stellarator, uses large mirror ratios between the coils to create the hot electron rings and a helical axis to provide rotational transform. Optimization criteria for these configurations are discussed.

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4.3.1.3 A Novel Method of Aligning ATF-1 Coils¹⁰⁸

J. A. Rome
J. H. Harris*

G. H. Neilson*
T. C. Jernigan*

The ATF-1 torsatron coils may be easily aligned before the machine is placed under vacuum. This is done by creating nulls in the magnetic field by energizing the coils in various configurations. All of the nulls in B_z occur on the z -axis. When the nulls coincide, the coils are properly aligned.

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4.3.2 Equilibrium and Stability—Abstracts

4.3.2.1 "Averaging Method Approach to Equilibrium and Stability Studies of Helical Axis Configurations"¹⁰⁹

B. A. Carreras
T. C. Hender

J. A. Rome

The averaging method approach to MHD equilibrium and stability studies of stellarator

configurations has proven to be efficient and reliable when applied to planar-axis configurations. We have developed a generalized version of this method that permits the study of helical, as well as planar, magnetic-axis configurations. We derive an averaged equilibrium equation in the vacuum field flux-coordinate system $(\rho_v, \theta_v, \phi_v)$, in which the Jacobian is proportional to the square of the vacuum magnetic field. The equation is similar to the Grad-Shafranov equation and depends on the vacuum magnetic field through the averaged vacuum metric element. The numerical solutions of this equation compare well with the results of the 3-D equilibrium code NEAR.

4.3.2.2 "Equilibrium and Stability Properties of High-Beta Torsatrons"¹¹⁰

B. A. Carreras
H. R. Hicks
J. A. Holmes
V. E. Lynch

L. Garcia
J. H. Harris*
T. C. Hender
B. F. Masden

Equilibrium and stability properties of high-beta torsatrons are investigated using numerical and semianalytical techniques based on the method of toroidal averaging. The averaged equilibria are compared with those obtained using full 3-D codes. Good agreement is obtained, thus validating the averaging method approach. The stability of plasmas for configurations with different aspect ratios and numbers of field periods is studied. The role of the vertical field is also studied in detail. The main conclusion is that for moderate-aspect-ratio torsatrons ($A_p \leq 8$), the self-stabilizing effect of the magnetic-axis shift is large enough to open a direct path to the second stability region.

4.3.2.3 "Ballooning Modes in 3-D Stellarators"¹¹¹

W. A. Cooper
T. C. Hender

B. A. Carreras

The ballooning stability of 3-D stellarator equilibria is determined from the solution of a second-order ordinary differential equation (ODE) on each magnetic field line. A boundary-value ballooning mode code has been constructed that employs a shooting method to obtain the eigenstructure. As a complementary approach, an initial-value scheme has been implemented that advances in time quantities proportional to the radial velocity, the pressure, and the radial B -field perturbations on a field line. These codes have been applied to the flux surfaces of vacuum torsatron equilibria on which plasma pressure gradients are arbitrarily varied. The central region of the plasma has a shallow magnetic well and has moderate growth rates that do not vary significantly with radial wave number or magnetic field line. The plasma edge region has large magnetic shear but also a magnetic hill, and the growth rates are larger and vary noticeably with radial wave number. The eigenfunctions on each field line tend to peak in the neighborhood where the curvature on average is most destabilizing.

4.3.2.4 "Ballooning Modes in 3-D Stellarators with Shear"¹¹²

W. A. Cooper

T. C. Hender

Pressure-driven ballooning and interchange instabilities in 3-D vacuum stellarator equilibria similar to those of the Heliotron-E device are investigated. The toroidal curvature dominates the mode structure, which concentrates where the field line bending is weakest. The Mercier criterion yields a more stringent condition for stability than the incompressible ballooning mode equation. The growth rates vary significantly with the radial wave number only

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on those field lines located on high-shear flux surfaces close to the edge of the plasma. They remain almost constant from field line to field line of a flux surface. An outward shift of the plasma induced with a vertical magnetic field increases the vacuum magnetic well, which improves the conditions for ballooning stability. An inward shift decreases the vacuum magnetic well, which deteriorates the conditions for ballooning stability.

4.3.2.5 "Equilibrium Studies for Low-Aspect-Ratio Torsatrons"¹¹³

L. Garcia
B. A. Carreras
J. H. Harris*

H. R. Hicks
V. E. Lynch

Three-dimensional MHD equilibrium studies have been done for low-aspect-ratio torsatrons. These studies cover continuous-coil and modular torsatrons. The equilibrium properties improve with aspect ratio, as is expected. The role played by the vertical field has also been investigated. Outward shifts cause the flux surfaces to deteriorate. Inward shifts improve the flux surfaces at the expense of stability properties.

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4.3.2.6 "3-D Equilibrium and Stability Calculations in Flux-Surface Coordinates"¹¹⁴

T. C. Hender
B. A. Carreras
L. Garcia

J. A. Holmes
H. R. Hicks
V. E. Lynch

A new code, NEAR, has been developed to study equilibrium and stability for nonaxisymmetric systems. To achieve an economic representation, the flux-surface coordinates proposed by Boozer are employed. Thus, for example, the contravariant component of the radial magnetic field is represented as

$$B^{\rho}(\rho, \theta, \phi, t) = \sum_{(m,n)} B_j^{\rho}(t) \sin(m\theta + n\phi) ,$$

where ρ , θ , and ϕ are generalized radial, poloidal, and toroidal variables, respectively. Such a coordinate system is particularly efficient in studying the stability of stellarator-type configurations in which the full machine must be represented. Also, the fine radial grids, which may be used, will allow realistic studies of physical resistive effects. These coordinates are generated numerically from real coil configurations using a modified version of a code developed at ORNL. This code computes the Fourier series representation of standard cylindrical coordinates in the flux-surface variables by following vacuum field lines. Using this information, the metric elements are then generated. Various interrelationships show that the only independent metric elements that must be generated are $g_{\rho\rho}$, $g_{\rho\theta}$, and $g_{\theta\theta}$.

In its present, initial implementation, the algorithm used to relax the MHD equation is very similar to that of the Chodura-Schlüter code. The ideal MHD equations

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) ,$$

$$\frac{\partial P}{\partial t} = -\mathbf{V} \cdot \nabla P - \gamma P \nabla \cdot \mathbf{V} ,$$

and

$$\mathbf{F} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla P$$

are advanced by specifying the velocity ($\mathbf{V}$) with a conjugate gradient iteration scheme (where $\langle F^2 \rangle = \int \mathbf{F}^2 d\tau$ and $\alpha \leq 1$):

$$\mathbf{V}^{n+1} = \mathbf{F}^{n+1} + \alpha \frac{\langle F^2 \rangle^{n+1}}{\langle F^2 \rangle^n} \mathbf{V}^n .$$

NEAR has been used to study modular and continuous torsatron systems. Figure 4.2 shows a sequence of increasing beta equilibria for a 12-field-period continuous torsatron, which has been chosen as the ATF design.

Fig. 4.2. Equilibrium flux surfaces for ATF.

The equilibrium results show favorable comparisons with equilibria obtained from both the Chodura-Schlüter code and average method. The normalized shift as a function of central beta for the ATF configuration, given by NEAR, the Chodura-Schlüter code, and the average method, is shown in Fig. 4.3. Figure 4.4 shows a comparison of equilibrium flux surfaces, pressure, and current profiles between NEAR and the Chodura-Schlüter code.

In conclusion, the calculation of equilibria in flux-surface coordinates has been shown to be viable and efficient. A significant improvement in resolution and computation time is obtained over comparable calculations with the Chodura-Schlüter code. An examination of the benefits of various other iteration techniques is currently being made. Also, a linear-

ized version of NEAR is being constructed to study stability.

Fig. 4.3. Normalized shift ($\delta/\bar{a}$) as a function of central beta (β_0), where $\beta_c = 2r^2(a)/R$.

Fig. 4.4. Comparison of flux surfaces (upper plot), toroidal current (J_z), and pressure profiles (P) for equilibria from NEAR and Chodura-Schlüter code.

4.3.2.7 "Inverse Plasma Equilibria"¹¹⁵

H. R. Hicks
R. A. Dory

J. A. Holmes

In inverse equilibrium models, space variables $|X|$ are determined as functions of magnetic variables $|M| = \{\psi, \theta, \zeta\}$, using the usual equations $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$, $\nabla \cdot \mathbf{B} = 0$, and $\mathbf{F} = \nabla_p - \mathbf{J} \times \mathbf{B} = 0$. Inverse models in two dimensions have led to a progression of increasingly sophisticated numerical codes [Potter (1976); Takeda and Tsunematsu (1979); Vabishchevich, Degtyarev, and Favoriskii (1976); and Lao, Hirshman, and Wieland (1981)], as well as analytical models that clarify the physics of both equilibrium and stability [Zakharov and Shafranov (1978)]. In three dimensions, a similar progression of models has occurred [Bauer, Betancourt, and Garabedian (1978); Bhattacharjee and Dewar (1982); Hirshman and Whitson (1983)]. These are reviewed in this paper.

We illustrate in some detail a 2-D solver that was constructed to analyze tokamak configurations and stellarators in the context of the average method. To ensure that the method is suitable not only to determine equilibria but also to provide appropriately distributed data for stability analysis, it is important to be able to control the Jacobian [$J = \partial(R, Z)/\partial(\psi, \theta)$] of the solution in order to preserve numerical accuracy for stability codes. The form chosen is $J = J_0 \rho^l$ where $J_0 = \text{const}$, $\rho = \psi^{1/2}$ is the mean radius of a magnetic surface, $|X| = \{R^0, \theta, Z\}$ provides cylindrical coordinates, and l is an integer. The initial implementation is for a prescribed conducting region boundary, but a "virtual casing" model could be used to allow extension to an infinite domain.

4.3.2.8 "Inverse Equilibria as Input to Stability Calculations"¹¹⁶

H. R. Hicks
B. A. Carreras

J. A. Holmes
V. E. Lynch

Inverse-moment methods have been shown to be efficient for obtaining 2-D equilibria. Encouraged by this, an inverse equilibrium code has been designed to provide tokamak or stellarator (using the stellarator expansion) 2-D equilibria for input to MHD linear-stability and nonlinear MHD codes. The solutions $R(\rho, \theta)$ and $Z(\rho, \theta)$, where ρ is a flux-surface label, are expressed as Fourier series in the generalized poloidal angle θ . The Jacobian can be constrained so that field lines are straight in the resulting coordinate system. This method provides improved resolution compared to Cartesian grid solutions.

4.3.2.9 "Limits on the Construction of Numerical Equilibria Using the Stellarator Expansion Technique"¹¹⁷

H. R. Hicks
B. A. Carreras
J. A. Holmes

V. E. Lynch
B. F. Masden

Calculations of equilibria in stellarator configurations have been carried out with a variety

of 3-D computer codes. An important function of these calculations is to determine, for coil configurations of interest, the highest beta for which an equilibrium can be found. Alternatively, the stellarator expansion can be used. With this approximation, the problem is reduced to a 2-D one. This fast technique can be used to scan large regions of parameter space, with critical cases being confirmed by one of the 3-D codes.

These are all constructive techniques. When the calculations confirm that an equilibrium exists, they describe it. However, when the codes do not find an equilibrium, one cannot tell if there is no solution or if the construction technique has just failed to find solutions that exist.

Here, we report on recent efforts to improve the numerical techniques involved in obtaining axisymmetric equilibria using the stellarator expansion. The vacuum field plays an important role. We discuss several improvements in the representation for the vacuum field, starting from a Cartesian representation.

For the equilibrium calculation itself, we have traditionally used a Cartesian representation. Here, we propose an inverse method in which, given the desired Jacobian, one solves for the spectral representation of the coordinates

$$R = \sum_m [R_m^c(\rho) \cos m\theta + R_m^s(\rho) \sin m\theta] ,$$

and

$$Z = \sum_m [Z_m^s(\rho) \sin m\theta + Z_m^c(\rho) \cos m\theta] ,$$

where R and Z are Cartesian, ρ is a flux coordinate, and θ is a generalized poloidal angle. This approach is desirable because it can produce an accurate solution that is in a convenient form for input to a stability calculation using flux coordinates.

4.3.2.10 "Steepest-Descent-Moment Method for Three-Dimensional MHD Equilibria"¹¹⁸

S. P. Hirshman

J. C. Whitson

An energy principle is used to obtain the solution of the MHD equilibrium equation $\mathbf{J} \times \mathbf{B} - \nabla p = 0$ for nested magnetic flux surfaces that are expressed in the inverse coordinate representation $\mathbf{x} = \mathbf{x}(\rho, \theta, \zeta)$. Here, θ and ζ are poloidal and toroidal flux coordinate angles, respectively, and $p = p(\rho)$ labels a magnetic surface. Ordinary differential equations in ρ are obtained for the Fourier amplitudes (moments) in the doubly periodic spectral decomposition of $\mathbf{x}$. A steepest-descent iteration is developed for efficiently solving these nonlinear, coupled-moment equations. The existence of a positive-definite energy functional guarantees the monotonic convergence of this iteration toward an equilibrium solution (in the absence of magnetic island formation). A renormalization parameter λ is introduced to ensure the rapid convergence of the Fourier series for $\mathbf{x}$, while simultaneously satisfying the MHD requirement that magnetic field lines are straight in flux coordinates. A descent iteration is also developed for determining the self-consistent value for λ .

4.3.2.11 "Effect of Vertical Field Coils on the MHD Stability for the ATF-1 Device"¹¹⁹

V. E. Lynch

J. A. Holmes

B. A. Carreras

W. R. McKinney*

H. R. Hicks

The addition of vertical field coils to the ATF device gives great flexibility to the device. This allows changes to the vacuum rotational transform and the magnetic well depth. When the q profile is maintained below unity, changes to the magnetic well can affect

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strongly the stability of localized modes. We have investigated the stability of resulting equilibria to Mercier-type modes using the averaging method. Improved stability conditions are achieved when the averaged surfaces become strongly "bean" shaped.

4.3.3 Transport Theory—Abstracts

4.3.3.1 "Monte Carlo Calculations of Diffusion Coefficients in Stellarators"¹²⁰

R. H. Fowler

J. A. Rome

A Monte Carlo technique has been used to calculate diffusion coefficients in stellarators. Particles are pitch-angle and energy scattered along their drift orbits, which are computed in field-line coordinates. Diffusion coefficients are obtained as a function of the radial electric fields for a model field and for the actual ATF-1 configuration. Comparisons are made with the analytic theory of K. C. Shaing.

4.3.3.2 "Neoclassical Transport in a Multiple-Helicity Torsatron in the Low-Collisionality Regime"¹²¹

K. C. Shaing

In a recent paper, we have shown that a torsatron with multiple poloidal harmonics but only a single toroidal harmonic can be described by a simple model:

$$\frac{B}{B_0} = 1 + \epsilon_T + \epsilon_H \cos(\eta + \chi) , \quad (4.1)$$

where $\epsilon_T(r, \theta)$ and $\epsilon_H(r, \theta)$ are the effective toroidal and helical modulations, $\chi(r, \theta)$ is a phase angle, and $\eta = l\theta - m\phi$. We calculate the neoclassical transport coefficients based on this model in the low-collisionality regime ($\nu_{\text{eff}} < \omega_h$, the bounce frequency of helically trapped particles). In the strong electric field case ($\omega_E \gg \omega_D$, the magnetic drift frequency), besides the usual collisionless detrapping and boundary layer processes, a new effect arises due to the strong pitch-angle

dependence of the radial drift induced by $\partial\epsilon_H/\partial\theta \neq 0$. Thus, even deeply trapped particles can participate in the transport process. In the weak electric field case ($\omega_E < \omega_D$), the usual plateau and superbanana transport calculations are carried out for the model field Eq. (4.1). The optimization of the fluxes is performed in terms of the harmonics of ϵ_T and ϵ_H .

4.3.3.3 "Neoclassical Transport in a Multiple-Helicity Torsatron in the Low-Collisionality Regime—Strong Radial Electric Field Limit"¹²²

K. C. Shaing

Analytic expressions for neoclassical fluxes in a multiple-helicity torsatron are calculated in the strong radial electric field limit—where the poloidal $|\mathbf{E} \times \mathbf{B}|$ drift frequency ω_E is much larger than the poloidal ∇B drift frequency $\omega_{\nabla B}$. The expressions are valid in the collisional-frequency regime characterized by $\omega_E > \nu_{\text{eff}}$, the effective collisional frequency for helically trapped particles. Besides the usual collisionless detrapping and boundary layer processes, a new effect arises due to the strong pitch-angle dependence of the radial drift induced by $\partial\epsilon_H/\partial\theta \neq 0$, where ϵ_H is the effective helical modulation.

4.3.3.4 "Status of Neoclassical Transport Theory of Multiple-Helicity Stellarators"¹²³

K. C. Shaing

Previous stellarator transport calculations are based on either a single helicity or a conveniently assumed magnetic-field model. A realistic stellarator magnetic field has multiple helicities. The magnetic field of the ATF-1 torsatron can be modeled with multiple poloidal harmonics but only one toroidal harmonic. Assuming the rotational transform per field period is small, the adiabatic invariant J can be calculated. This allows us to calculate the fluxes in the low-collisionality regime

($\nu_{\text{eff}} < \omega_{bh}$, bounce frequency of helically trapped particles). In the regime $\omega_{bh} > \nu_{\text{eff}} > \omega_d$ (poloidal drift frequency of helically trapped particles), we obtain the usual $1/\nu$ flux, but with a correction (up to ten times) due to multiple helicity. In the regime $\nu_{\text{eff}} < \omega_{bh}$, we adopt the strong $|\mathbf{E}|$ field assumption valid if $|e\Phi| \gtrsim |T|$. Assuming that all the toroidally trapped particles will be trapped in a helical well in a time shorter than the drift time, the Galeev-Sagdeev scaling law obtains. In the strong $|\mathbf{E}|$ limit, the flux is much smaller than the flux caused by the superbanana orbits in the zero $|\mathbf{E}|$ limit, because the large $|\mathbf{E} \times \mathbf{B}|$ drift reduces the size of the orbits. To study implications of the $|\mathbf{E}|$ field, we adopt the usual results for a single-helicity stellarator and construct a formula for the particle flux valid for $\nu_{\text{eff}} < \omega_{bh}$. This formula compares favorably with Monte Carlo calculations. For some temperature ranges, there are several values of $|\mathbf{E}|$ for which the electron and ion particle fluxes are equal. Usually, one root confines electrons, one confines ions, and the third is unstable. On the ion root, the electric field decreases as T increases; on the electron root, it remains high. Thus, it is preferable to be on the electron root, and strong electron heating may improve confinement.

4.3.3.5 "Transport Associated with Collisionless Detrapping/Retrapping in a Non-axisymmetric Torus"¹²⁴

K. C. Shaing

Recent transport studies in the low collisionality regime in a stellarator have yielded two different scalings associated with the collisionless detrapping/retrapping processes. We find that the fundamental difference in these two scalings results from the assumption of the retrapping rate of the toroidally trapped (banana) particles. If this retrapping rate is faster than the poloidal drift frequency of the helically trapped particles, we obtain the scaling of Galeev and Sagdeev (1969). Otherwise, we obtain the scaling of Kovryzhnykh (1982). We further note that the singularity that leads

to the $\nu^{3/4}$ scaling of Kovryzhnykh is due to the local minimum of the helical well depth. However, we observe that this local minimum can only change the topology of the particle orbits without increasing the radial step size, contrary to his implicit claim. With this observation, we obtain a scaling that is proportional to ν instead of $\nu^{3/4}$. Similar phenomena in a rippled tokamak are discussed.

4.3.3.6 "Viscosity-Driven Impurity Transport in a Stellarator"¹²⁵

K. C. Shaing

The viscosity-driven impurity transport in a stellarator in the $1/\nu$ and collisionless detrapping regimes is calculated. It is found that the impurity flux tends to go inward radially if all the species are in the $1/\nu$ regime and tends to go outward if all the species are in the collisionless detrapping regime.

4.3.3.7 "Neoclassical Flows and Transport in Nonaxisymmetric Toroidal Plasmas"¹²⁶

K. C. Shaing

J. D. Callen

The moment equation approach to neoclassical transport theory has been generalized to nonaxisymmetric toroidal systems under the assumption of the existence of magnetic surfaces. In particular, the parallel plasma flows and bootstrap current are calculated in both the Pfirsch-Schlüter and banana regimes. It is found that both parallel plasma flows and the bootstrap current can be reduced as the toroidal bumpiness increases in an otherwise axisymmetric system.

4.3.3.8 "Neoclassical Transport in a Multiple-Helicity Torsatron in the Low Collisionality ($1/\nu$) Regime"¹²⁷

K. C. Shaing

S. A. Hokin*

For a sufficiently high number of field periods ($m/\iota > \ell$), the magnetic field of a

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multiple-helicity torsatron can be reduced to a simple form such that the second adiabatic invariant J can be calculated. It is found that the particle and the heat fluxes for a multiple-helicity torsatron in the low collisionality ($1/\nu$) regime have the same geometric dependences. An optimization of both quantities is carried out for a given equilibrium constraint. It is shown that the transport fluxes can be smaller than those of the conventional stellarator by an order of magnitude. The effect of finite plasma beta on the neoclassical fluxes is also studied.

4.3.3.9 "Transport Associated with the Collisionless Detrapping/Retrapping Orbits in a Nonaxisymmetric Torus"¹²⁸

K. C. Shaing
J. A. Rome

R. H. Fowler

The differences among the various scalings in the transport calculations associated with the collisionless detrapping/retrapping orbits in a nonaxisymmetric torus are clarified. A simple random walk argument indicates that these differences are mainly due to an implicit assumption made about the retrapping rate of the toroidally trapped particles.

4.3.3.10 "A Fluid Approach to Radial Transport in a Tandem Mirror"¹²⁹

K. D. Siebert*
J. D. Callen

K. C. Shaing

The nonaxisymmetry of the tandem mirror geometry can lead to particle drift orbits similar to the superbanana orbits of toroidal confinement devices. This results in enhanced cross-field transport. The fluid or moment equation approach to neoclassical transport in toroidally axisymmetric systems developed by Hirshman and Sigmar, as well as an extension of this work to nonaxisymmetric toroidal sys-

tems by Shaing and Callen, is being further extended to determine flow and transport properties of tandem mirrors. Developments to date are presented.

4.3.4 Transport Simulation—Abstracts

4.3.4.1 *Neutral Beam Heating in Stellarators: A Numerical Approach*¹³⁰

S. A. Hokin*
J. A. Rome

T. C. Hender
R. H. Fowler

Calculation of neutral beam deposition and heating in stellarators is complicated by the twisty stellarator geometry and by the usual beam focusing, divergence, and cross-sectional shape considerations. A new deposition code has been written that takes all of this geometry into account. A unique feature of this code is that it gives particle deposition in field-line coordinates, enabling the thermalization problem to be solved more efficiently.

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4.3.4.2 "Stellarator Transport Modeling in the Collisionless Ion Regime"¹³¹

W. A. Houlberg

K. C. Shaing

Fluid models for electron and ion particle and heat flow are incorporated into a 1-D time-dependent transport code for stellarators and applied to present and near-term devices. The expressions for the electron and ion particle fluxes, valid in both the high and low collisionality regimes, are used to determine the self-consistent radial electric field through an ambipolarity constraint. In the collisionless-ion, collisional-electron regime, the transport becomes dominated by electrons. The transition from ion-dominated losses to electron-dominated losses causes a reversal of the self-consistent radial electric field and produces resonant losses. The transition and resonant-loss process should be accessible in both the Heliotron-E and ATF-1 experiments with low magnetic fields and densities.

*The University of Wisconsin, Madison.

4.3.4.3 "Stellarator Transport Modeling"¹³²

W. A. Houlberg
J. F. Lyon*

K. C. Shaing

A number of issues related to transport modeling in existing and planned stellarator experiments are addressed. Of particular importance is the transition from an intermediate collisionality regime in which transport coefficients scale as ν^{-1} to the low-collisionality regime where the scaling changes to ν . This transition is shown to occur at relatively high collision frequencies ($\nu_i = \nu_i/\epsilon\omega_b \approx 10$) and should thus be observable in some existing and planned experiments. Once the transition to the low collisionality regime occurs, electron losses are shown to be a dominant factor in determining the radial electric field, $E_r = -\phi'$, and net confinement properties. Algebraic equations for ϕ' yield multiple roots. Analysis of these roots shows that a single root cannot generally be guaranteed to exist at all plasma radii, even with a modest range of plasma parameters. Thus, the algebraic model leads to discontinuous jumps in the radial field. A differential equation must then be developed for ϕ' to provide continuous solutions and thereby smoothly connect the electron-loss-dominated regime to the ion-loss-dominated regime.

*Tokamak Experimental Section.

4.4 COMPUTING SUPPORT

The computing support group provides the FED with computing resources in two areas: operation of the User Service Center (USC) and development of the experimental data acquisition network. The USC provides (1) access to the large computing systems at NMFECC at the Lawrence Livermore National Laboratory (LLNL) and (2) immediate analysis and storage of experimental data. The data-handling network supports the division's experimental efforts by providing a rapid, state-of-the-art means of acquiring and storing experimental data.

4.4.1 USC Operations

H. E. Ketterer
D. N. Clark

J. V. Hughes
G. B. Wootton

During 1983, several additional terminals were procured to provide the division staff with better access to the USC. A DCA355 network processor was added to the system to provide additional terminal ports. This network processor is connected to several of the experimental area computers, as well as the USC PDP-10 and the ORNL (X-10) central network processor. Thus, any terminal connected to the DCA355 can select from among these systems without the need to run additional lines.

A DN20 front-end processor was added to the USC to augment file transfers from the experimental data acquisition computers. This processor uses DECnet (Digital Equipment Corporation's network) software to provide these transfers via 1-megabyte/s links.

Memory was upgraded from 1-megaword core to 1.5-megaword solid state. Two 500-megabyte RP07 disk systems were added. One provides storage for general user data and programs; the other provides storage for the Large Coil Program (LCP) data. A new controller was installed to permit the use of two Versatec V80 printer/plotters directly from the PDP-10. The computer room itself was expanded from 111.5 to 223 m³ (1200 to 2400 ft²).

Software additions to the system during 1983 included:

- VDRIVE—a program that allows generation of high-quality textual output (including alternate character sets, such as Greek and mathematics symbols) on a Versatec printer/plotter
- NCP CALC—a computer spreadsheet
- Tell-A-Graf—an interactive front end to DISSPLA, providing easy generation of graphics output
- KERMIT—a method for transferring files to or from a CP/M-based personal computer and the DECsystem-10

This site became a field test site for Version 7.02 of the TOPS-10 operating system in March 1983. This is the latest version of the

operating system and is required to run DECnet. This version will be released to the general public in April 1984.

4.4.2 "Overcoming Computer Shock"—Abstract¹³³

D. N. Clark

Many people who know nothing about computers will soon need to use them in their everyday tasks. The experience of learning to use computers can be traumatic for these people and, depending upon the way in which they are taught by computer professionals, can cause them to accept or reject computer use entirely. This paper examines some commonly overlooked problems that computer professionals encounter when trying to teach these people and offers some suggestions for making the transition to computers a pleasant and effective process.

4.4.3 Experiment Support

The Experiment Support organization within Computing Support provides service to the experimental groups within the division. Those services include:

1. anticipating the needs of each experimental group,
2. specifying those needs, and
3. resolving those needs via hardware acquisition, software acquisition, and software development.

This section summarizes the activities of the EBT and ISX computing support groups during 1983. Other significant activities are reported in Chaps. 1 and 2.

4.4.3.1 EBT experiment support

R. D. Burris
J. E. Francis, Jr.
S. R. Maddox
J. B. Mankin

D. R. Overbey
B. G. Peterson
C. E. Schmid
K. G. Young

The major effort during the year in the EBT support effort was the introduction of a VAX-

11/780 computer into the support environment. This new computer enabled us to make extensive improvements in the Experiment Coordinator (EC) interface and provide much more extensive and rapid support of diagnostics that investigate transient phenomena. It also allowed us to move support of some diagnostics from overcrowded PDP-11 computers to the VAX. As a result, there are no hardware or processing bottlenecks in EBT computing support. Figure 4.5 shows the current EBT computer configuration.

Fig. 4.5. Current EBT computer configuration.

Two major new software systems on EBT have resulted in qualitative changes in the operation of the device. One, the generalized diagnostic system, allows full support of most diagnostic requirements in minutes, including data acquisition, preliminary plotting, and archiving on the division DEC-i0. The second development was the XY plot system in which any datum acquired by the background sampling program (which includes all machine condition parameters, such as magnetic field, power, density, and pressure, as well as a few temporary signals) may be plotted as the independent variable and any other one or two such data plotted as the dependent variable. This plotting occurs in real time, so experiments that used to take hours or days may now be performed in minutes.

In addition to the work mentioned above, considerable efforts were directed to diagnostic

support. During the year, ten diagnostic systems were newly developed or underwent major modifications, while eight additional systems received significant evolutionary attention.

Finally, we made many major improvements in support systems, notably the graphics, translation, and data base systems. The functionality of the graphics and translation systems was greatly improved, and they were also supported on the VAX. The performance of the data-base system was considerably improved, and it was also implemented on the VAX system for the support of diagnostic systems that reside only there.

4.4.3.2 ISX experiment support

W. R. Wing*	B. G. Peterson
J. D. Bell	J. R. Reagan
E. T. Blair	C. R. Stewart, Jr.
D. E. Greenwood	K. A. Stewart
K. L. Kannan	

The majority of significant projects accomplished this year for ISX were directly related to operations on VAX computer systems. Those accomplishments may be divided into four areas: torus control, new diagnostics, converted diagnostics, and support systems.

This year it became possible for the responsible physicist to control the torus gas-puff system from a time-sharing VAX. In this system, waveforms are used to control the gas feed system. Those waveforms may be manipulated in either tabular or graphic form, saved and later recalled, etc., all in interactive mode. This capability will be extensively used on the ATF.

There were two major diagnostics developed during the year. One supports residual gas analysis (RGA) diagnosis. The other, perhaps the most demanding code being run for ISX, supports the heavy ion beam probe (HIBP) diagnostic. This system acquires and analyzes 200,000 words of data for every shot (as

opposed to other diagnostics which, while acquiring more data, do so for only occasional shots).

Many diagnostic systems were converted from older computers to the VAX, including laser fluorescence, infrared camera, charge exchange, and Thomson scattering. These conversions, especially Thomson scattering, allow much more data analysis between shots and have permitted significant changes in the way the torus is operated.

There were several support systems developed or completed during the year. The SAMS synchronization software system, which permits user codes to synchronize with the shot cycle, was completed and put into operation. Code permitting the transfer of files from VAX systems to the DEC-10 was completed. Finally, as a spinoff of that code, a capability for a VAX program to retrieve data from DEC-10 files was implemented and used extensively for HIBP analysis.

4.4.3.3 The Computer Data Acquisition and Control System for Thomson Scattering Measurements—Abstract¹³⁴

K. A. Stewart	E. A. Lazarus†
R. D. Foskett*	C. E. Thomas†
R. R. Kindsfather†	

The Thomson Scattering Diagnostic System (SCATPAK II) used to measure the electron temperature and density in the ISX is interfaced to a Perkin-Elmer 8/32 computer that operates under the OS/32 operating system. The calibration, alignment, and operation of this diagnostic are all under computer control. Data acquired from 106 photomultiplier tubes installed on 15 spectrometers are transmitted to the computer by eighteen 12-channel, analog-to-digital integrators along a CAMAC serial highway. With each laser pulse, 212

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channels of data are acquired: 106 channels of signal plus background and 106 channels of background only. Extensive use of CAMAC instrumentation enables large amounts of data to be acquired and control processes to be performed in a time-dependent environment. The

Thomson scattering computer system currently operates in three modes: user interaction and control, data acquisition and transmission, and data analysis. This paper discusses the development and implementation of this system, as well as data storage and retrieval.

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Chapter 5

Plasma-Materials Interactions

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5. PLASMA-MATERIALS INTERACTIONS

Summary of Activities

The Plasma-Materials Interactions Program addresses issues related to the interaction between the fusion plasma and surrounding material surfaces. Consideration of plasma-materials interactions will dominate materials-selection and impurity-control strategies for the next-generation, long-pulse, tritium-burning experiments. Specific issues include erosion and impurity control, particle handling and tritium inventory, and high-heat-flux component survivability. The ORNL program includes extensive characterization of edge plasmas and surface conditions in fusion devices, in situ observation of erosion and hydrogen recycling, development of advanced wall-conditioning and particle-control concepts, and laboratory studies of related phenomena. The program focuses on research at major fusion installations—including the Impurity Study Experiment (ISX-B), the TEXTOR and ASDEX tokamaks in the Federal Republic of Germany (FRG), and the Joint European Torus (JET)—and includes participation of the ORNL Fusion Energy, Metals and Ceramics, and Solid State divisions.

During 1983 the program emphasized limiter and divertor erosion studies in ISX-B and ASDEX, edge-characterization and wall-conditioning experiments in TEXTOR and JET, particle control with pump limiters in ISX-B (a collaboration with the Tokamak Experimental Section), advanced gettering development, and graphite erosion studies at high temperatures. Laser-induced fluorescence (LIF) was used to monitor iron release from wall and limiter-like probes during ISX-B discharges. An isotopic marker technique was used to measure carbon and impurity erosion/deposition for graphite probes in the ASDEX divertor. Surface-carburization experiments in TEXTOR and JET resulted in dramatic decreases in low-Z impurities. Fundamental performance data were obtained for chromium and zirconium-aluminum getter pumps. Laboratory sputtering experiments established the threshold energy, activation energy, and nuclear-stopping dependence of the radiation-enhanced sublimation of graphite. Details of these and other experiments are given in the following pages.

5.1 EROSION MEASUREMENTS AT WALL AND LIMITER-LIKE POSITIONS IN ISX-B USING LASER-INDUCED FLUORESCENCE

P. W. King

T. B. Cook

The LIF installation on ISX-B has been used to study metal atom release from the wall and from limiter-like probes during ohmic and beam-heated discharges. Measurements of the

production and ionization of metallic impurities from the first wall of the tokamak were performed for a variety of plasma conditions—both for iron from the vacuum vessel and for titanium deposited during gettering. For these measurements, the pulsed laser beam was introduced into the tokamak at the mid-plane along a major radius. Ohmic discharges produce few impurities from the wall, typically $<10^{12}$ atoms·cm⁻²·s⁻¹, while beam-heated

discharges result in release rates approximately an order of magnitude higher. From the decrease of neutral-metal density as a function of distance from the wall, an ionization length on the order of 4 cm was deduced¹ for neutral atoms at a distance of 2 cm from the wall for moderate-density, beam-heated discharges. Assuming particle release by sputtering, this result is in approximate agreement with predictions based on Langmuir probe measurements of edge density and temperature.

Measurements were also initiated to study erosion of limiter-like probes in the plasma edge. For these experiments, the laser beam passed on the ion side near the surface of a stainless steel reference limiter positioned 2 cm outside the mushroom-limiter radius. Neutral ion atoms released from the face of the reference limiter during ohmic discharges were detected from the induced fluorescence. Preliminary time-resolved erosion results are shown in Fig. 5.1. Large removal rates are seen during the ramp-up and near the end of the shot. During the quiescent portion (i.e., from 100 to 200 ms), erosion rates are found

Fig. 5.1. Time-resolved erosion rate for a stainless steel limiter-like probe exposed to ohmic deuterium plasmas in ISX-B.

to be on the order of a monolayer per second. This result is in good agreement with yields expected for the ion flux inferred from Langmuir probe measurements performed on the same flux surface. Ionization lengths for these particles were also measured by moving the probe relative to the laser beam and were typically in the range of 0.35 to 0.5 cm during the quiescent phase of the shot. Figure 5.2 shows the decrease in atom density with distance at 250 ms into the tokamak shot. Excellent agreement is found with calculated ionization lengths based on Langmuir probe measurements of electron density and temperature, assuming the erosion is due to sputtering by the working gas.

Fig. 5.2. Decrease in neutral iron density as a function of distance from a stainless steel limiter-like probe in ISX-B.

Overall, these results establish the usefulness of LIF for time-resolved measurements of impurity densities, ionization lengths, and erosion near limiter and first-wall surfaces during tokamak discharges. The erosion rates deduced from these experiments would correspond to a steady-state material loss of approximately 0.1 mm/year at the wall and 1 cm/year at the limiter.

5.2 CHARACTERIZATION OF DEUTERIUM AND IMPURITY FLUXES IN THE TEXTOR PLASMA EDGE USING DEPOSITION PROBE TECHNIQUES²

R. A. Zuhr

Deposition probe techniques have proven an effective method of studying the plasma-edge region of magnetic-confinement fusion devices.³ In the present work, these techniques have been used to characterize the scrape-off layer of the TEXTOR tokamak at Kernforschungsanlage (KFA) in Jülich, FRG. These experiments are performed as part of the U.S. participation in plasma-wall interaction experiments on TEXTOR, as outlined in the International Energy Agency (IEA) Implementing Agreement.

Deposition probe exposures using carbon (Papyex) and single-crystal silicon collectors were made along a major radius in the horizontal midplane of TEXTOR about 19° in the ion drift direction from the main outside limiter. The insertion and positioning of the probe were microprocessor controlled with complete electrical isolation, using optical couplers, between the tokamak and the diagnostic area. Exposures were made as functions of radius and direction. Time-resolved measurements were made by electrically rotating a cylindrical sample behind a fixed slot. All exposures were made with the probe at floating potential. After exposure, the samples were transferred in air to an accelerator facility for analysis. Rutherford ion backscattering (RBS) with 2.0-MeV ^4He was used for impurity detection, while elastic recoil detection (ERD) with 1.75-MeV ^4He at 30° and nuclear reaction analysis (NRA) with the $\text{D}(^3\text{He},\text{p})^4\text{He}$ reaction were used for the hydrogen isotopes. Typical operating parameters during the present investigations were: toroidal field, $B_t = 2$ T; toroidal current, $I_p = 300$ kA; and average electron density, $\bar{n}_e = 2 \times 10^{13} \text{ cm}^{-3}$.

Time-resolved deuterium deposition rates were measured with a time resolution of

± 150 ms using the rotating system previously described. The results are plotted in Fig. 5.3, along with independent measurements of the loop voltage V , the plasma current I_p , and the average electron density $\bar{n}_e$, for exposures to two different sets of deuterium discharges. The upper deuterium curve (Fig. 5.3) presents the flux deposited on a carbon probe exposed in the ion direction to three discharges that are typified by the voltage, current, and density traces above it. These discharges last 2.5 s and show minimal disruptive activity, as demonstrated by the constant loop voltage. After the initial peak, which has been observed

Fig. 5.3. Time-resolved D retention rate is compared with loop voltage V , plasma current I_p , and average electron density $\bar{n}_e$, for two different discharge types in TEXTOR.

during startup in the scrape-off layer of many machines,³ the retained flux is low and steady, indicating a stable, centered plasma that is not interacting strongly with the limiters. These discharges also show the lowest levels of metallic impurities in the plasma edge.

The lower half of Fig. 5.3 shows the deuterium retained on samples exposed in the electron direction to five discharges, two of them as just described and three as typified by the lower set of voltage and current curves. Here the discharges become disruptive, as evidenced by spikes in the loop voltage, and terminate in less than 1 s. The disruptive behavior results in increased deuterium flux to the probe from 0.5 to 1 s. Substantially higher metallic impurity levels are also observed for this type of discharge.

A number of exposures were made to determine the trapping or saturation behavior of hydrogen and deuterium in the probe material. Such data can be used to estimate the flux and energy of the incident particles. At 3 to 7 cm outside the limiter radius, the incident deuterium fluence was estimated at $1\text{--}1.5 \times 10^{16} \text{ cm}^{-2}$ per discharge, with a Maxwellian energy distribution and $kT = 100 \text{ eV}$. The principal impurities in the edge were found to be carbon, oxygen, iron, nickel, and chromium. Fluxes deposited on the probe were on the order of $10^{15} \text{ cm}^{-2}\cdot\text{s}$ for carbon and oxygen and $1\text{--}5 \times 10^{14} \text{ cm}^{-2}\cdot\text{s}$ for the total of the transition metals. Iron was the dominant metal, showing an approximate ratio of 4:2:1 to nickel and chromium. The radial dependence was found to be relatively flat from 3 to 5.5 cm outside the limiter radius with a peaking, especially of the metallic impurities, near the liner. This peaking shows an e-folding length of $\sim 1.2 \text{ cm}$ and is believed to be due to the ionization of metallic neutrals from the liner located 10 cm behind the limiter. Accumulation of impurities in the plasma edge was not observed during long (2.5-s) ohmic discharges in TEXTOR.

Measurements were also made of the in situ erosion rate of a 2.5-nm gold film deposited on a polished silicon substrate. The film thickness

was measured before and after exposure to the plasma using RBS. Erosion rates in TEXTOR for samples perpendicular to the magnetic field in the ion drift direction were close to the limits of detection in both hydrogen and deuterium plasmas, making accurate measurements difficult. However, the average erosion rate for radii between 3 and 7 cm behind the limiter was $\sim 5 \times 10^{13} \text{ atoms}\cdot\text{cm}^{-2}\cdot\text{s}$, and an upper limit on erosion of $10^{14} \text{ cm}^{-2}\cdot\text{s}$ during normal discharges can be assigned.

5.3 USE OF ISOTOPICALLY ENRICHED CARBON PROBES FOR EROSION/DEPOSITION MEASUREMENTS IN THE ASDEX DIVERTOR

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O. W. Holland†

An isotopic marker technique has been developed and used to measure near-surface erosion and carbon and impurity deposition on carbon samples exposed in the ASDEX divertor chamber. Papyex graphite samples were enriched to $\sim 20\%$ ^{13}C over the first 1000 Å by ion implantation. The implanted ^{13}C can be clearly distinguished from ^{12}C of the host by RBS using 2.7-MeV ^4He . Carbon erosion and deposition can be determined from changes in the depth distribution of the ^{13}C while impurity accumulation is simultaneously monitored in the backscattering spectrum. Laboratory experiments have demonstrated the stability of the ^{13}C distribution under severe thermal conditions, including low-energy hydrogen bombardment at temperatures above 1800 K. Other experiments have demonstrated the usefulness of the probes in sputtering, ion-mixing, and self-diffusion studies.

In ASDEX, the ^{13}C -enriched probes intercepted a cross section of the diverted flux in front of the upper divertor plate. Both integrated and time-resolved exposures were

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made for plasmas with neutral injection or lower hybrid auxiliary heating. Profiles of ^{13}C remained sharp in spite of high heat fluxes to the samples (sufficient to melt stainless steel) and showed clear evidence of simultaneous erosion and deposition of carbon and impurities.

Time-resolved results for diverted discharges with 2.4-MW neutral injection are shown in Fig. 5.4. These data are for a carbon sample that was rotated behind a slit facing the diverted flux at the center of the upper divertor throat. Prior to the onset of neutral injection, net deposition of both carbon and heavy impurities was observed. During injection, net carbon erosion increased dramatically to exceed $250 \text{ \AA/s}$. The carbon erosion persists well beyond the neutral injection period in spite of significant iron and titanium impurity accumulation on the sample. These results are for the

highest flux region in the ASDEX divertor ($\sim 10^{19} \text{ D}\cdot\text{cm}^{-2}\cdot\text{s}$) and suggest that erosion is much larger than impurity deposition under high-power conditions in the divertor throat. The results also demonstrate the applicability of the ^{13}C technique for erosion/deposition experiments at high-heat-flux surfaces such as a limiter or divertor plate.

5.4 WALL-CONDITIONING STUDIES ON THE TEXTOR AND JET TOKAMAKS

R. E. Clausing

L. Heatherly

During the past year, a significant series of collaborative experiments has been carried out on the cleaning and conditioning of the walls and surfaces facing the plasmas in TEXTOR and JET. ORNL provided the equipment and personnel for surface analysis and participated in the day-to-day planning of the "cleaning" or conditioning operations. Radio-frequency (rf)-assisted glow discharges in hydrogen were used in both cases. The walls were heated to temperatures above 150°C . The TEXTOR liner is Inconel 625, while the JET wall is Inconel 600.

The rate of removal of oxygen as water vapor from TEXTOR was initially about 200 atom layers per hour, slowing to $1/e$ of the original value in 1 h. This permitted tokamak discharges after 1 h and good plasma conditions after two nights of cleaning. Oxygen surface concentrations of 10 to 14 at. % were obtained. Previous studies^{4,5} suggested that the purposeful addition of carbon to the walls should reduce the levels of oxygen even further. This was tried and proven effective not only in removing oxygen to less than 8 at. %, but also in speeding hydrogen recycling rates by a factor of 10 (refs. 6-9). Plasma parameters were improved and oxygen impurities reduced during the entire cleaning campaign, but the most dramatic improvements were the result of the carbon treatment.

The same techniques were used very successfully at JET during the startup period in July

Fig. 5.4. Time-resolved carbon erosion and deposition and impurity accumulation for a carbon probe exposed in the ASDEX divertor throat for ten discharges with 2.4-MW neutral injection.

1983. Oxygen levels were reduced below 10 at. % by glow-discharge cleaning in hydrogen with the walls at elevated temperatures, but a vacuum leak caused hydrocarbons, oxygen, and other impurities to increase again. The addition of carbon in the form of methane to the glow discharge produced a thin layer of carbon on the wall and completely eliminated other impurities. This led to the first high-current discharges (600 kA) not limited by impurity radiation. Figure 5.5 shows the dramatic effect of carbon (July 22 analysis) in reducing the surface concentration of other light elements.

The results of these studies follow.

1. Glow-discharge cleaning combined with wall temperatures above 150°C can produce very effective wall conditioning.
2. There is surface site competition among light impurities that leads to the possibil-

ity of replacing the less desirable ones with carbon.

3. Replacement of oxygen, sulfur, nitrogen, and chlorine with carbon was accomplished successfully in JET.
4. Optical spectroscopy of tokamak plasmas confirmed that impurities in the plasma follow those on the wall (e.g., when surface oxygen decreased, so did plasma oxygen, and when chlorine became a major surface impurity in JET, it also became a major plasma impurity). Improvements in wall conditions generally led to improvements in plasma parameters.
5. Surfaces cleaned by the carbon treatment tended to have very fast hydrogen-recycle rates and apparently led to plasmas with better overall properties in both TEXTOR and JET.

Fig. 5.5. Surface composition changes during the initial cleanup of JET using an rf-assisted hydrogen glow discharge. Baking and discharge cleaning conditions were gradually improved during the time shown. Methane was added to the glow discharge prior to the July 22 analysis only.

5.5 CHROMIUM GETTERING DEVELOPMENT

J. E. Simpkins
P. K. Mioduszewski

L. C. Emerson

Chromium gettering has been suggested as an alternate to titanium in fusion experiments.¹⁰ The main advantage is that the pumping capacity of chromium for hydrogen is only about one monolayer adsorbed on the surface without any evidence of bulk diffusion, whereas titanium pumps large quantities of hydrogen by surface adsorption and subsequent bulk diffusion.¹¹ This precludes the use of titanium gettering in fusion experiments involving tritium operation, because the tritium inventory must be minimized.

To investigate the performance of chromium as a getter in the tokamak environment, it was necessary to develop a suitable large-scale chromium sublimation source.¹² This new source resembles in appearance the Varian Ti-BallTM and consists of a hollow chromium cylinder with hemispherical ends (approximately 3 cm in diameter and 4 cm in length) and an incandescent filament for radiation heating from inside the ball. Since the surface geometry of the Cr-ball so closely resembles the Ti-ball, the conventional sublimation source in ISX, surface coverage in the tokamak should be very similar.

Measurements at various temperatures and corresponding sublimation rates were made on the Cr-ball and compared to the corresponding Ti-ball data, which served as a baseline. From these measurements, the sublimation rate R_{subl} as a function of temperature was computed (shown in Fig. 5.6). The input power required to achieve a given sublimation rate is somewhat lower for chromium than for titanium. The titanium sublimation rate during the gettering cycle in ISX is typically 10^{16} atoms·cm⁻²·s, which is easily obtained with the Cr-ball.

Fig. 5.6. Measured sublimation rates (atoms·cm⁻²·s) as a function of temperature for chromium and titanium. Solid lines were calculated from vapor pressure curves. The data represented by triangles were obtained by setting the Varian Ti-ball power supply at 0.1 g/hr.

5.6 PERFORMANCE OF Zr-Al GETTER PUMPS UNDER TRANSIENT LOAD CONDITIONS

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J. E. Simpkins

A number of features of commercially available Zr-Al getter pumps* make them particularly attractive for application in hydrogen-plasma devices, and chief among them is their ability to pump the hydrogen isotopes reversibly and the common gaseous plasma impurities irreversibly. This attribute will take on

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added importance during fueling operations in the next generation of tokamak devices in which large quantities of tritium will be involved. Another feature of these pumps is the nonevaporable getter material that allows the pumps to be used near viewports and near sensitive diagnostics that would be affected by coatings and/or flaking of foreign material.

These features, combined with the high pumping speed and small physical size, have made this getter pump attractive for use in the pump-limiter experiments on ISX-B.¹³ Prior to the installation of the limiter modules on ISX-B, a series of laboratory experiments was carried out to determine the operating characteristics of the getter pumps under the transient load conditions anticipated in the tokamak. The pumps were mounted in a well-instrumented vacuum chamber into which gas was introduced by means of a piezo valve that was opened by a single, square voltage pulse variable in both amplitude and width. Prior to pump activation, the throughput of the valve was measured for hydrogen and carbon monoxide as a function of both the manifold pressure and the magnitude of the voltage pulse.

The pumps were then heated from room temperature in 50°C increments, during which hydrogen and carbon monoxide were introduced to the chamber and the pumping speed was measured. The results are shown in Fig. 5.7. No pumping was observed until a pump temperature of 400°C was reached. From that temperature, the pumping speed for both gases increased monotonically with increasing temperature until the maximum temperature of 750°C was reached, at which pumping speeds of 1890 and 480 L/s were measured for hydrogen and carbon monoxide, respectively. At this point, the pumps had a total gas load of 18.3 torr·L of hydrogen and 4.5 torr·L of carbon monoxide. Following this, the pump temperature was lowered to the normal operating temperature of 400°C, and the measured speeds were observed to drop as indicated by the dashed curves in Fig. 5.7. The duration of the gas puffs throughout this test was initially 100 ms and was increased to

Fig. 5.7. Pumping speed for H₂ and CO vs temperature for an initially deactivated Zr-Al getter panel.

200 ms as the pumping speeds increased. Maximum gas pressures observed in the pumping chamber did not exceed 16 mtorr after the pump was activated, although pressures higher by an order of magnitude were observed before activation in which the pumping speeds were greatly reduced.

From the earlier data, it was possible to evaluate the performance of the pump under various transient gas loads. This would be typical of the performance expected during

tokamak operation, since the gas puff necessary to maintain the plasma density falls within the range of this data. The results indicated an essentially constant pumping speed for hydrogen as a function of the throughput up to levels of 13 torr-L/s.

5.7 ENHANCED SPUTTERING OF GRAPHITE AT HIGH TEMPERATURE¹⁴

J. Roth
J. B. Roberto

K. L. Wilson*

Recent measurements¹⁵⁻¹⁷ of the sputtering yield of graphite under kiloelectron-volt ion bombardment have revealed an enhanced erosion above 1000 K, which increases to 10 to 20 times the room-temperature value at 2000 K. This enhanced erosion occurs for a variety of incident ion species and is not associated with the release of volatile compounds characteristic of the reactive or chemical sputtering of graphite under hydrogen bombardment at 700–1000 K. The resulting high erosion rates seriously limit the usefulness of graphite as a high-temperature, plasma-side material in fusion reactors. In ref. 14, we report measurements of sputtering yield for H, C, O, and Ar ions at various energies between 0.13 and 150 keV on graphite targets at temperatures ranging from 300 to 1800 K. The results are compared with calculations of elastic and inelastic energy losses for the various incident conditions and with possible models for the enhanced erosion process.

The erosion measurements were performed using 35- to 150-keV H, C, O, and Ar ions from an ion-implantation accelerator at ORNL and 0.13- to 8-keV hydrogen ions from a high-current ion source at the Max-Planck-Institut (FRG). Papyex graphite samples approximately $4 \times 20 \times 0.5 \text{ mm}^3$ were mounted on electrical leads in a vacuum chamber and

heated resistively. Sample temperature was monitored using an optical pyrometer with an absolute accuracy of $\sim 20^\circ\text{C}$ and a relative reproducibility of $< 10^\circ\text{C}$. Relative erosion yields were determined in situ from the analysis of carbon atoms collected on silicon catches in front of the sample, using resonant backscattering of 1.75-MeV hydrogen ions from a Van de Graaff accelerator. Absolute erosion yields were determined from the weight change of the samples.

In Fig. 5.8, erosion yields are plotted against inverse temperature for incident Ar, O, C, He, and H ions. These data are consistent with activation energies for the enhanced erosion process that vary from 0.5 eV for heavy ions to 1.1 eV for low-energy light ions. Such activation energies would lead to significant thermal evaporation at temperatures well below 1000 K, assuming normal pre-exponential factors. This suggests that additional steps

Fig. 5.8. Graphite erosion yields vs inverse temperature for several incident ion-energy combinations. Arrhenius plots and activation energies derived from subtracting the room temperature yields are also shown.

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may be involved in the erosion process. (For comparison, the activation energy for ordinary thermal sublimation of graphite is ~ 8 eV.) The data of Fig. 5.8 scale linearly with the nuclear deposited energy over a wide range of incident particle masses and energies, suggesting a collisional contribution to the enhanced erosion. There is no correlation between the enhanced erosion yields and inelastic energy losses.

The threshold behavior of the erosion yield at 1800 K is indicated in Fig. 5.9 for incident hydrogen ions. The solid and dashed curves in Fig. 5.9 are TRIM calculations of the nuclear deposited energy at the surface for the incident conditions, assuming a 5- and 30-eV displacement threshold, respectively. Also shown in the figure are similar data and calculations for argon, carbon, and deuterium ions on graphite. All of the energy-dependent data scale approximately with the deposited energy. The low-energy hydrogen measurements clearly suggest that the enhanced erosion process is char-

acterized by a displacement threshold near 5 eV, comparable to the threshold for room-temperature sputtering of graphite. This is much lower than the generally accepted displacement threshold energy in bulk graphite of 30 eV, which suggests the formation of a surface defect with a much lower threshold energy than would be characteristic of bulk interstitials.

In summary, the enhanced erosion of graphite above 1000 K has been investigated for a wide variety of incident ion masses and energies. Erosion yields up to 20 times room-temperature values have been observed at 1800 K. The results clearly indicate a collisional origin for the erosion with a transferred energy threshold near 5 eV. The temperature dependence of the erosion process is characterized by an activation energy of 0.5 to 1.1 eV. These results, taken together with earlier measurements, suggest a radiation-enhanced sublimation mechanism.

Fig. 5.9. Energy dependence of the erosion yield and the calculated nuclear deposited energy for H, D, C, and Ar on graphite at 1800 K. The deposited energy curve most closely reproduces the low-energy data for a 5-eV transferred energy threshold.

5.8 "ION-BEAM SURFACE ANALYSIS FOR PLASMA-EDGE STUDIES"³—SUMMARY

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Advances in plasma-surface interactions research require an understanding of particle fluxes and energies in the plasma edge, transport properties of the edge, local surface conditions, and relevant particle-solid interaction phenomena. A convenient method for studying plasma-surface interactions is to monitor surface modification and the collection of material on surfaces exposed in the plasma edge. These experiments can vary from the determination of surface conditions in long-term wall samples to the analysis of retained particle fluxes on collector probes exposed during single tokamak discharges. Collector-probe measurements are particularly useful in plasma-edge studies since many of the particles in the plasma edge are

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low energy and/or neutral and, therefore, are difficult to detect using other techniques.

Near-surface analysis of plasma-edge collector probes requires quantitative detection of a wide variety of atomic species with high sensitivities and good depth resolution. These techniques involve the use of ion beams to scatter, excite, or remove the atoms of interest on the collector probe. They include ion scattering and the channeling effect, ion-induced nuclear reactions, and secondary ion mass spectrometry (SIMS). The collector probes are not species specific, so ion-beam techniques can be used to study hydrogen isotopes and a variety of impurity atoms in a single sample. The retention and depth of implanted atoms in the probes can be related to incident flux and energy. Many of the techniques are nonde-

structive, which allows multiple and comparative analyses on the same sample.

The primary emphasis of this study is a relative assessment of the various ion-beam surface analysis techniques, along with numerous examples of their use for plasma-edge investigations. The elements of interpretation involved in relating these measurements to tokamak parameters are discussed, and a brief comparison to other techniques used in plasma-edge studies is given. The methods described here for collector probe experiments using ion-beam surface analysis have provided much of the existing data on plasma-surface interactions, including particle fluxes and energies, impurity fluxes, and surface modification and erosion in the plasma edge.

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Chapter 6

Plasma Technology

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6. PLASMA TECHNOLOGY

Summary of Activities

Advanced positive ion source development continued with the demonstration of 75-kV/40-A operations of 30-s pulses. Significant characteristics of this source are a divergence angle of 0.47° rms at a field ratio of 1.8, an optimum perveance of $1.8 \mu\text{perv}$, an atomic species fraction of better than 80% at full current density, a low gas throughput of $10 \text{ torr}\cdot\text{L}\cdot\text{s}^{-1}$, very low grid loadings and beam transport losses, and excellent reliability and reproducibility of source performance.

An important event that ensured the successful operation of the long-pulse source was the installation of a high-heat-flux swirl tube beam stop in the Medium Energy Test Facility (METF). This target has handled hundreds of 30-s beam pulses with total powers up to 3.5 MW and power densities of $>5 \text{ kW}/\text{cm}^2$ on the tube surfaces.

New accelerator designs have been incorporated into the surface ionization transverse extraction (SITEX) negative ion source. Experiments indicate a normalized emittance of $6 \times 10^{-4} \pi\cdot\text{cm}\cdot\text{mrad}$ for an angular divergence of $\theta_{\text{rms}} \approx 0.28^\circ$.

In the pellet-fueling area, testing of the Advanced Mechanical Injector (AMI) and the Advanced Pneumatic Injector (API) continued during 1983. The AMI operated for 30-s intervals at 42 pellets per second with pellet speeds of 730 m/s. Whole-pellet transmission reliability was greater than 70%. This injector will be used for injection experiments on Doublet III (DIII) in 1984. The API achieved record pellet velocities of approximately 1580 m/s in the single-shot mode and velocities of approximately 1000 m/s at a steady-state rate of one per second. In the area of confinement applications, Alcator-C reported the achievement of Lawson criteria levels of $n\tau \approx 8 \times 10^{13} \text{ s}\cdot\text{cm}^{-3}$ using an ORNL multipellet injector for fueling.

In the rf area, work was initiated in developing several candidate antenna configurations including "cavity" and "ridge-loaded waveguide" concepts. Full-scale bench models were fabricated to determine and optimize operating characteristics. Several Faraday-shield configurations have been fabricated for analysis of electrical and thermal characteristics. RF-current-feed designs have been refined and fabrication was started on two feeds for testing in 1984. Two-dimensional (2-D) and three-dimensional (3-D) Helmholtz and Poisson equation codes have been developed as aids in geometrical analysis of component development.

The ORNL rf test facility was proposed as a test bed to support concept selection and development of ion cyclotron heating (ICH) launchers for the DIII-D upgrade, the Tokamak Fusion Test Reactor (TFTR), and the Tokamak Fusion Core Experiment (TFCX). The facility is to be a simple mirror configuration using two superconducting coils. With a central field of 1.3 T and a plasma with a density of $\sim 5 \times 10^{12} \text{ cm}^{-3}$ and a temperature of $\sim 5 \text{ eV}$, this facility is expected to test rf components and systems up to 1-MW continuous wave (cw) power levels in the frequency range of 40 to 80 MHz in 1985.

ORNL was assigned the lead for National Ion Cyclotron Heating (NICH) technology development. The principal goal is to demonstrate the capability to deliver reliable, long-pulse, cw, high-power ICH energy to a reactor-grade plasma. Initial efforts now under way are devoted to developing 5-MW launcher system modules for DIII-D and TFTR.

In the area of gyrotron development, 60-GHz, 200-kW, cw, gyrotron operation was achieved by Varian Associates, Inc., and 60-GHz, 200-kW operation for 100-ms pulse lengths was achieved by Hughes Aircraft Company.

6.1 NEUTRAL BEAM HEATING

6.1.1 Positive Ion, Long-Pulse Source Development

6.1.1.1 Introduction

Major magnetic confinement fusion experiments—such as TFTR, DIII-D, and the Mirror Fusion Test Facility (MFTF-B) in the United States, the Joint European Torus (JET) in Europe, and the JT-60 in Japan—are expected to use multisecond neutral beam injection at multimewatt power levels (10–30 MW).¹ Among these applications, the longest pulse length requirement is for the MFTF-B experiment, in which ten injectors (each with a 30-s pulse duration) will be used. The ORNL neutral beam program has been directed toward the development of such quasi-steady-state injectors. Apart from the long-pulse requirement, the MFTF-B application is characterized by high beam brightness (beam divergence of $\leq 0.5^\circ$ at a deuterium current density of $\geq 0.15 \text{ A}\cdot\text{cm}^{-2}$), high gas efficiency (a gas flow from each 50-A source of no more than $10 \text{ torr}\cdot\text{L}\cdot\text{s}^{-1}$), high atomic species content (90%), and ultralow impurity content (10^{-5} parts per injected D^0). Because the last requirement is difficult to achieve in a conventional scheme, a magnetic beam purification scheme is being considered that will also lower the requirement on atomic species content to about 80%. A high degree of reliability (99%) is implied because of the simultaneous use of ten long-pulse and twelve short-pulse (500-ms) injectors.

In what follows, we will summarize briefly the major design features and describe the experimental results.

6.1.1.2 Major design features

The plasma generator. The plasma generator (Fig. 6.1) is of the duopIGatron type² with several modifications to enable long-pulse operation. Unlike the short-pulse sources employed in the Princeton Large Torus (PLT) and Poloidal Divertor Experiment (PDX) injectors,^{3,4} the long-pulse source uses two electron feeds, each incorporating an indirectly heated cathode. The details of the plasma generator and the indirectly heated cathode have been published elsewhere.^{5,6} The cathodes have La_2O_3 -doped molybdenum as emitting material and are radiatively heated to about 1900 K using graphite heaters. The double-feed plasma generator has a 28- by 60- cm^2 anode cross section and a 30-cm anode length. Improved cooling is accomplished by active water cooling, using electroformed water circuits, of all the components exposed to high heat fluxes. To increase the cusp-field strength, the permanent magnets are mounted on thin electroformed copper liners located inside the anode chamber (Fig. 6.1).

The accelerator. The ion accelerator is designed (using the 2-D ion extraction code⁷ developed at ORNL) to minimize the aberration-limited beamlet divergence to 0.26° rms at a current density (D^+) of $0.15 \text{ A}\cdot\text{cm}^{-2}$. The aperture shapes are described elsewhere.^{8,9}

Fig. 6.1. The duoPIGatron ion source.

and include features to minimize the heat loadings on the accelerator grids. The grids, with 13- by 43-cm² active grid patterns and serpentine cooling passages, are fabricated using electroforming techniques.¹⁰

6.1.1.3 Experimental results

The arc discharge. The plasma generator was operated at a 120-V, 1200-A, arc-discharge level for 35-s pulses (Fig 6.2). The

plasma uniformity was measured at a reduced pulse length (0.1 s), and the available uniform extraction surface was found to be 18 by 48 cm. In an attempt to estimate the lifetime and reliability of the cathode, a single cathode was operated at a 500-A discharge level for thousands of 30-s-long pulses at a 30% duty cycle. The discharges were reliable, as illustrated by the chart in Fig. 6.3 that shows individual discharge pulses (vertical lines) as a function of operating hours.

Fig. 6.2. Oscillogram of a 120-V, 1200-A, 35-s arc discharge.

Beam optics. The ion source was operated at beam energies up to 80 keV for short pulses (0.1–0.5 s) in order to characterize the beam optics. The beam profile was measured 420 cm downstream with a calorimetric probe. The beam optics is a function of the ratio of the electric fields in the first two gaps, and the numerical design is based on a field ratio of 2 between the second gap and the first gap. Measurements were made at a field ratio of 1.8. Because the accelerator is focused on a point 950 cm downstream and because the profile measurement was made 420 cm downstream, the beamlet divergence was computed based on the best fit with the experimental data. A divergence angle of 0.47° rms at a field ratio of 1.8 was obtained, assuming Gaussian beamlets, perfect focusing, and constancy

in perveance and field ratio during the entire pulse length.

Optimum perveance and tunability. Figure 6.4 shows a plot of power loading on different components as a function of perveance (defined as the ratio of the extracted current to the three-halves power of the acceleration voltage). The perveance is varied at constant acceleration voltage by varying the extracted current. The figure illustrates that the source can be tuned over a wide range of perveance. The optimum perveance that corresponds to the maximum power transmission to the target is about $1.8 \mu\text{perv}$. The grid loadings do not change appreciably with changes in perveance. It may be noted that these data are obtained using 100-ms pulses with a gas flow to the source significantly higher ($\sim 50\%$) than that necessary for long-pulse operation. The rise time of the pulse, during which the beam is appreciably off its optimum perveance, is about 10 ms. These effects increase both the heat loadings on the grids and the beam transport losses. The power flow measured at a lower gas flow when the beam pulse length was 30 s appears further in this section.

Atomic species. The species mix from the source was measured by scanning the ion-deflection magnetic current and noting the signal from a calorimetric probe. However, the technique was limited to low current densities because the deflection magnet was designed for

Fig. 6.3. Sample of chart recorder output illustrating the cathode performance.

Fig. 6.4. Power dissipation vs perveance.

a 50-keV beam. The beam pulse length was restricted to 0.06 s due to power density limitations on the ion dump. To complicate the measurement further, the gas flow from the source was not adequate to provide equilibrium neutralization. Additional gas, which had to be injected into the neutralizer, could enhance the half-energy component. Measurements of atomic species fraction at current densities up to $0.076 \text{ A} \cdot \text{cm}^{-2}$ yielded values up to 69.5%. This should extrapolate to better than 80% at full current density, based on the familiar scaling of atomic fraction with current density observed with the PLT and PDX sources.¹¹ The actual atomic species content at the plasma extraction surface should be several percentage points above 80% if the collisional processes in the accelerator region are taken into account.¹²

Long-pulse operation. The beam pulse length was gradually extended at 3 MW of extracted power (75 kV, 40 A) to the full 30 s. During this exercise, the energy dissipated on different components of the ion source and the beam line was measured calorimetrically with the help of a computerized data acquisition system. A swirl tube calorimeter,¹³ designed to intercept up to 5 MW of beam power at peak power densities of $25\text{--}30 \text{ kW/cm}^2$, was employed to stop the beam. The energy dissipated in the swirl tube calorimeter was measured by noting the rise in the temperature of the water circulating through the calorimeter and the total water flow. However, this temperature signal was not compatible with the computerized data acquisition system. Therefore, in order to illustrate that the beam optics was not altered as the beam pulse length was extended, the energy dissipated on the beam scrapers located just before the calorimeter (at 520 cm downstream) is plotted along with the accelerator grid dissipation values in Fig. 6.5. With an increase in extracted energy (as the pulse length is increased), the dissipation on all the components increases linearly, establishing the integrity of the ion source design at energy levels approaching 100 MJ.

Power flow. For a 75-kV, 40-A beam pulse of 30-s duration (Fig. 6.6), the power flow along the beam line is shown in Fig. 6.7. (Note that more than 90% of the power from the ion source is transmitted to the target located 520 cm downstream). The gas flow to the source for this pulse was $10 \text{ torr} \cdot \text{L} \cdot \text{s}^{-1}$, and this low gas flow and the excellent beam optics have resulted in the low grid loadings and beam transport losses shown in Fig. 6.7.

Reliability. With the ion source regapped to provide increased beam currents, we have operated a sequence of 600 shots of 30-s pulse lengths at extracted power levels of 3.2–3.5 MW (72–74 kV, 42–48 A). Approximately one-third of the pulses were clean, with no interruptions, and the average number of interruptions per 30-s pulse length was 1.5.

Fig. 6.5. Energy dissipation vs beam pulse length.

Fig. 6.6. Oscillogram of a 75-kV, 40-A beam pulse of 30-s duration.

Thus, the reliability and reproducibility of the ion source performance are quite good.

6.1.1.4 Summary

A quasi-steady-state ion source has been developed and the operating characteristics determined. The ion source was demonstrated to be suitable for neutral beam injection applications involving beam pulses up to 30 s at power levels up to 3.5 MW.

Fig. 6.7. Power flow along the beam for a 3-MW, 30-s pulse.

6.1.2 Negative Ion Source Development— Abstracts

The following abstracts of papers presented at the Third International Symposium on the Production and Neutralization of Negative Ions and Beams at Brookhaven National Laboratory (1983) summarize the activities in the negative ion source development program.

6.1.2.1 "Normalized Emittance of SITEX Negative Ion Source"

W. L. Stirling
W. K. Dagenhart

J. H. Whealton
J. J. Donaghy

An emittance measurement employing two techniques is being made on SITEX. To this end, a 2-D calculation was performed to design the accelerator to reduce electric field aberrations. The calculated normalized emittance is $6 \times 10^{-4} \pi \cdot \text{cm} \cdot \text{mrad}$ for an angular divergence $\theta_{\text{rms}} \approx 0.28^\circ$. The status of the experimental findings is presented and a comparison is made to the calculated value that will yield the ion sputter energy.

6.1.2.2 "Short-Pulse Operation with the SITEX Negative Ion Source"

W. K. Dagenhart
W. L. Stirling
G. M. Banic

G. C. Barber
N. S. Ponte
J. H. Whealton

The successful high current, long-pulse SITEX source experiments with H^- beams have been extended to D^- operation and to short-pulse H^- and D^- beam acceleration. Extracted D^- beam current densities of 100 mA/cm^2 at the plasma grid have been achieved for 3 s at a total beam of 260 mA and 10 keV. The extracted electron-to- D^- ratio is $<5\%$ with $\sim 100\%$ of the extracted electrons collected at 2 keV. Short-pulse beams down to 10 ms in length have been accelerated with the minimum pulse length determined by the power supply time constants. The optics of the accelerated beam is $\theta(1/e)_\perp = \pm 0.48^\circ$, which corresponds to a normalized emittance perpendicular to the slot of $0.0007 \pi \cdot \text{cm} \cdot \text{mrad}$. These data place an

upper limit on the surface conversion D^- ion temperature of 0.7 eV.

6.1.2.3 "2-D Accelerator Design for SITEX Negative Ion Source"

J. H. Whealton
R. J. Raridon
R. W. McGaffey

D. H. McCollough
W. L. Stirling
W. K. Dagenhart

Solving the Poisson-Vlasov equations

$$\nabla^2 \Phi = \int f dv - e^{-\Phi}$$

and

$$(\mathbf{v} \times \mathbf{B} + \nabla \Phi) \cdot \nabla_v f + \mathbf{v} \cdot \nabla f = 0,$$

where the magnetic field $\mathbf{B}$ is assumed constant, we optimize the optical system of a SITEX negative ion source in an infinite slot geometry. Algorithms designed to solve the above equations were modified to include the curved-emitter boundary data appropriate to a negative ion source. Other configurations relevant to negative ion sources are examined.

6.1.2.4 "End Effects in Slot Extraction for a SITEX Negative Ion Source"

R. W. McGaffey
P. S. Meszaros
J. H. Whealton

R. J. Raridon
D. H. McCollough

A 3-D solution to the Poisson-Vlasov equation of the form

$$\nabla^2 \Phi = \int f dv - e^{-\Phi}$$

and

$$(\mathbf{v} \times \mathbf{B} + \nabla \Phi) \cdot \nabla_v f + \mathbf{v} \cdot \nabla f = 0$$

is obtained in the extraction region using the technique of ref. 14. A constant magnetic field $\mathbf{B}$ is imposed. Algorithms designed to solve these equations were modified to include the curved-emitter boundary data appropriate

to a negative ion source. The end of the slot was optimized to minimize aberrations.

6.1.3 Theoretical Ion Optics—Abstracts

The following abstracts describe progress in the area of theoretical ion optics during 1983, including work on space-charge-dominated accelerator design, ion energy straggling while undergoing acceleration, and atomic ion post-acceleration separators.

6.1.3.1 "An Example of Energy Straggling in an Ion Accelerator"¹⁵

R. J. Raridon	R. W. McGaffey
J. H. Whealton	D. H. McCollough
J. W. Wooten	C. C. Tsai

We solve the Poisson-Vlasov equations for volume-produced ions, fast neutrals, and backstreaming electrons in an MFTF-B, 80-keV preprototype neutral beam source:

$$\nabla\Phi \cdot \nabla_v f(v) + v \cdot \nabla f(v) = -(\nu_e + \nu_i)f(v) ,$$

$$\nabla\Phi \cdot \nabla_v f_i(v_i) + v_i \cdot \nabla f_i(v_i) = \nu_i \delta(v_i) ,$$

$$\nabla\Phi \cdot \nabla_v f_e(v_e) + v_e \cdot \nabla f_e(v_e) = \nu_e \delta(v_e) ,$$

and

$$\nu_n \cdot \nabla f_n(v_n) = \nu_n f(v) ,$$

where the electric fields $\nabla\Phi$ are computed from the solution of

$$\nabla^2\Phi = f(v)dv - e^{-\Phi} ,$$

and

$$\nabla\Phi \cdot \nabla_v f(v) + v \cdot \nabla f(v) = 0 ,$$

and $f(v)$ is the primary ion-distribution function. Neutral pressure distributions are estimated from the known gas feed rate and calculated accelerator column conductance and are

calibrated by comparing measured and calculated electron backstreaming power (computed by solving another Vlasov equation). The depletion of atomic yield from these volume processes will be computed for sources in which the atomic yield is 100% in the extraction region. The energy distribution of neutral will also be shown.

6.1.3.2 "Grid-Embedded Magnetic Field Separator for Pure Monoenergetic Neutral Beams"¹⁶

R. J. Raridon	D. H. McCollough
J. H. Whealton	C. C. Tsai

Some applications of neutral beam heating of plasmas require a monoenergetic beam of very low divergence. A means of achieving a monoenergetic beam is by embedding permanent magnets in the last accelerator electrode.¹⁷ We will examine the effect of this magnetic field on the optical aberrations of the beam by solving the following equations:

$$\nabla^2\Phi = \int f dv - e^{-\Phi} ,$$

$$\nabla^2\mathbf{A} = -\nabla \times \mathbf{M} ,$$

and

$$(v \times \nabla \times \mathbf{A} + \nabla\Phi) \cdot \nabla_v f + v \cdot \nabla f = 0 .$$

We use the solution of Eq. (2) in ref. 18 and the technique of ref. 19 for solutions to the first and third equations.

6.1.3.3 "2-D Accelerator Designs for 18-kV and 40-kV Triodes and 120-keV Low Field Ratio Tetrodes"²⁰

M. A. Bell	R. J. Raridon
J. H. Whealton	R. W. McGaffey
D. H. McCollough	

Two-dimensional solutions to the Poisson-Vlasov equations of the form

$$\nabla^2 \Phi = \int f dv - e^{-\Phi}$$

and

$$\nabla \Phi \cdot \nabla f + v \cdot \nabla f = 0$$

are obtained by the method of refs. 19 and 21 for cylinder and oo slot geometry. Configurations considered include (1) 18-keV triodes for application to TMX, (2) 40-keV triodes for P2B2, and (3) 120-keV low-field-ratio tetrodes.

6.1.3.4 "Expeditions 3-D Poisson-Vlasov Algorithm Applied to Ion Extraction from a Plasma"¹⁴

J. H. Whealton
R. W. McGaffey

P. S. Meszaros

A new 3-D Poisson-Vlasov algorithm is under development that differs from the preceding algorithm in two respects: (1) the mesh lines are cartesian and (2) the Poisson equation is solved iteratively. The resulting algorithm has been used to examine the same boundary value problem as considered in ref. 22, except that the number of nodes is twice as great. The same physical results were obtained, except that the computational time was reduced by a factor of 60 and the memory requirement was reduced by a factor of 10. This algorithm at present restricts Neumann boundary conditions to orthogonal planes lying along mesh lines. No such restriction applies to Dirichlet boundaries.

6.1.4 Test Stand Update

The upgrading of the Medium Energy Test Facility (METF) to permit testing of 80-keV, 50-A, 30-s neutral beams was completed in 1983. This primarily involved installation of the high-heat-flux swirl tube beamstop¹³ (Fig. 6.8).

The target consists of 126 swirl tubes—each with 0.95-cm outside diameter, 0.16-cm-thick walls, and ~1-m length—arranged in a V shape. Water-cooled copper swirl tubes were

Fig. 6.8. Schematic of the swirl tube target.

chosen for the heat-transfer medium because of the enhancement in burnout heat flux over conventional axial-flow tubes. Two arrays of parallel tubes inclined at an angle α to the beam axis form the V shape, and this geometry reduces the surface heat flux by a factor of $1/\sin \alpha$ (for the present target, $\alpha = 13^\circ$ and 21°).

The target has handled up to 3-MW, 30-s beam pulses (100 MJ of energy deposited) from the ORNL long-pulse ion source. The peak power density was estimated at 15 kW/cm^2 normal to the beam axis (5.4 kW/cm^2 maximum on tube surfaces). The water flow rate through the target was 41.6 L/s (660 gpm) or 0.33 L/s (5.2 gpm) per tube. The corresponding pressure drop across the target was 1.14 MPa (165 psi) with an inlet pressure of 1.45 MPa (210 psi).

Results from individual swirl-tube tests suggest that the target should handle peak densities in the range of 25 to 30 kW/cm² normal to the beam axis (10 kW/cm² maximum on tube surfaces) with the present flow parameters. This translates to beam power levels of 5 to 6 MW for equivalent beam optics.

6.2 PELLET FUELING

6.2.1 Advanced Injector Development

Testing of the Advanced Mechanical Injector (AMI) and the Advanced Pneumatic Injector (API) continued during the last year. Both injectors are repetitive devices intended to demonstrate steady-state fueling systems in reactor-relevant parameter ranges. The injectors utilize high-speed deuterium extruders to provide frozen material for the acceleration section of the injector. In the AMI, pellets are accelerated by centrifugal forces in a high-speed rotating track; in the API, pellets are accelerated in a barrel with compressed helium or hydrogen propellant.

Performance of the AMI has been characterized in laboratory operation. A two-stage, 3-m guide, tube-type injection line with several diagnostic stations was added to simulate injection into a tokamak. The system has been operated for 30-s pulses at 730 m/s and 20 to 42 pellets per second. The measured velocity was within 1% of the theoretical value. A shock transducer mounted at the end of the injection line indicated 97% transmission through the system. Photographs taken at the entrance section showed that 72% of the pellets were whole and 22% were broken into two large fragments. The AMI is scheduled to be shipped to GA Technologies, Inc., in San Diego in early 1984 for pellet-injection experiments on DIII.

In the API facility, individual deuterium pellets (2.1 mm diam by 2.5 mm long) were accelerated up to velocities of about 1580 m/s with hydrogen propellant (device operating in single-shot mode for these tests). The injector now produces 100% intact pellets in the single-shot mode. We were able to operate at

a steady-state rate of 1 s⁻¹ for up to about 30 s (extrusion time) in the repeating mode with pellet velocities of about 1000 m/s. The rate limitation has been attributed to heating of the gun block above the freezing point for deuterium by the hydrogen (room temperature) propellant and a consequent melting of the deuterium feed before it enters the pellet chambering section. The chambering mechanism can easily operate at 50 Hz. Thus, greater repetition rates should be achievable with modifications to the gun-block design. We also have been experimentally studying the effects of various parameters on pellet velocity in the API, including propellant gas (helium and hydrogen), propellant temperature (~300 K and 500 K), barrel length (20 to 100 cm), and pellet size (1.8 and 2.1 mm diam). We are presently modifying the gun section to accommodate 3.4-mm-diam pellets in order to demonstrate acceleration of even larger pellets, which are needed for future fueling applications (on TFTR, for example).

The ORNL single-pellet injector has been loaned to the University of Illinois for a magnetohydrodynamic (MHD) rail-gun study to be conducted in collaboration with the ORNL Pellet Fueling Group. The rail-gun approach is a possible candidate to accelerate pellets to velocities greater than 2 km/s, which may be needed in future pellet-fueling applications.

A conceptual design of a tritium-pellet-injection system for TFTR has been completed. The design of the system is continuing with special emphasis on the aspects dealing with tritium. This experiment will mark the first experience with tritium in pellet injectors.

6.2.2 Confinement System Applications

Three, four-pellet pneumatic injectors are now in operation, one each on PDX, Alcator-C, and ISX-B. (Results from ISX-B operation are described in detail in Chap. 2.) Alcator-C reported that the "Lawson Criteria" was surpassed for the first time using an ORNL multipellet injector for fueling the plasma, achieving an $n\tau$ of 8×10^{13} s·cm⁻³ in a deuterium plasma with a central temperature of 1.5 keV.

6.3 RF HEATING

6.3.1 RF Technology Development

The rf component development is broken into four areas: antennas, Faraday shields, current feeds, and rf modeling. The bulk of our development is in conjunction with the National Ion Cyclotron Heating (NICH) program, although some work has more generic application.

The antenna development is focused on the possible candidate configurations for DIII-D, TFTR, and TFCX. Full-scale bench models of these candidates were fabricated, tested, and altered. Specifically, a "cavity" and "ridge-loaded waveguide," operable in the 60- to 80-MHz range, were tested for optimum feed point, voltage maxima, and impedance characteristics. Furthermore, a variety of magnetically coupled receiver antennas were developed to permit high-power tests without a plasma load. Tests at high power (with plasma) will commence when the test facility is completed.

Development efforts in Faraday shields are twofold. The reduction in loading and the power absorbed by various Faraday shields were observed for the cavity antenna. Typically, the Faraday shield could reduce coupling by 30%. In addition to the electrical characteristics of the Faraday shield, the thermal-load-handling capabilities were explored by exposing a series of tubes (swirl, straight, finned, and titanium-carbide coated) to power densities up to 7 kW/cm^2 for pulse durations up to 1 s. The survivability of the tubes and their surface temperatures were observed as a function of flow rate. The swirl tubes fared well, so a prototype array was fabricated to test the combined effects. This array is a full-scale model of a Faraday shield for the cavity antenna. Tests on this array are just starting.

The rf-current-feed development is relying on the strength of the ELMO Bumpy Torus (EBT)-ion cyclotron resonance heating (ICRH) experiment. We have designed and started fabrication of the two, 7.9-cm (3-1/8-in.), 50- Ω axial current feeds based on the existing cw, 100-kW, 15.6-cm (6-1/8-in.)

current feed. Tests at up to 10:1 VSWR, 40 kW, and 200 MHz are expected to start soon. In addition, a 35.6-cm (14-in.) coaxial current feed that tapers to a 15-cm (6-in.) port is presently being designed for possible 1-MW tests.

Two- and three-dimensional Helmholtz and Poisson equation codes have been developed to help in geometrical analysis of component development. A 3-D Helmholtz finite-difference code has been used to analyze the resonant electric fields in the ridge-loaded waveguide. In addition, all six field components were coupled by the dielectric tensor to simulate a plasma in the waveguide. A 2-D Poisson code was also developed to make potential contours in the rf-current feed. Other codes include a 2-D finite-element Helmholtz equation solver and a 3-D Poisson equation solver.

6.3.2 The ORNL RF Test Facility

Fusion devices that will use large amounts of rf heating (DIII-D, TFTR, and TFCX are being emphasized) must be simulated well enough by an rf test facility to provide an appropriate test bed to support antenna concept selection and subsequent development. The ORNL rf test facility was conceived to be such a development support tool to guide the advancement in antenna-systems capability. The facility is sized to accept actual full-scale prototype antennas that may be used on DIII-D and TFTR. It will be used not only for thorough evaluation of these prototypes but also for checking all production units before installation. Furthermore, the test facility will have sufficient flexibility in design so that fields, plasmas, and dimensions can be modified to reflect different applications. This facility, shown conceptually in Figs. 6.9 and 6.10, will become operational in mid-1985.

Specifically, the rf test facility will have a simple mirror configuration using two of the three superconducting development coils from the ELMO Bumpy Torus Proof-of-Principle (EBT-P) program. Spacing between coils is to

RF TEST FACILITY

ORNL-DWG 534861 FED

Fig. 6.9. Cutaway drawing of the ORNL RF Test Facility.

Fig. 6.10. Schematic of the rf test stand.

be 85 cm, and the main access port size will be 42 by 165 cm. Good diagnostic access will be available through 26 small ports. In addition, there will be various subsystems required to make this facility operational, including a turbopump-based vacuum system, a closed-loop helium refrigerator/liquifier system, an integral instrumentation and control package, and a calorimetrically monitored cooling-water system.

With respect to facility capabilities, the fully operational magnetic field strength will be 3.4 T in the coil throats and 1.3 T at the mirror center. The plasma, produced by a 200-kW, cw, 28-GHz gyrotron, will have a density in the range of 10^{12} to 10^{13} cm^{-3} and a temperature of ~ 5 eV. When brought to full operating status, this facility will be capable of testing rf components and systems to 1-MW, cw power levels in the frequency range of 40 to 80 MHz.

6.3.3 Theoretical Support and Code Development—Abstracts

The following abstracts describe progress in this area during 1983.

6.3.3.1 "Recent Development in Finite Difference Multidimensional Solutions to Maxwell's Equations for Application to RF Technology"²³

J. H. Whealton
J. W. Wooten
R. W. McGaffey
D. H. McCollough
R. J. Raridon

M. A. Bell
P. S. Meszaros
A. M. Goswitz
D. J. Hoffman

Radio frequency technology algorithms have been developed at ORNL that (1) solve the Laplace equation $\nabla^2 \Phi = 0$ in 2-D with dielectrics present in arbitrary geometry and composition, (2) solve the scalar homogeneous Helmholtz equation $(\nabla^2 + \omega^2)\Phi = 0$ in 2-D, and (3) solve the complex inhomogeneous vector Helmholtz equation $(\nabla^2 + \omega^2)\mathbf{E} = i\omega\mathbf{J}$ in 3-D. Solution to the Laplace equation is useful in designing feedthroughs. Solution to the 2-D scalar Helmholtz equation is useful in analyzing simple waveguides and has been a vehicle for establishing a stable eigenvalue and eigenfunction solution technique. Solution to the inhomogeneous vector Helmholtz equation, along with $\mathbf{B} = \nabla \times \mathbf{E}/(i\omega)$, constitutes a solution to Maxwell's equation in 3-D for the

spatial dependence of the vacuum electromagnetic fields Fourier transformed in time. This is a suitable model for consideration of fields near antennas in a vacuum. In its present form, the computer time required for a vector solution for E of the 3-D Helmholtz equation is 30 min.

6.3.3.2 "Finite-Element Algorithm for Multidimensional Solutions to Maxwell's Equations for Application to RF Technology"²⁴

J. W. Wooten
D. H. McCollough

J. H. Whealton
G. S. McNeilly

Finite-element rf technology algorithms have been created and deployed that (1) solve the Laplace equation $\epsilon \nabla^2 \phi = 0$ in 2-D with dielectric present in arbitrary composition and geometry and (2) solve the vector inhomogeneous Helmholtz equation $(\nabla^2 + \omega^2)E = 0$ in arbitrary 2-D geometry. Solution to the Laplace equation is useful in designing feed-throughs. The treatment of the 2-D Helmholtz equation allows arbitrarily shaped Neumann boundaries that couple the components of the field, unlike the present state of a finite-difference algorithm intended for similar applications.²³ A new solution algorithm was created to reduce the resource utilization by a factor of 4000 (1/200 of memory and 20 times faster for $20 \times 20 \times 20$ nodes and three coupled equations) compared to previous deployments²² for complex problems with a large number of nodes. A 3-D finite-element algorithm was created for solution of the inhomogeneous vector Helmholtz equations with tensor dielectric for simulation of plasma near rf antennas.

6.3.4 The National Ion Cyclotron Heating Program

In 1983 the Office of Fusion Energy (OFE) of the U.S. Department of Energy (DOE) assigned ORNL the lead role for Ion Cyclotron Range of Frequencies (ICRF) rf technology

development. Concurrently, the National Ion Cyclotron Heating (NICH) Program was established as the main objective for ORNL's rf development program. The principal goal of NICH is to demonstrate the technological capability to deliver reliable long-pulse (cw), high-power ICRF energy to a reactor-grade plasma. This objective, in addition to the concomitant plasma physics goal of further characterizing the ICRF heating potential, requires the development of appropriate technology and the application of significant quantities (megawatts) of ICRF power.

The first phase of the NICH program now under way is devoted to developing 5-MW ICRF launcher antenna systems appropriate for major building-block elements for the heating systems planned for DIII-D and TFTR. The existing Fusion Materials Irradiation Test (FMIT) Facility power units made available by DOE will be modified to serve as 1.5- to 2-MW building blocks for powering these ICH systems, as well as for TFCX. The desired launcher concepts for each of the machines still need to be determined by technology developments and by subsequent physics heating adequacy checks on appropriate confinement devices. Candidate antenna concepts that could meet the requirements of all three machines, as well as provide a basis for designing reactor ICH systems, are being evaluated. Wave-launching techniques under development (as described in Sect. 6.3.1) are to be supplemented with other candidate evaluations from research studies contracted with industrial findings experienced in this and related fields.

ORNL is providing the leadership for NICH and integrating all related activities with GA Technologies and the Princeton Plasma Physics Laboratory (PPPL). An advisory committee has been formed consisting of two representatives each from ORNL, DOE-OFE, GA Technologies, and PPPL. The pacing requirement is the application of ~ 1.5 MW of ICH on DIII-D in mid-FY 1986. The prime candidate launcher concept is a cavity-backed loop. A simple loop is being carried as the backup.

6.4 GYROTRON DEVELOPMENT PROGRAM

The ORNL Gyrotron Development Program continued to manage the development of gyrotron tubes by two industrial subcontractors—Varian Associates and Hughes Aircraft Company. In tests by Varian in June 1983, cw output of 200 kW at 60 GHz

was achieved. Work on this development is still in progress, with specific goals of improving mode purity of the output power and demonstration of 30-s pulsed operation. The 60-GHz pulsed design was scaled for successful operation at 53 GHz. Hughes completed the design of a 60-GHz, 200-kW cw tube. Testing to the 200-kW level in 100-ns pulses was attained.

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Chapter 7

Superconducting Magnet Development

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7. SUPERCONDUCTING MAGNET DEVELOPMENT

Summary of Activities

The Large Coil Program (LCP) continued to manage the manufacture of three superconducting magnet coils that will be tested in the Large Coil Test Facility (LCTF). General Dynamics-Convair Division (GDC) finished its coil and delivered it in June. Work on reinforcing the structure and completing the assembly of the General Electric Company (GE) coil was initiated in the shops of the Oak Ridge Gaseous Diffusion Plant (ORGDP). Westinghouse Electric Corporation (Westinghouse) finished development of manufacturing procedures and began winding its coil.

ORNL continued to represent the United States as Operating Agent for the international Large Coil Task (LCT). The coil provided by the Japan Atomic Energy Research Institute (JAERI) was installed in the LCTF. Siemens-AG completed the coil for Euratom and delivered it to Kernforschungszentrum Karlsruhe (KfK) for testing before shipment to Oak Ridge. Brown-Boveri Company (BBC) completed manufacture of the Swiss coil and began final checking before shipment. All LCT participants were represented in day-to-day planning and execution of work at the LCTF. Training of LCTF operators and supervisors was completed. Acceptance testing of the complex helium refrigeration system for the LCTF was accomplished between January and August. Acceptable performance was achieved. Construction of the LCTF was virtually completed. The last major milestone was met in November on the schedule and within the budget established early in 1981.

Immediately after the GDC coil installation was completed in November, vacuum and helium systems were put into operation in preparation for facility shakedown with two coils.

Work by the Magnetics and Superconductivity (M&S) Section included notable progress in support of the LCP, testing of conductor for the 12-T coil project, advanced conductor development, testing of prototype coils for the ELMO Bumpy Torus Proof-of-Principle (EBT-P) Project, and development of coil concepts for the Advanced Toroidal Facility (ATF).

7.1 INTRODUCTION

The ORNL Fusion Energy Division continues to play a leading role in the development of superconducting magnets for toroidal fusion reactors. The greatest effort in 1983 was in the LCP, which entails designing, building, and testing 8-T toroidal field (TF) coils about one-third the size of those envisioned for tokamak reactors. Staff at ORNL guided and monitored GDC and Westinghouse in the design and manufacture of one coil each. A third

coil, designed and partially completed by GE before delivery to Oak Ridge, is being completed at ORGDP under the supervision of the LCP. In addition, through an International Energy Agency (IEA) agreement, Euratom, Japan, and Switzerland are engaged in the LCT and are building one coil each to LCP specifications for testing in the LCTF, along with the U.S. coils. Facility operation and coil testing will be performed by ORNL, which is acting on behalf of the Department of Energy (DOE) as the Operating Agent for the LCT.

Supporting research and development activities for the LCP, carried out in the M&S Section, include work on instrumentation and diagnostics, conductor verification tests, cryogenic tests, and coil winding technology.

In addition to supporting the LCP, the M&S Section has a role in the U.S. 12-T Coil Program initiated in 1978 to supplement the goal of the LCP. In this program, ORNL is working with industrial subcontractors in developing large Nb₃Sn conductor suitable for tokamak TF coils to be operated at fields to 12 T.

The efforts at ORNL continue to advance magnet technology in areas specific to fusion applications by developing better analysis techniques, generating basic design information, and evaluating small quantities of experimental conductor embodying advanced concepts. In 1983, the advanced conductor development program continued to concentrate on developing multifilamentary (MF) Nb₃Sn, understanding force-cooled magnets, and gaining perspective on ac losses—all closely tied to the LCP and 12-T Coil Program activities.

The principal magnet technology project of the M&S Section was the successful testing to full design values of development magnets for the EBT-P Project. Development of the helical copper coils for the ATF was also initiated.

7.2 LARGE COIL PROGRAM

7.2.1 Program Management

LCP management worked with UCC-ND Labor Relations, the UCC-ND Law Department, and DOE to draft agreements that define responsibilities for special equipment and that provide for work at LCTF by personnel from industrial firms under contract to foreign participants. Agreements between UCC-ND and each foreign participant were concluded after several months of negotiations.

When completion and delivery of the GDC coil was delayed, ORNL and DOE reviewed plans for the LCT test program and concluded that it was in the best interests of the program

that the facility shakedown include both GDC and Japanese (JA) coils. A proposal for revision of the schedule to allow inclusion of the GDC coil was sent to all participants. At the semiannual meetings of project officers and executive committee in April, this proposal was debated and finally accepted. The Plan for Implementation of the LCT was revised and approved.

LCP management provided coordination among the LCTF construction project, coil installation, and facility operations. A great deal of attention was given to resolution of problems associated with the helium refrigerator system, including response to criticism of quality by foreign participants during the spring semiannual meeting.

Questions associated with completion of the GE coil were addressed and resolved. An ad hoc panel convened by the DOE Office of Fusion Energy (OFE) reviewed the stress calculations in April. The advice of the LCP Advisory Committee, solicited and received in May, was to complete the coil for background service. ORNL management concurred and proposed this course to DOE, who approved it in June. It was decided that the work would be done at ORGDP because of the necessity of development concurrent with fabrication and because the work had to be initiated by the summer months to avoid impacting the six-coil schedule.

There was intensive interaction with projects at GDC, Airco, and Westinghouse on resolution of quality assurance problems and other decisions affecting schedule and costs. Negotiations with GE continued with regard to disposition of equipment and closing out the contract.

Two representatives of JAERI arrived during the year for long-term assignments at the LCTF. One Hitachi engineer spent several weeks immediately after coil delivery, and another came later to install the sensor leads to the JA coil. DOE approval of the assignment of eight other JAERI representatives was secured.

Another representative of Euratom arrived, and the previous representative returned to KfK. The Swiss representative returned to Switzerland to participate in completion of the Swiss coil.

Semiannual meetings of LCT project officers and executive committee were held in Oak Ridge in September. Agreement was reached on objectives for forthcoming two-coil tests.

7.2.2 LCTF Construction

Facility design (Title II Engineering) activities were completed in April. A significant level of engineering effort continued throughout the year on inspection and acceptance testing (Title III).

Procurement and construction activities during 1983 were mostly associated with additional equipment required for six-coil tests. (With minor exceptions, construction sufficient for three-coil tests had been completed late in 1982.) This included vapor-cooled leads, dewars, electrical supply and dump systems, and the helium vent system for the forced-flow coils.

Other procurement and construction included various essential modifications to the helium refrigerator, a full-flow purifier for the helium system, the pulse coil system, and the Japanese special equipment.

The last major milestone of the LCTF Construction Project was satisfactorily completed in November. Work continued through the end of the year on tasks that were included in the scope of the project but which had been deferred until it was certain that project funds would not be fully expended on more critical jobs. At the end of the year, it was evident that the project could be closed out on the schedule and within the funding limits established nearly three years earlier.

7.2.3 U.S. Test Coils

7.2.3.1 GE coil

The unfinished GE coil was thoroughly inspected after arrival at ORCDP for storage.

Diagnostic measurements to determine the situation regarding shorts led to a decision to attempt electrical burnout of these shorts, which was accomplished successfully in January within the bounds of parameters established by the diagnostic work.

ORNL completed analysis of the GE coil-case stress distributions and completed the design of reinforcements needed in several locations to reduce stresses to acceptable levels. It was then possible to define with reasonable confidence the scope of shop work necessary to complete the coil.

A thorough review led DOE to direct ORNL to design to ensure only the capability of operating the GE coil as a background coil and to achieve capability for operation at 100% design current only if this could be accomplished without significant impact on cost or schedule.

After careful consideration of subcontracting the work, a decision was made to complete the GE coil in the ORGDP shops. A major consideration in this decision was the need to initiate shop work by the last quarter of the fiscal year to avoid delay in the six-coil tests. Bolt-torquing procedures were developed and successfully implemented to achieve the necessary level of preload in the case bolts without galling or seizing. Electrical diagnostic tests performed after bolt torquing showed that no new shorts had occurred as a result of the bolting operations. Coil-case seal welding and welding of structural reinforcements were completed in October, and final machining of all exterior interface surfaces was under way in December.

GE completed inventory and shipment of surplus materials to ORNL. Further work to close out the subcontract (mainly the disassembly and disposition of the government-owned portion of the winding equipment) was deferred to FY 1984. Negotiations with GE were under way at year end.

7.2.3.2 GDC coil

GDC completed closeout welding of the main coil case in January. After injection of

polyurethane to fill the annular void between the winding pack and coil case, the remaining structural welding (e.g., torque boxes to main coil case) was completed in March. The remaining closeout activities (e.g., main lead installation and sensor wire feedthrough installation) were completed in April. Final machining (under subcontract to L&F Industries in Los Angeles) was completed in May, and the coil was delivered to the LCTF in early June.

7.2.3.3 Airco conductor

Airco completed the tube mill modifications initiated in 1982 to eliminate the cause of burrs and "slivers" on the conductor jacket surface. Production was resumed in February on the ninth length (of 48), and sheathing of all 48 lengths was completed in September. The tube mill and related production equipment were placed in a standby mode until Westinghouse completed production winding.

7.2.3.4 Westinghouse coil

Westinghouse was completing conductor winding in December on the third plate pair on each of the two winding lines (i.e., nearing completion of 12 plates of 24) and began winding the second plate pair on each line. Three-shift operations and six-day work weeks were initiated in August. A potentially serious problem was discovered with the first 14 conductor lengths delivered to Westinghouse subsequent to the tube mill modifications at Airco; that is, the lengths were found to be 30.5 to 38 cm (12 to 15 in.) short of nominal [specified tolerance is 22.48 cm (8.85 in.) of a nominal full length averaging about 110 m (360 ft)]. Fortunately, Westinghouse was able to implement minor design changes to the header region of affected plates to utilize these out-of-specification conductors, and Airco made a correction in their operations that allowed the remaining 26 conductors to fall within length specifications. The schedule impact of this problem was thus minimized, but it still amounted to an initial 2 to 3 weeks of lost production while a solution was being identified

(plus an additional 4 to 6 weeks of delay caused by implementing the solution on the various plates affected).

7.2.4 Other Test Coils

The postdelivery inspection of the JA coil had just been completed, quite satisfactorily, at the beginning of the year. At various stages in the installation and operation of the coil, electrical and helium leak tests were performed, always with satisfactory results.

Construction of the Swiss coil by BBC was completed. At the end of the year, room-temperature tests were being performed in Switzerland just before shipment to the LCTF.

Siemens-AG finished construction of the Euratom coil and delivered it to Karlsruhe in November. Installation in the TOSKA facility at KfK began immediately.

7.2.5 LCTF Installation and Operation

Startup and acceptance tests of the helium system extended from January through August. A field engineer representing the refrigerator supplier (Koch Process Systems) was on site from February through August, actively participating in startup operations. It was necessary for him to adjust or modify valves and to install sensors and other items that had been left out. Koch and UCC-ND worked together on the cold box to repair a helium leak, to repair shipping damage to insulation, and to install an additional line to allow concurrent operations, as required by purchase specifications. Temperature sensors installed by Koch were replaced, and additional sensors were added in the cold box after the first cooldown (in May) revealed that the original sensors were quite inadequate to provide information necessary for process control. During the next period of operation (in June), one of the turbo-expanders suffered damage. Koch arranged for inspection and repair by Sulzer Bros., the turbine designer and manufacturer. Changes in equipment and restriction of operating pressures were recommended by Sulzer and were incorporated. Control of pressures during

changes in operating condition proved to be quite difficult, after resulting in burst rupture disks and admission of air, which had to be removed before resumption of cold operation. A water leak in a gas cooler and air inleakage at joints in components operating at subatmospheric pressure were other causes of delays.

The final series of acceptance tests determined maximum liquefaction rate (about 480 L/h) and capabilities under different conditions simulating coil testing and standby. Analysis of the data showed that the system generally met performance specifications, giving reasonable assurance of adequacy for the planned coil test program.

Training of candidate LCTF operators and supervisors continued throughout the first ten months of the year, including both classroom lectures and on-the-job training. Final examinations in November showed that all candidates were qualified for coil-testing operations.

Operations resumed late in November with evacuation of the large vacuum vessel and cleanup of the helium in the coils and piping systems. During December numerous small air leaks into the vessel (mainly at sensor-lead penetrations) were found and repaired, bringing air inleakage down to an acceptable level. Two helium leaks occurred in prefabricated assemblies in the helium vent system for the JA and GDC coils. Operation was interrupted while repairs were made.

The LCTF Operations Group completed drafts of the Safety Analysis Report¹ and Operational Safety Requirements.² Work on the Operations Manual continued throughout the fiscal year as modifications were found necessary. The Testing and Analysis Group completed detailed procedures for preliminary testing with the GDC and JA coils installed in the test stand.

A Quality Assurance Assessment of LCTF operations and a Quality Assurance Plan to limit all risks to acceptable levels were prepared and implemented.

The JA coil was set in the test stand on January 20. Excellent yoking to the bucking post was obtained. Immediately after conclu-

sion of the enabling amendment of the personnel-exchange agreement, an Hitachi engineer came to the LCTF to connect the sensor leads between the JA coil and the outer face of the vacuum vessel. This task was completed late in April. Meanwhile the high-current superconducting buses were connected by UCC-ND personnel. Connections of helium lines were necessarily deferred until after completion of the refrigeration tests.

Preparation of the GDC coil for installation began upon receipt June 8. Structural coolant piping and external sensors were attached in the first five weeks. A leak test showed no leakage to the outside, but seals on the current leads (that limit helium transfer between coil and superconducting buses) leaked excessively. After a month spent on modifying the seals, the coil was set in the test stand on August 17. Structural, helium, electrical, and instrumentation connections were made in the next two months. High-potential tests of the coil and sensor leads in October revealed defects in electrical insulation that took until late November to correct.

7.2.6 LCP Research and Development

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7.2.6.1 Coil monitoring

GE coil instrumentation. Work on electrical diagnosis of the GE coil was organized and initiated during January. ORNL scientific personnel performed measurements on the coil in its location at ORGDP. Continuity and resistance measurements of the GE coil sensors and heaters were made at the ends of their leads. Both ac and dc voltage-gradient measurements were made to determine what, if any, changes had occurred between the time when attempts were made to burn out a shorted lead at GE (May 1982) and the arrival of the coil at Oak Ridge. No change was discovered.

Findings were as follows. One voltage tap lead is open, another is missing, and others appear to be in good condition. Two carbon-glass thermometers are open; others are acceptable. One heater is shorted to the conductor. Two thin-film thermometers have open leads. One thin-film thermometer (TFT-14-B) is shorted to the conductor. Confirmation was obtained by charging the coil to 0.1 A and discharging it across 100, 250, 500, and 1500 Ω while monitoring the induced voltage in the shorted turns and comparing this value to the voltages in the two pies nearest the short, as well as the voltage across the entire coil. The insulation between the windings and the coil case appears to be good.

Examination of photographs and other manufacturing records indicated that the short associated with TFT-14-B was most likely a section of 32-gage wire, about 5 cm long, across three or four turns of conductor.

On March 3, the data were discussed with consultants R. J. Thome of the Massachusetts Institute of Technology (MIT) and L. R. Turner of Argonne National Laboratory (ANL) in a meeting at Oak Ridge. One result was a recommendation to attempt a room-temperature burnout of the shorted sensor lead. The one shorted heater will not be used in coil testing. It was agreed that the discharge resistor would be changed to reduce dump voltage during operation—the value to be determined by further analysis. The condition of the coil did not appear to require that its operation be otherwise limited.

Plans were made for further analysis by the consultants to establish parameters for burnout attempts and to provide a better basis for decisions on operation. Subsequently low-current dump tests will be performed at liquid-helium temperature during startup to provide more confirmation.

GE coil short resolution. After meeting in March with consultants from MIT and ANL, ORNL staff provided them with additional information needed for their computer modeling (i.e., dimensions of the coil, details on turns per pancake, details on pie with short, and con-

ductivity of the steel bobbin). Subsequent calculations performed at MIT fairly well duplicated the low-voltage transient data that J. F. Ellis took on the GE coil here in Oak Ridge. With confidence thus established, further calculations were done to evaluate burnout techniques. By late June we were certain that we could only burn out the short and not vaporize or disintegrate the short wire (32 gage). Measurements by S. S. Shen showed that the energy must be deposited in the short on the order of a millisecond or less in order to vaporize the wire. Calculations by Thome (MIT) have established that we cannot put the energy in the short much faster than 100 ms due to the time constant (shielding) of the coil bobbin unless extremely high and dangerous discharge voltages are used.

The short in the GE coil caused by a TFT sensor lead was successfully burned out on June 27. Burnout was accomplished by inducing current in the shorted loop by the application of 800 V at 3.25 A, 60 Hz (ac) to the coil terminals. The burnout required about 1 s and was indicated by a slight but sudden increase in voltage across the loop, as indicated by a differential scope trace between the TFT-14-B leads and a voltage tap (VT-28). The power required was consistent with calculations by Thome. Following the burnout, temporary terminal boards were mounted in the stack, and all sensor and heater leads were attached to it. Continuity, resistance, and dc-voltage gradient measurements were made of all sensor leads. The coil was charged to 100 mA (dc) and discharged through a 100- Ω dump resistor, and the voltage-decay rate across the previously shorted loop was recorded. This, when compared to the decay characteristics of the loop before the burnout and to the whole coil before and after the burnout, indicated that the wire shorted to the coil had indeed been melted through.

During July 1-3 and again on August 23, the continuity of all the sensor leads in the coil was measured and a dc-voltage gradient test was performed by Fusion Energy Division personnel at the ORGDP shops. Between the

two sets of tests the bolts had been tightened, welding had begun, and the coil had been turned over several times. Results indicated no significant change in the condition of sensors and leads, except for one voltage tap (VT-24) at which lead resistance increased (indicating something had partially opened up) and one carbon-glass thermometer (CG-3-A) that became noisy (presumably due to some kind of damage).

GE structural analysis. The GE unsupported conductor in the service stack was re-examined, and there did not appear to be any problem with the stress levels in either the conductor or the insulation. The winding pack was predicted to bulge approximately 1.5 mm (0.06 in.) into the service stack for the loading case considered. The design of the GE lead exits, lead block terminators, and related structure must be reviewed to ensure that an unrestrained relative movement of this magnitude can occur. If not, minor modifications will be necessary.

Westinghouse LCP coil. A staff member visited the Westinghouse plant at East Pittsburgh, Pennsylvania, to witness high-potential tests of the groundwall insulation on Conductors D and C in Plate 2. Conductor D was ramped with negative voltage to breakdown, failing at 31 kV. Conductor C received ten ramps to +20 kV and ten ramps to -20 kV, with a 20-s hold at maximum voltage for the first five ramps at each polarity. Leakage current was less than 1 μ A in all cases. Conductor C was then ramped to 40 kV and held for 10 min, with a leakage current of 27-35 μ A. Conductors A and B were tested later. Both sustained 60 ramps to 20 kV with a polarity change every ten ramps, followed by 1 min at +40 kV on Conductor A and 1 min at -40 kV on Conductor B, with no breakdowns. Hence, the groundwall insulation should sustain the maximum test voltage of 16.5 kV envisioned for proof testing during coil manufacture without difficulty.

Westinghouse manifold. A mockup of a Westinghouse large coil coolant manifold with "Chemglaze" coating was thermally cycled to

liquid-helium temperature and back. Despite earlier successful tests with the current Chemglaze application procedure, the manifold coating was cracked badly during the test, especially near the welded-on, vertical, helium supply/return riser. Further tests were conducted at Westinghouse with two Emerson and Cumming materials, Stycast 2850 FT and Eccocoat 582, which we have used with good success. Both materials survived thermal cycling, but the Eccocoat had unacceptable electrical strength. It appears that a coating of seven alternating blue and black layers of Stycast 2850 FT will have sufficient dielectric strength and thermal cycling capability. Thinning the resin with 7% (by weight) toluene allows spraying with procedures very similar to those for the Chemglaze, although extra curing time will be required.

Westinghouse/Airco LCP conductor. Tests at ORNL measured the resistance of the welded cable joints in the Westinghouse/Airco LCP conductor. Values less than 10^{-9} Ω were found, a low enough resistance to ensure good performance.

Preparations were made to obtain high-sensitivity measurements of the superconducting strands after reacting, straightening, rebending, and handling to see if there is sufficient current-carrying property per strand to make the loss of the strands with resistive joints of no consequence. (In a typical length of conductor, 20 to 40 of the 486 strands contain strand joints.)

Tests were performed at ORNL in June to measure any deleterious effects of bending in the swage and in the cable-swage transition region. Two samples prepared at Westinghouse and Airco were connected in series, arranged so that transition and about 15.24 cm (6 in.) of the swage were in the high field. An additional 8 cm (3.15 in.) of swage was in a magnetic field, dropping from maximum to about zero. At zero field and at 6 T, no significant voltage (sensitivity was about 5 mV) appeared up to almost 20 kA. At 8 T, some damage occurred to one of the transitions, and a voltage of about 10 mV appeared

just above 20 kA. Because the samples will be operated at about 16–18 kA in a field of about 5 T, there appears to be no problem in normal operation.

Eight samples of full-scale LCP conductor plus two resistance-welded joints were tested in a split solenoid capable of up to 8 T over a conductor length of 15 cm. The available current supply could provide 24 kA into two samples connected in series with a joint at the lower and in a low-field region. The samples included sections of the transition between swaged end and cable, good quality conductor, and some conductors that were heavily sintered. All were bent around various diameters, then straightened for testing. In six of the eight samples, the critical current at 8 T was greater than 24 kA. Thus, a quantitative determination of degradation due to these various factors could not be made for these samples. However, the fact that only two samples of the eight tested showed degradation to about 21–24 kA at 7.6 T gives confidence that the conductor performance should not be limited by the various bending operations in the coil, if the conductor is handled carefully. The resistance-welded joints tested showed a resistance of $10^{-9} \Omega$ at 20 kA and 3 T—a satisfactory value for the LCP coil.

Quench pressure in the Westinghouse LCP coil. A brief analysis of the quench pressure in the Westinghouse LCP coil was carried out. The analysis included consideration of (1) whether an entire hydraulic path quenches all at once or whether the quench starts locally, (2) the effect of the swaged ends necessitated by the short-conductor problem, (3) whether or not the coil is in extended operation (Alt. C or E), and (4) whether or not the normal zone triggers an immediate dump. The analysis was based on recent experimental and theoretical work done at ORNL. The upshot of the calculations was that the Westinghouse LCP coil could probably withstand quenches that originated from local disturbances but that stress levels exceeding yield strength might occur in the conductor sheath if an entire hydraulic path quenches all

at once. The initial testing of the coil will determine if extended operation can be carried out. In the unlikely situation of an entire hydraulic path quenching simultaneously, extended operation would not be practical due to the possibility of structural damage.

Tests of pressure taps for Westinghouse conductor. Testing was done to evaluate three different types of pressure taps that had been considered for the Westinghouse conductor sheath. Three test samples were fabricated by a variety of Y-12 Maintenance personnel using sheath samples previously reacted by Airco. Each sample had three or four identical taps. Seven of the taps were installed with reinforcing buttons and a silver braze (Easy Flo 45), which Westinghouse is presently using at several places in its coil and which can be applied without degrading the strength of the full-processed JBK-75 sheath. The remaining three taps were made by welding the 304L capillary tube [3.175-mm (0.125-in.) OD by 0.86-mm (0.034-in.) wall] directly to the sheath, with no attempt made to recover the strength of the sheath material annealed during the welding. When tested in liquid helium, none of the ten samples failed when the sheath and taps were pressurized internally to approximately 26,000 psi—the highest pressure that could be produced at the Y-12 MID Pressure and Vacuum Laboratory. This 1800-atm test pressure is substantially larger than the Westinghouse design pressure of 180 atm.

General Dynamics-Convair coil. During July and August, an intensive effort was made to develop improved seals for the high-current feedthroughs on the GDC coil. This was successfully accomplished in a three-week period. When leak tests disclosed excessive leakage by the feedthrough seals, a simple test stand was assembled in the laboratory to permit testing of mockups of the GDC seals and proposed alternatives. Disassembly and inspection of the coil feedthroughs revealed that the copper and stainless steel surfaces were not coplanar and that there had not been a complete sealing of urethane between the G-10 bushings and the metal surfaces. By then,

moreover, mockup tests had shown that even if well fitted, joints similar to the GDC design developed excessive leakage after cycling to cryogenic temperatures. Therefore, a program decision was made to explore alternative concepts. A series of mockup tests led to a choice of indium wire gaskets, trapped in grooves and compressed during final assembly of the seal parts. The coil seals were modified in this manner and were shown to have acceptably low leak rates.

7.2.6.2 Large Coil Test Facility

Two-coil LCTF operation. Consideration was given to the question of feasibility of testing the JA coil if the GDC coil has a leak (e.g., such as the JA coil suffered in their domestic test). If the GDC coil leaks, heat transfer by direct molecular collision from the tank wall to the JA coil will increase. It was calculated that the JA coil probably cannot be operated at an ambient pressure higher than 10^{-4} torr. The LCTF vacuum pumping system can keep the pressure below this value if the leak in the GDC coil is about $1.2 \text{ torr} \cdot \text{L} \cdot \text{s}^{-1}$. The conclusion was that if any leaks in the GDC coil (e.g., at the instrument feedthroughs) are no worse than those reported for the JA coil, it should be possible to operate the JA coil and complete the testing program.

Protecting dewars from rupture. A simple formula was developed for the diameter of the vent pipe from an open dewar that will keep the maximum quench pressure below some predetermined level. The diameter D of the vent pipe (m) is given as $D = 0.76 \dot{Q}^{1/2} \rho_o^{1/4} P_{\max}^{-3/4}$, where $\dot{Q}$ is the power into the dewar (W), $P_{\max}$ is the maximum pressure in the dewar (Pa), and ρ_o is the helium density ($\text{kg} \cdot \text{m}^{-3}$) at the time the maximum pressure is attained. According to an estimate based on the above equation, a 15.24-cm (6-in.) vent pipe (GDC coil) can safely handle fast dumps even if 10% of the magnet energy is dissipated in the dewar (i.e., 90% of the stored energy is removed and deposited in the dump resistor).

Tests of LCTF tank high-voltage feedthrough. A sample of the proposed Douglass Engineering isolated-flange feedthrough was ice chilled, leak tested, and high-potential tested to 5 kV dc and 60 Hz ac in the presence of 5 mtorr to 1 atm of helium gas. No gas leakage was detectable with 2×10^{-9} torr background. No dc leakage was detected with 10^{-7} -A meter sensitivity or by eye in a darkened room. With alternating current, leakage current was linear with voltage; the first discharge was visible at 3 kV (rms) (60 μA). With 200-V (rms) ripple superimposed on 4800-V dc current, 35- μA leakage was observed, without visible discharge. Finally, LCTF dump breaker action was simulated by repeatedly applying a 3.6-kV step function with 700-V overshoot; no discharge was noted. Posttest visual examination of the feedthrough, potting, and carefully handled in-tank cabling (using a low-power binocular microscope) did not show degradation. The potted feedthroughs are considered acceptable for use at the LCTF tank wall.

LCTF power supplies. Tests at PWR, Inc., in April and again in June showed that the three-coil power supplies then under construction had a 60-Hz ripple component that was slightly in excess of specified limits. During the week of July 25-29, J. F. Ellis (ORNL) and L. E. Nickels (consultant from Milwaukee, Wisconsin) went back to PWR to assist them in determining the cause of the unexpected 60-Hz ripple component. After a variety of tests, it was concluded that the 60-Hz component was the result of a mixture of the second harmonic in the delta section (120 Hz) and the third harmonic in the Wye section (180 Hz); that is, the "beat note" of the two harmonics was 60 Hz.

It was further concluded (with agreement by all parties) that to eliminate the source of the problem (assuming the analysis was correct) would require extensive rebuilding of the main power transformers, the results of which would still be uncertain. Furthermore, it was unanimously concluded that the latest measured ripple was only slightly out of specification and

that the addition of a few more capacitors to the filter would bring it to within specification.

As soon as PWR completed the suggested modifications, Ellis returned to repeat the ripple tests on the two 25-kA and one 16-kA power supplies. In tests performed Aug. 28-30, all measurements (excepting one) indicated that the ripple of all three units was within specification. The one case that was out of specification occurred only with one unit with one set of parameters (in one mode) when the peak-to-peak 60-Hz ripple component reached 325 mV (the specified limit is 250 mV). PWR filed a deviation request to cover this one case, and the three supplies were shipped to the LCTF. Plans were made for final-acceptance testing after installation.

7.2.6.3 LCTF verification testing

General Electric coil/UCC-ND. The first superconducting bus duct for the GE coil was high-potential tested in both ambient air and pressurized helium gas. The duct held 5 kV for 30 s in both air and 4 atm (absolute) of helium. As the helium pressure was reduced to values of 3, 2, and 1 atm, current leakage was noted at voltages ranging from 4.5 kV down to 2.7 kV. These tests indicated that the duct should provide 5-kV insulation when filled with 1-atm liquid helium or helium gas at temperatures up to 75 K.

General Dynamics-Convair coil. The vapor-cooled lead pair destined for installation in the GDC position of the LCTF was tested at currents up to the design current (16 kA). The leads have high thermal inertia, well beyond requirements, and have acceptable standby losses. However, they do not meet specifications for helium consumption at the design current (about 10% over specifications). In addition, they are apparently not fully stable in the self-demand mode at the design current; both leads showed a slow, but steady, increase in voltage with time.

Japanese coil. At the request of the JA on-site representative, both of the current leads for the JA coil were high-voltage tested in

1-atm helium gas. Each lead was mounted in an LCTF lead dewar, so that the electric fields around it would be the same as during operation. Helium gas was purged through the dewar until an oxygen analyzer showed an oxygen content of less than 0.5%. Both leads successfully withstood +3000 V dc (10% more than the test voltage for the JA coil) for 1 min.

Pulse coil. Ceramic electrical breaks manufactured by the Latronics Corporation are used to supply liquid nitrogen to individual pancakes of the LCTF pulse coils. These are specified to withstand 6000 V (rms) (8485-V peak) in 1-atm, 77-K nitrogen gas. Because the coil groundwall insulation will probably withstand much higher voltages, the ultimate breakdown voltage of these breaks is of interest. A mockup containing a break, adapter coupling, and hollow coil leads was suspended in cold gas just above the surface of a liquid-nitrogen bath and tested for high-voltage flashover characteristics. The ceramic break withstood 5 min at 10 kV dc with no sign of electrical breakdown and 1 min at 20 kV with slight audible corona discharge. If the electrical current feedthroughs made for the coils by the same manufacturer show similar withstand voltages, it should be possible to increase the discharge rate on the pulse coils to better simulate a plasma disruption.

7.2.6.4 Testing and analysis support

Quench detection in cable-in-conduit superconductors. Calculations were performed at ORNL with results that suggest that a nascent quench in a hydraulic path of the Westinghouse coil will cause a noticeable thermal expulsion of helium from the ends of the path in the first half second. The change in outflow can serve as a cheap and reliable quench-detection system. Quench detection is potentially a very important problem in tokamak systems in which plasma disruptions and other noise may preclude electrical means from serving as a reliable quench-detection system. However, even if voltage-tap signals can be

used in a noisy environment for quench detection, pressure measurements may still be useful as a backup or redundant method.

Computer developments. A modular set of computer codes was developed to calculate the intrinsic calibration curves for the GDC coil sensors. Those sensors that have been curve fitted using the computer codes are the carbon-glass and germanium thermometers and the magnetoresistance and Hall probes. Plans were made to use the same codes on the Euratom sensors.

Instrumentation. Of the 30 planned Acoustic Emission (AE) sensors, 27 were mounted on the GDC coil case and nearby structures. MIT and ORNL personnel completed checking of these sensors. A test report describes these sensors in detail and presents the calibration data. Similar sensors are planned for both the Euratom coil and JA coil.

7.3 12-T COIL DEVELOPMENT PROGRAM

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7.3.1 12-T Development Program—IGC

Under a material development contract, Intermagnetics General Corporation (IGC) has delivered a multifilamentary (MF) Nb_3Sn cabled conductor with a design critical current in excess of 20 kA at 12 T in He-I at 4.2 K. The 5.2-cm by 1.1-cm conductor, which consists of 672 external bronze-process MF Nb_3Sn strands and 1680 barrier-protected stabilizer strands, was wound and reacted on a test mandrel designed to allow test in our Coil Winding Test Experiment (CWTE) High Field Test Facility (HFTF).

7.3.2 Internally Cooled Superconductor

A 62-m-long internally cooled superconductor (ICS) was fabricated and shipped to the Swiss Institute for Nuclear Research (SIN) in Villigen, Switzerland, for test in the SULTAN

facility (a joint collaboration among the Netherlands, Italy, and Switzerland) at fields up to 11 T and temperatures down to superfluid He-II (1.8 K). Strands of the ICS are Cu/NbTi composite and copper with an overall copper-to-superconductor (Cu:SC) ratio of 2.3:1. Void fraction available for the flow is about 33%. Estimated critical current (I_c) for the cable is about 3100 A at 8 T (1.8 K) and about 1500 A at 11 T (1.8 K). Normalizing heat pulses will be delivered to the conductor by discharging a capacitor bank through an induction heater coil wrapped tightly around the conductor. We have also provided analysis of the energy transferred to the conductor for sizing the induction heater coils and capacitive discharge power supply to be used in stability testing. It is expected that this conductor will be wound into a 0.6-m-diam coil for testing in SULTAN.

7.4 ADVANCED CONDUCTOR DEVELOPMENT

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7.4.1 Quench Energies of Potted Magnets

Formulas for the quench energies of potted magnets have been obtained for two extreme models of the winding: (1) treating it as an anisotropic three-dimensional (3-D) continuum and (2) ignoring heat conduction in the epoxy and treating it as a one-dimensional (1-D) continuum. The formulas are fixed, up to an undetermined constant, by a combination of dimensional and group-invariance arguments. The constants are estimated by solving the heat-balance equation with the method of local similarity. The formulas have been compared with experimental data of C. A. Scott (from the 1982 Saclay Stability Workshop), and agreement is good. The formulas may be used to select stability-optimized conductor compositions. A paper has been written about this work (submitted to *Cryogenics*).

7.4.2 Transient Heat Transfer in He-II

The clamped-flux problem of transient heat transfer, solved earlier in plane geometry, has been studied in cylindrical geometry. There is an interesting difference between the two geometries. Whereas in plane geometry the clamped-flux problem has no steady state, in cylindrical geometry it does. This means that in plane geometry the heater temperature always rises, eventually reaching the transition temperature between superfluid helium He-II and normal helium (burnout) He-I, no matter what the flux. In cylindrical geometry, on the other hand, the heater temperature may level off at a temperature less than the superfluid transition temperature for low enough fluxes.

7.4.3 Similarity Solution for Transient Heat Transfer in He-II

A similarity solution in analytic form of the Gorter-Mellink heat-balance equation has been found for the problem of a pulsed-point source in a long channel. This problem has been studied experimentally by Van Sciver³ at the University of Wisconsin, who measured temperature profiles (ΔT vs z) at various times t . Written in terms of the similarity variables $\Delta T \cdot t^{2/3}$ and $z/t^{2/3}$, all of Van Sciver's temperature profiles collapse to one single curve. The curve calculated from the similarity solution agrees extremely well with the measured curve. A paper describing this work and earlier related work was presented at the 1983 Cryogenic Engineering Conference.⁴

7.4.4 Applied Superconductivity Problems Text

The method outlined in the book *Similarity Solutions of Nonlinear Partial Differential Equations*, by L. Dresner,⁵ has been used to solve a variety of practical problems of applied superconductivity. Among the problems are the distribution of current among the filaments near current leads, transient heat transfer in superfluid helium, thermal expulsion of helium

from quenching cable-in-conduit superconductors, and quench energies of potted magnets.

7.5 MAGNET TECHNOLOGY

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7.5.1 EBT-P Magnet Development Program

The *first development* coil (built by ORNL and encapsulated in a dewar by GDC) was tested to a maximum field of 5 T (60-GHz resonance field) a number of times at different ramp rates. The coil performed well, but there are still some concerns about the cryogenic performance of the dewars and cryogenic system used in the tests. The coil could be charged to full field in 1 min and 40 s, which was the fastest rate consistent with safe operation of the protection system. The rate of charging was not limited by the magnet stability or power supply voltage, but rather by the instrumentation in the quench-protection circuit. The field was held at 5 T (60 GHz) for 30 min to show steady-state operation and to measure helium boiloff. The magnet was further tested to its fully rated maximum field of 7.5 T (90 GHz) in a 10-min charging rate from the 60-GHz field. It was held at this maximum field for 5 min and then manually dumped.

As pleasing as these results are, the really exciting results are the simulated X-ray heating loads at the 60-GHz field. Although the design value is 10 W, the calculations indicated that no more than 2 W will be imposed on the magnet. Therefore, it was quite pleasing to see that an order of magnitude over the anticipated heating or 20 W could be sustained by the magnet for a steady-state period, some 10 min, without any difficulty other than a slight rise in dewar pressure and, therefore, a slight rise in bath temperature to about 4.4 K.

During the heating tests, it is necessary to continuously fill the dewar because it does not

have the capacity to hold enough liquid helium to complete the test. Instead of filling the dewar at the top to allow the liquid-helium surface to act as a phase separator, the bottom fill line was used. This means that the coil was cooled by a mixture of helium vapor and liquid helium. This method is very similar to the flooded system being planned now for EBT-P. The coil operating properly under these conditions is a very good indication that the flooded design will work in EBT-P.

The static boiloff rate of the dewar is the expected rate of 14 L/h; however, when trying to continuously fill the dewar during a long test, like the heating test described above, the apparent usage rate is 2 to 3 times higher than the static boiloff rate. We do not have a satisfactory explanation for this condition.

Open dewar testing of the *prototype* EBT-P superconducting coil was successfully completed at ORNL in early March by the ORNL-McDonnell Douglas-General Dynamics magnet development team. The magnet was charged to the levels required for both 60- and 90-GHz operation at rates slightly in excess of 0.5 kG/s (i.e., full field in 1.75 and 2.5 min, respectively) without training or undergoing a quench. Simulated X-ray heating tests of up to 20 W were applied for 10 min at both the 60- and 90-GHz levels of operation without any effect on the magnet stability. Considering the design criteria of about 0.05 kG/s and 10 W of X-ray heating, these tests (along with earlier development magnet tests) continue to support our confidence in the design of the superconducting magnet, which is a key component of the EBT-P Project. General Dynamics is to be congratulated for producing a superior prototype.

The performance characteristics of the prototype and development coils were quite comparable, except for the ability to sustain X-ray-simulated heating load at 7.5 T (90-GHz operation) where the prototype coil was superior. The superior conductor of the

prototype coil (conventional monolith with CuO coating, compared to the development coils' 100% compacted cable with bare surface) enabled it to withstand 20 W of steady heating, whereas the development coils could withstand only 10 to 20 W.

An abbreviated version of the single-coil test of the second development coil (the one with possible copper-finger contaminants) was completed. The main purpose of the test was to determine if the copper fingers that had broken off would create problems. To complete the test in the one-day period available, we did not do a simulated X-ray heating test. D2 operated perfectly in the tests and showed no evidence of degradation due to the broken copper fingers.

7.5.2 Copper Coils for ATF-1

The conductor for the ATF-1 helical coils is made of a copper bar with a 3.5-cm (1.375-in.) by 14-cm (5.5-in.) cross section. Sixteen half-turns of these conductors are nested together and potted in a bundle. During assembly, each conductor butts up to its matching conductor in the adjacent bundle. Making reliable demountable joints presents quite an engineering challenge. Originally, these were intended to be bolted joints, but it is hard to conceive of bolted joints that are both electrically and mechanically reliable.

We therefore proposed a concept that looks promising. It involves filling a split hole at the butted interface with MIG welding. The feasibility of this approach can be determined by some bench tests in the welding lab. For disassembly, the welded hole is drilled out (or the whole bundle can be sawed apart). Another concept that may prove feasible is a soft-soldered, dogbone-shaped locking piece that slips into the butted ends of each conductor. The dogbone pieces will have embedded tubes. A torch blowing through the tubes will melt the soft solder during assembling and

disassembling. The tube could also carry water for additional cooling during coil operation.

Many of the potential bidders for the ATF prototype helical-coil segments expressed concern about meeting the tight tolerances for the copper conductors. Consequently, the new plan is to receive from the supplier conductors that fit in a liberal window size. The final precision shaping of each conductor will be done just before the coil segment is assembled. To verify stiffness calculations on such a twisted shape, a single full-scale conductor was fabricated and annealed in our shops. After this conductor was supported in the middle and at one end, a force was applied to the edge of the free end. The copper began to yield with forces that were in excess of 136 kg (300 lb). A force greater than 45.4 kg (100 lb) was required to induce yielding on the flat side. These forces are manageable, and we concluded that final shaping before assembly is a reasonable

approach. Hopefully, this approach will help lower the manufacturing cost.

7.5.3 ATF Helical Field Coil Joint Tests

The ATF helical field (HF) coils will be fabricated by joining together 24 coil segments. Probably the most critical task for the ATF device will be fabrication and assembly of reliable, low-resistance, segment joints. Many joint concepts have been proposed and the most promising ones were tested in our laboratory. The conductors tested were one-half width so that our power supply could approach the rated steady-state current densities ($\sim 10 \text{ kA/in.}^2$) needed for ATF. The first mode of operation was pulsed at $\sim 20 \text{ kA/in.}^2$, but joint cooling is more critical in the steady-state mode. Our test fixture also applied a tension force to the joint [$\sim 1134 \text{ kg}$ ($\sim 2500 \text{ lb}$)], while the current was flowing. All the proposed joints will be fully tested and evaluated before the decision is finalized in March 1984.

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Chapter 8

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8. ADVANCED SYSTEM STUDIES

Summary of Activities

Advanced system studies at ORNL are comprised of the activities of the Fusion Engineering Design Center (FEDC) and the Fusion Environmental Assessment Program. These activities in 1983 included work on the preconceptual designs for the Tokamak Fusion Core Experiment (TFCX), an upgrade of the Mirror Fusion Test Facility (MFTF- α +T), the International Tokamak Reactor (INTOR), and the generic environmental impact statement (GEIS) that will be required as fusion technology approaches commercial reality.

During 1983 the Design Center progressed toward its goal of defining the next step in the national magnetic fusion program as the TFCX concepts were defined and initial comparative evaluations were initiated. The emphasis this year has been on meeting the mission objectives at low cost. Two concepts received major design attention. These were the all-superconducting toroidal field (TF) coil concept and one design (the hybrid) that incorporates a copper resistive-magnet insert to augment the toroidal field on-axis. Preconceptual design support was also provided to Lawrence Livermore National Laboratory (LLNL) on the definition of the MFTF-B upgrade (MFTF- α +T). As a major participant in the INTOR activity, significant involvement was directed at critical design issues, including configuration, impurity control, and auxiliary heating.

8.1 FUSION ENGINEERING DESIGN CENTER

8.1.1 Introduction

The Design Center (Fig. 8.1) was established in 1978 by the U.S. Department of Energy (DOE) as a centralized laboratory/industry team hosted by ORNL and responsible for developing the design of the fusion device to follow the Tokamak Fusion Test Reactor (TFTR).

The work performed in 1982 on upgrades of TFTR and MFTF-B evolved into significant work during 1983. The work on TFTR upgrades narrowed to focus on an all-superconducting TF coil device (TFCX-S) and a hybrid device that employs superconducting

TF coils and copper TF coil inserts. These devices were configured to satisfy two principal mission objectives: (1) ignition and (2) long-pulse operation.

The MFTF-B upgrade effort was focused principally on a version designated MFTF- α +T; whereas the TFCX machines were new devices, the MFTF- α +T is a modification and an eventual replacement for MFTF-B. The mission for MFTF- α +T features aggressive end-cell physics, production with deuterium-tritium (D-T) fuel of reactor-like nuclear conditions, and integration of technologies representative of a demonstration type of device. In 1983, the FEDC resources were equally applied to tokamak and tandem mirror programs.

Fig. 8.1. Fusion Engineering Design Center building.

8.1.2 Tokamak Fusion Core Experiment

Work on TFCX began in 1982, with the definition of a series of concepts to be considered as upgrades to TFTR. Work on these concepts and their evolutions was carried into 1983. For the major part of 1983, design and analysis activities focused on two designs: (1) TFCX-S, using all-superconducting TF coils similar to the Fusion Engineering Device (FED) Baseline of the previous year¹ but smaller in size, and (2) TFCX-H, using superconducting TF coils supplemented by copper TF coils.

The mission of the TFCX concepts became one of achieving ignition, demonstrating a long-burn capability, and implementing as many reactor-relevant technologies as feasible.

Toward the end of the year, the FEDC was asked by DOE to consider concepts employing all-resistive TF coils. Work was initiated both at Princeton Plasma Physics Laboratory (PPPL) and at FEDC. The Princeton work concentrated on discrete copper TF coils, while the work at FEDC included both discrete and continuous copper coils. The discrete coil concept is designated as TFCX-DCTF, and the

continuous copper coil concept is labeled TFCX-CCTF.

The following discussion, organized on a functional subsystem basis, is generally applicable to all concepts. Notable exceptions are in the systems' trade studies and TF coil details.

8.1.2.1 Options

At the end of 1983, the options for TFCX consisted of TFCX-S, TFCX-H, TFCX-DCTF, and TFCX-CCTF. Figures 8.2 through 8.7 are configuration drawings. Summaries of the major machine parameters are presented in Tables 8.1 through 8.4.

Major parameter variations studied this year were in the peak toroidal field. This variation was 8 and 10 T for TFCX-S and TFCX-H both. In the copper coil designs, the plan was to study so-called high- and low-field (on-axis) configurations. At the end of 1983, the low field (4.3 T on-axis) was being studied for the discrete coil case, and the high field (6.1 T on-axis) was being studied for the continuous coil configuration.

Fig. 8.2. Elevation view of TFCX-S.

Configuration work on the hybrid and the all-superconducting options based on the 1983 design guidelines is complete to the point at which valid comparisons may be made with other options. Figures 8.2 and 8.3 illustrate the elevation and plan views of the TFCX-S. Included in Fig. 8.2 are some of the details of the installations, such as coolant line routing beneath the device. Shown in Fig. 8.3 are layouts of the lower hybrid resonant heating (LHRH) coax lines and the coolant line manifolds. The major parameters for the TFCX-S are shown in Table 8.1. A major design effort has been expended in developing the design details of the major components in order to understand how they impact the overall reactor

configuration and to establish a basis for costs that is as accurate as possible.

The TFCX-H elevation and plan views are shown in Figs. 8.4 and 8.5. Design details for this concept were developed only for those components affected by the unique features of the TFCX-H. The elevation view (Fig. 8.4) shows cuts through the TF coil on the right and through the center of the replaceable shield module on the left.

During the development of the general configuration drawings, detailed layouts were completed to assess key areas of the configuration. These areas are the limiter, copper TF coil insert and intercoil structure, removable shield module, and poloidal field (PF) coil arrange-

Fig. 8.3. Plan view of TFCX-S.

Fig. 8.4. Elevation view of TFCX-H.

Fig. 8.5. Plan view of TFCX-H.

ment. This assessment concluded that the configuration concepts are valid for the final parameters of the TFCX-H, with minor dimensional changes. The final parameters are shown in Table 8.2.

Toward the end of 1983, copper TF coil concepts were introduced into the configuration options. The discrete copper coil approach is being developed by PPPL, with FEDC reviewing and critiquing the development. The initial

arrangement as presented to DOE in the official proposal for TFCX is shown in Fig. 8.6, and the major device parameters are shown in Table 8.3.

An additional task that FEDC assumed in support of the TFCX program is an evaluation of the Long-pulse Ignited Test Experiment (LITE) type of tokamak design as a candidate option for TFCX.² This work is being done in close collaboration with the Massachusetts

TFC COPPER TF CONFIGURATION

Fig. 8.6. Elevation and section views of TFCX-DCTF.

Fig. 8.7. Isometric view of TFCX-CCTF.

Table 8.1. TFCX-S parameters^a

Parameter	Value
Major radius, m	3.75
Minor radius, m	1.07
Beta (volume averaged), %	6.06
Plasma current, MA	7.70
Safety factor (axis)	0.95
Safety factor (edge)	1.98
Elongation	1.60
Upper triangularity	0.30
Lower triangularity	0.30

^aVolt-seconds (resistive) = 17.1;
volt-seconds (PF system) = 17.5.

Table 8.2. TFCX-H parameters

Parameter	Value
Major radius, m	3.60
Minor radius, m	0.97
Field on-axis, T	4.84
Beta (volume averaged), %	5.6
Plasma current, MA	7.23
Safety factor (axis)	1.00
Safety factor (edge)	2.00
Loop voltage, V	0.06
Bucking cylinder inner radius, m	1.12

Table 8.3. TFCX-DCTF parameters

Parameter	Value
Major radius, m	3.25
Minor radius, m	1.31
Aspect ratio	2.49
Plasma current, MA	10.5
Field on-axis, T	4.0
Beta, %	6.0
Fusion power, MW	240
Wall load, $\text{MW} \cdot \text{m}^{-2}$	0.91
Pulse length, s	445
TF resistive power, MW	460

Table 8.4. TFCX-CCTF parameters

Parameter	Value
Major radius, m	2.44
Minor radius, m	0.84
Plasma elongation	1.6
Inboard shield thickness, m	0.15
Magnetic field, T	6.13
Plasma current ($q = 2.4$), MA	8.11
Beta	0.051
$Q = (\eta E)_{\text{MIRNOV}} / (\eta E)_{\text{ignition}}$	1.5
Neutron wall loading, $\text{MW} \cdot \text{m}^{-2}$	2.33
Fusion power, MW	300
TF magnet resistive power, MW	276
EF magnet power, MW (for normal conductor)	125

Institute of Technology (MIT) staff. The FEDC staff, while retaining the continuous copper coil features of LITE, is considering alternate approaches to structurally supporting the coils. Figure 8.7 isometrically illustrates the LITE concept arrangement. Table 8.4 presents the LITE parameters as they were initially developed by MIT.

8.1.2.2 Plasma engineering

Plasma engineering tasks were accomplished in support of TFCX and consisted of plasma performance assessments, startup scenario

development, plasma control requirements, and an evaluation of alpha particle losses due to TF ripple.

8.1.2.3 Plasma performance assessments

TFCX-S plasma performance has been studied via WHIST code simulations with sawtoothing that is triggered when $q(o) < 1$. A discrete model flattens the plasma density and temperature within the sawtoothing region. Current-profile evolution is crucial in determining the extent of the sawtoothing region. The current-diffusion time scale is enhanced to advance the magnetohydrodynamic (MHD) equilibrium rapidly toward steady state. Finite operation times (≤ 300 s) require dynamic evolution of the current profile. Plasma performance operation contours are shown in Fig. 8.8. Table 8.5 gives the plasma parameters and confinement models used in this study. The minimum ignition point is at $1.1 \times 10^{14} \text{ cm}^{-3}$ and 14.8 keV, corresponding to 350 MW of fusion power, $\beta_T = 8.5\%$, $\beta_p = 0.8$, and $\eta\tau \sim 1.5 \times 10^{14} \text{ cm}^{-3} \cdot \text{s}$. A study of additional scalings will be included at a later date.

Fig. 8.8. Plasma performance operation contours in density-temperature space for TFCX: (a) quasi-static rf power, (b) fusion power, (c) toroidal beta, and (d) poloidal beta.

Table 8.5. Plasma transport models

Scrape-off layer: 0.1 m
Fueling by gas puffing and recycling at wall
Electron energy confinement: $\chi_e = 2\chi_e^{neo} + \chi_e^{GMS}$
$\chi_e^{GMS} (\text{cm}^2 \cdot \text{s}^{-1}) = 65 [1 + 4(r/a)^2] a (\text{cm}) \sigma^{1/2} / I (\text{MA})$
Ion energy confinement: $\chi_i = 2\chi_i^{neo} + 1\chi_{iR}^{TF} + 1\chi_{iB}^{DB}$
Particle confinement: $D = 2D^{neo} + 0.2\chi_e^{GMS}$
Continuous sawtoothing
No impurities
TF ripple: ripple trapping (χ_{iR}^{TF}) + banana drift (χ_{iB}^{DB})
Sawtoothing for $q(r=0) < 1.0$
Local, instantaneous alpha particle power deposition
Ohmic heating
ICRH auxiliary heating (75% to ions, 25% to electrons, Gaussian spatial deposition)

Plasma control requirements. A conceptual control system design study was performed for TFCX to make a preliminary evaluation of several alternate control options that may be used for operation in the subignition and ignition ranges near the design point. During study operation, the plasma power input must equal the power losses from radiation and particle heating transport. Power input to the plasma is derived from two sources in the subignition range: (1) radio-frequency (rf) power injection and (2) alpha particle heating. When ignition occurs, the rf power is theoretically not needed if operation is in the inherently stable high-power, high-temperature region (Fig. 8.9). However, these conditions of stable alpha power and plasma temperatures may exceed the TFCX design point. If operation is in either the subignition range or the low-temperature ignition range, active feedback control will be required. The loss lines of Fig. 8.9 are based on Mirnov scaling; Fig. 8.10 is another scenario based on Hugill-Sheffield scaling.

Alpha particle losses due to TF ripple. The Monte Carlo, Fokker-Planck simulator

Fig. 8.9. Alpha power and loss power—Mirnov scaling.

(DESORB) has been used to study 3.5-MeV alpha particle losses due to TF ripple. A correction was made to the model for randomly distributing the alpha particle birth points in poloidal angle. The results of two, 1000-particle simulations are summarized in Table 8.6. For convenience, these studies were based on INTOR conditions and parameters.

Here, N is the number of Monte Carlo particles followed, of which N_{loss} hit the wall. The f values are the alpha power fractions to the ions (f_i), electrons (f_e), the thermal plasma (f_{th}), and wall (f_{wall}). The energy-loss spectra in Figs. 8.11(a) and (c) show substantial thermalization before loss. For the higher Z_{eff} case [Fig. 8.11(c)], there is less thermalization before loss, due to increased pitch-angle scattering by the (oxygen) impurities. Figures 8.11(b) and (d) show a strong localization

Fig. 8.10. Alpha power and loss power—Hugill-Sheffield scaling.

Table 8.6. Alpha particle losses

	Case 1	Case 2
Z_{eff}	1	1.5
N_{ion}/N	0.071	0.069
f_i	0.317	0.316
f_e	0.648	0.644
f_{th}	0.011	0.011
f_{wall}	0.024	0.029
Peak load, MW/m ²	0.34	0.23

of the wall loading between the TF coils, as well as strong peaking poloidally on the outboard wall. The higher Z_{eff} case [Fig. 8.11(d)] has slightly less localization, also due to pitch-angle scattering by the impurities.

Tokamak systems code. The third revision to the tokamak systems code was completed and is in operation. The systems code is a computer program that integrates the system physics parameters with the major physical and performance relationship of the subsystems, maintenance features, and facilities. An important output is system cost. This code is invaluable for system trade studies and for studying the impact of physics requirements on engineering characteristics. In this last revision, the following modifications were incorporated:

- New tritium processing subroutine
- New torus vacuum subroutine
- New remote-maintenance equipment subroutine
- New instrumentation and controls (I&C) subroutine
- Revised first-wall/shield subroutine
 - New neutronics model
 - Alternate rectangular bulk shield shape added
 - Option added to extend outboard shield beyond the outer TF coil leg
- Revised TF coil subroutine
 - Copper TF coils
 - Hybrid TF coils
- Revised TF electrical subroutine
- Revised ac power subroutine

8.1.2.4 Systems engineering

Systems engineering tasks in 1983 included system configuration development (discussed in Sect. 8.1.2.1), operation of the systems code to perform systems trade studies, engineering testing, and facility design (including tritium systems).

Systems code trade studies. A major trade study comparing the hybrid and superconducting options at maximum fields at 8 and 10 T was completed. Key parameters are listed in Table 8.7. A comparison of radial builds is presented in Table 8.8. Although the higher-field devices have smaller plasma radii, they are larger overall because of a higher

Fig. 8.11. INTOR energy-loss spectra and wall-loading distributions.

Table 8.7. Key parameters in $B_{\max}$ trade study for TFCX options^a

Parameter	TFCX-S		TFCX-H	
	8 T	10 T	8 T	10 T
Major radius, m	3.55	3.75	3.60	4.38
Minor radius, m	1.45	1.07	0.97	0.82
Volt-seconds required, V·s	12.6	17.1	18.9	25.5
Plasma current, MA	10.8	7.7	7.2	5.8
PF, MA-turns	68	79	78	85
Aspect ratio	2.44	3.51	3.71	5.35
Field on-axis, T	2.62	4.34	4.84	7.10
Beta	0.085	0.059	0.056	0.039
Electron density, 10^{14} cm ³	0.52	1.00	1.17	1.75
Energy confinement time, s	3.75	1.97	1.68	1.14
Neutron wall load, MW/m ²	0.3	0.9	1.1	2.1
Fusion power, MW	110	230	250	490
SC/CI, ^b MA-turns	46/0	81/0	63/24	121/34
ICRH power, MW	15	24	25	43
Relative cost comparison	0.88	1.00	0.97	1.24

^aConstants are $\kappa = 1.6$, $\delta = 0.3$, $q = 2.0$, ignition parameter = 1.0, $T_{\text{burn}} = 300$ s, $T_i = T_e = 13$ keV, rf-driven startup.

^bSC = superconducting; CI = copper insert.

Table 8.8. Radial builds in $B_{\max}$ trade study for TFCX options (all units in meters)

	TFCX-S		TFCX-H	
	8 T	10 T	8 T	10 T
OH bore	0.33	0.45	0.68	1.18
Bucking cylinder	0.11	0.15	0.15	0.24
TF coil	0.37	0.67	0.36	0.62
Shield	0.47	0.58	0.59	0.65
Plasma	1.45	1.07	0.97	0.82
Gaps, dewar, etc.	0.82	0.83	0.84	0.87
Major radius	3.55	3.75	3.60	4.38

volt-second requirement, increased shield/coil/bucking cylinder thickness, and increased difficulty in shaping the plasma. In all of the cases shown, the conditions held constant were: $\kappa = 1.6$, $\delta = 0.3$, $q = 2.0$, ignition parameter = 1.0, $T_{\text{burn}} = 300$ s, $T_i = T_e = 13$ keV, and rf-driven startup.

Tritium systems. The fuel processing and handling systems for TFCX were assessed for

two cases: (1) 20-s pulses, one run per hour for 6 h, and (2) 300-s pulses, six runs per hour for 6 h. All other cases could be handled by the same systems that handle these cases. Tritium inventories would be intermediate between these two cases.

The flow paths between the tritium systems are shown in Fig. 8.12. The solid lines are major gaseous tritium pathways; the dashed lines are secondary containment pathways. The main components needed for a tritium processing system have been determined and size dimensions established.

The atmospheric detritiation units are an integral part of any fusion plant in which tritium is used or produced. Their role is to remove from the atmosphere the tritium released from primary or secondary containments in areas in which tritium is handled on a routine basis. The units are required during normal, maintenance, or accident operations, and thus must be sized to handle all three conditions. When installed, the units are directly

Fig. 8.12. Tritium system flow paths for TFCX.

coupled to the ventilation systems and the venting systems used to maintain a negative pressure in the tritium areas. The units are part of the safety systems. They must either be redundant if supplied as one unit or be capable of supplying the capacity needed after the failure of one of several small units.

An analysis of the operating conditions expected within the TFCX plant was done to assess the minimum number of atmospheric detritiation systems needed. Both accident and maintenance scenarios were evaluated. The worst probable case was a release of 10 g of tritium in an accident in either the reactor building or the tritium processing building. A process flow rate of 0.2 vol %/min for the reactor should be adequate if all surfaces are designed to release any adsorbed tritiated water (HTO) at a rate 100 times faster than it is adsorbed. For the tritium processing buildings, a process flow rate of 0.5 vol %/min should be adequate, with the same qualification as above. Implicit in this analysis was the assumption that all buildings containing tritium routinely are relatively leaktight, that is, <1 vol %/h. The effects of the generation

and/or adsorption of HTO on surfaces in a given area for the 10-g release of either HT or HTO follow.

1. The minimum time required to attain $50 \mu\text{Ci}/\text{m}^3$ is four days.
2. The minimum time required to attain $50 \mu\text{Ci}/\text{m}^3$ during an HTO cleanup increases to six days if the release rate on surfaces is only ten times faster than the adsorption rate.
3. If the adsorption rate on surfaces is equal to the release rate for the HTO cleanup, tritium concentrations level off at approximately $400 \mu\text{Ci}/\text{m}^3$ after 10 d of detritiation.
4. To achieve cleanup in less than ten days to tritium levels of $50 \mu\text{Ci}/\text{m}^3$ with a process flow rate of 0.2 vol %/min requires that surfaces have to be designed such that the HTO release rate is 10 to 100 times faster than the adsorption rate.

The model used in the above analyses does not account for the elemental tritium that diffuses into surfaces, and the effect of cracks in surface coatings has not been addressed.

8.1.2.5 The torus and torus shield design

The overall torus of the TFCX-S and TFCX-H consists of the common cryostat, the replaceable shield modules, and the shield posts (Fig. 8.13). The common cryostat is made up of the ring modules and the window modules. The balance of the vacuum boundary is made up of the dome, the outer wall, and the doors.

The torus shield design consists of definitions of alternate concepts for the removable shield sector modules of the TFCX-S, proceeding to a level that permitted a reasonable cost estimate. The concepts differ principally in the nature of the bulk-shield material. One concept employs built-up steel plates layered in radial planes to minimize eddy current effects. The objective was to identify a least-cost approach. A second approach employs the steel material in

the form of balls. The structural steel encasement is similar for both concepts (Fig. 8.14). The steel balls are 1.3 cm (0.5 in.) in diameter; the packing fraction is 60% steel and 40% water. An outer layer of boron carbide and a layer of lead completes the shielding. A subset of the second approach is to borate the steel balls to replace the layer of boron carbide. Figures 8.15 and 8.16 show details indicating the design approach and the location of the steel balls.

A third approach is to use the layered steel plates in the inboard region and the steel balls in the outboard region. Table 8.9 is a summary of the shield costs. While the second option (steel balls) resulted in the least cost, it caused an increase in shield thickness in the inboard region of 10 cm and, hence, an increase of 10 cm in device major radius. For

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Fig. 8.13. Isometric view of TFCX-S.

Fig. 8.14. Structural steel shell for sector module.

this reason, the third option (a combination of plates and balls) was selected for the reference design.

8.1.2.6 Pumped limiter and inboard first wall

Limiter configuration and protective surface. A mechanical pumped limiter was designed for TFCX. Options for the limiter configuration and location in the torus were evaluated. As shown in Fig. 8.17, the limiter configuration

consists of a toroidal belt located at the bottom of the plasma chamber and features flat surfaces and a single leading edge for particle removal. The limiter surface consists of protective tiles that are directly exposed to the plasma; they are brazed to a water-cooled copper substrate.

The initial review of candidate protective tile materials was limited to materials in the low-Z regime. Materials considered were beryllium, beryllium oxide, and silicon carbide. Graphite

Fig. 8.15. Sectional details of the shielding concept.

Fig. 8.16. Sectional details of the shielding concept.

Table 8.9. Comparative shield costs

	Concept		
	1. Layered plates	2. Steel balls	3. Combination (1 and 2)
Structure	8,870,400	11,676,800	10,526,400
Bulk shield	15,208,000	7,963,200	10,232,000
B ₄ C	1,040,000	1,062,400	1,040,000
Lead	134,000	134,400	134,400
TOTAL COST	\$25,252,400	\$20,836,800	\$21,932,800

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Fig. 8.17. Limiter interface.

was precluded from consideration in these initial studies because enhanced sputtering erosion of graphite at elevated temperatures may excessively contaminate the plasma. An evaluation of limiter lifetime was performed, based on erosion due to sputtering and disruption melting and vaporization. Fatigue lifetime of the substrate was also examined and shown to be much less severe than the erosion lifetime limit. Beryllium oxide was selected as the reference tile material because it has the longest lifetime (13 h at full power).

The feasibility of fabrication of any of the candidate materials and the ability to survive thermal shock conditions are serious concerns. Evaluation of the stresses induced during the braze cycle indicated that small tiles (~1-2 cm square) are required. Studies of

the thermal shock heating conditions during plasma disruptions indicated that damage to the protective tiles is expected. However, since the nature of this damage is known, testing is recommended.

Limiter design for installation and removal. A conceptual design for the pumped limiter module for TFCX-S was completed. For each of 16 sectors, the limiter blade is segmented in two pieces to permit installation of the limiter through the limited access opening in the bottom of each sector. The general arrangement of the design and installation is shown in Fig. 8.18. The limiter blades are protected by a removable, expendable sleeve consisting of an actively cooled copper substrate with brazed BeO protective tiles. Support of the inboard end of the limiter is provided by matching

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Fig. 8.18. General arrangement of limiter.

machined rail fittings bolted to the limiter and the upper surface of the limiter access openings. The outboard end of the limiter is supported by bolted plates. Coolant manifolds are routed through the stainless steel core to provide cooling to the removable sleeve by lines connected by fittings that can be remotely welded.

Limiter removal is accomplished by removing the right segment first and then the left segment. The right segment is removed by translating the segment inward and downward to disengage and clear the inboard support and then outward to remove it from the sector. The left sector must be translated to the right side of the sector, inward and downward to clear the inboard support, and then outward to remove it from the sector.

Inboard first wall. Requirements for attachment of BeO disruption armor tiles to the inboard shield were examined. The contact conductance necessary to maintain 50-mm-thick tiles below 900°C is $3 \times 10^3 \text{ W/m}^2 \cdot \text{K}$. This conductance can be achieved by applying a contact pressure of about 2.7 MPa (~400 psi) between a bare BeO (uncoated) tile and a stainless steel surface. This contact pressure is unrealistically high for a bolted attachment.

The required contact pressure can be decreased by applying a layer of copper to the tile and/or shield surfaces. Copper may be applied to the stainless steel surface by roll bonding and may alternatively be applied to the BeO tiles by a coating process.

The thermal contact conductances are shown in Fig. 8.19 for several of the material combinations discussed previously. If a BeO tile is attached to a stainless steel shield with a thin layer of copper on its surface, a contact pressure of 0.34 MPa (50 psi) is required. A contact pressure of only 0.55 MPa (8 psi) is required if a layer of copper is applied to both the tile and to the shield surfaces.

Schemes for mechanically attaching the BeO disruption armor tiles to the inboard shield surface with copper layers applied to either the armor tile or to the shield surface are feasible.

Fig. 8.19. Thermal contact conductance of BeO protective tiles.

A mechanically attached tile technique is desirable because it permits individual tile replacement in situ. Further development and testing are required to ensure that the contact-pressure requirements can be reliably achieved.

8.1.2.7 Toroidal field coils

Several candidate superconductor TF coil technologies have been considered. Each requires development and includes:

- NbTi pool-boiled and superfluid cooled to 1.8 K
- NbTi forced-flow subcooled to 3 K
- Nb₃Sn/NbTi combination cooled to 4.2 K

A design using the second option was developed in the earlier FED Baseline design.³ Each of the other two designs was investigated in the TFCX studies.

A specific TF coil system was selected for preconceptual design for the TFCX-S. This configuration uses the first option noted in this

section, that is, an NbTi conductor cooled in a bath of 1.8-K superfluid helium. This conductor and cooling concept are being developed under a DOE 12-T conductor development program at General Atomic (GA).⁴

The NbTi winding can be cooled with saturated or subcooled superfluid helium. Each cooling option has advantages and disadvantages. For example, the refrigeration system is simpler for the saturated superfluid helium, as compared to that for the subcooled superfluid helium. Conversely, the conductor and winding perform better in the subcooled superfluid helium. Coil configurations using both superfluid helium approaches were developed. A system arrangement utilizing the subcooled helium is shown in Fig. 8.20.

Preliminary calculations were made to evaluate the feasibility of utilizing the superfluid-helium-cooled windings for the TFCX TF coils.

The GA conductor was used in this study. The coil windings are cooled with a superfluid helium bath. The TF winding utilizing the GA NbTi conductor was found to be feasible. The cable conductor is cryostable. A guideline from the Large Coil Program (LCP) is that each coil is designed so that it will recover to a superconducting state, should a one-half turn go normal. It has been verified that the TFCX superfluid-helium-cooled TF coils will meet this requirement. The permissible peak nuclear heating rate at the high-field conductor is estimated to be 9 mW/cm^3 , if only nuclear heat loads are considered. However, in practice, the coil must withstand other heat loads such as eddy current heating, conductor joint heating, and conduction heat loads from the warmer coil casing. Considering all heat loads, the permissible peak nuclear heat load is estimated to be approximately 5 mW/cm^3 .

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Fig. 8.20. Superfluid helium subcooled system.

Magnet windings. The winding layout arrangement was determined for the TFCX-S (all-superconducting option using superfluid-helium-cooled TF coil conductor). A structural analysis, which considers compressive winding loads both in the plane of the TF coils and normal to the plane of the coils (as well as dilational loads), shows that winding stresses are within allowables, except for a slight local over-stress condition in the centerpost region, where the effective (Von Mises) stress in the cowound conductor support channel is 3% above the allowable.

Figure 8.21 shows the conductor arrangement, as well as the double-wall case design. The conductor is cooled by He-II at 1.8 K, while the outer structural wall is cooled by He-I at 4.2 K. The conductor design is a modification of the GA design.³ In the design shown, the cowound support is a U-channel, whereas in the GA design, the support is a box completely surrounding the conductor strands. The use of the U-channel permits a higher winding current density.

The available winding space in the centerpost region accommodates 280 turns. To develop the ampere-turns needed to satisfy the

field-on-axis requirements, the TF coil conductor current must be 18 kA. Although the conductor was originally designed by GA to operate at 15 kA, the proposed operation at 18 kA was reviewed by GA and is considered feasible.

An alternate TF winding layout for TFCX-S using an NbTi internally cooled cable superconductor (ICCS) that operates at reduced temperature (approximately 3 K) was also developed. The conductor details and winding layout are shown in Figs. 8.22 and 8.23, respectively. The winding is a pancake, and each double pancake is wound with three conductors in parallel, to limit the length of the individual cooling paths for limiting the pressure drop to a reasonable value of 2 to 3 atm.

The helium manifolding, splicing, and current-lead details have been developed (Fig. 8.24). The helium inlet for the winding is located in the TF coil bore. The helium is supplied to the winding at the intersection between two adjoining pancakes. All of the

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Fig. 8.23. Winding configuration—internally cooled conductor.

splices, outlet helium manifolding, and current leads are located in the outer top region of the TF coils, where adequate space is available for making and adding support structure for splices. All the joints between pancakes are made in this region, whereas, at the helium inlet located at the bore side of the TF coil, a tubing would be carefully attached and welded. No conductor splices are made at the helium inlets. The helium manifolding region is epoxy impregnated and is mechanically supported with a stainless-steel-box-type structure (Fig. 8.24). The inlet/outlet helium manifolding can be accommodated in the available space inside and outside the TF coil bore.

Eddy current losses were calculated for the TF coil cases of the TFCX-S machine for 30-s startup and 30-s shutdown phases. The TF coil case utilizes 4-cm-thick plates in the straight-leg region and 5-cm-thick plates elsewhere. Losses in all TF coils during the startup and shutdown phases are 150 and

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Fig. 8.24. Helium manifolding and splices.

140 kV, respectively. The losses were also calculated for the case in which the plasma suddenly disrupts. If the field due to plasma changes is 0.1 s (as seen in the TF coils), the total loss induced in all TF coils is 8.8 MV. These losses will be proportionately smaller if the field changes experienced by the TF coils take place over a longer time period.

The structural design of many tokamak devices, such as FED Baseline and INTOR, is profoundly influenced by the pulsed nature of the magnetic loads and the large number of cycles. The potential for growth of structural flows to critical size under the action of cyclic loading leads to allowable design stresses well below the levels that would be acceptable in steady-state devices.

Design current densities. A study was made to select design current densities for the TF coils at field levels of 8, 10, 11, and 12 T. The evaluation was made on the basis of inputs from the coil-development programs currently in progress. The recommended current densities allow inclusion of all candidate winding technologies for a given field level. The current densities are summarized in Table 8.10 for the winding peak and for a specified peak field.

Magnetic field and force calculations were made for the TFCX-H TF coils. The magnetic field ripple was found to be within the required

limits in the plasma region. The normal TF coils have large out-of-plane forces that tend to pull the normal coil into the plane of the adjacent superconducting TF coils. It was concluded that high-strength materials must be employed for supporting the normal coils.

8.1.2.8 Poloidal field coil system

The PF coil system was configured (Fig. 8.25) for the TFCX-S and is compatible with the existing adjacent structures. All the coils are external to the TF coils and are superconducting. The conditions of plasma elongation, triangularity, and flux linkage during burn are shown in the figure, as is the major radius of the device. In addition, all the coils are required to have fields equal to or less than 8 T. One coil (7) is trapped by the existing structure (vacuum vessel outer wall) and, hence, would be extremely difficult to replace. Consequently, for this approach an additional coil is placed outside the coil (7) location—on the same elevation but at a larger radius—outside the vacuum vessel. If coil (7) fails, it is left in place, and the additional coil is activated. A small degradation in triangularity is experienced.

The TFCX device will be started by using rf current drive. This requirement leads to a very slow ramp-up of the PF coil currents. One

Table 8.10. Design current densities for TF coils at four field levels

Conductor options	Winding current density (A/cm ²)			
	12 T	11 T	10 T	8 T
LCP conductors NbTi (pool boiling or forced flow)				2600
ORNL NbTi forced flow at 3.0 K			2000	
GA NbTi (superfluid cooled)		1700	1600	
		1500 ^a	2000 ^a	
MIT Nb ₃ Sn forced flow at 4.2 K				
React and wind	1200	1700	2400	
Wind and react	1800	2400	2900	
Recommendation	1200	1700	2000	2600

^aWith modified support.

Fig. 8.25. Reference PF coil configuration.

implication of this requirement is that structural components such as the cryostat and the plasma vacuum vessel need not have very short electrical time constants. Another area of concern is the impact of a plasma disruption on the PF magnets. A study was made to determine induced voltages in various PF coils (all open circuited) following a plasma disruption. Induced voltages are shown in Fig. 8.26 as a function of an "equivalent vacuum wall thickness." It was determined that the induced voltage in any PF coil will be less than 3000 V, provided that the vacuum vessel wall is 12.7 cm (5 in.) or thicker. The same effect could be obtained by lining the cryostat wall with 0.5-cm (0.2-in.)-thick aluminum plate. In practice, the superconducting coils will be powered by low-impedance power supplies, and the peak voltage on the coils will be determined by this power supply impedance. Previous calculations have shown that the current

Fig. 8.26. Induced voltages in PF coils following disruption.

will increase by a small amount in the PF coils, following a disruption; this current rise is not sufficient to drive the superconducting coils normal.

8.1.2.9 Plasma heating system

The systems engineering process used in the preconceptual design of the heating system for TFCX has evolved a definition of three systems. One is employed for plasma preheating and is an electron cyclotron resonance heating (ECRH) system; one is a current-drive system employing LHRH; and the third is employed for bulk heating using ion cyclotron resonance heating (ICRH). The characteristics (parameters and performance) are summarized in Table 8.11. The LHRH rf port, a brambilla grill, is shown in Fig. 8.27. The ICRH launcher (Fig. 8.28) consists of four stacked, ridge-loaded waveguides. Figure 8.29 shows the results of an analysis of impedance power and cutoff frequency of the launcher versus

gap height. A 3-cm gap was chosen for the baseline—placing the impedance at approximately 23Ω at the TFCX frequency of approximately 70 MHz, which is 27% above the cutoff frequency. The theoretical power-handling capability is approximately 30 MW, but operation at less than 15 MW is planned. Only one port is required for the D-T phase of operation. An additional port is added for the hydrogen operation if the loss of alpha heating must be made up for by higher bulk heating power (70 MW vs 20 MW).

Two alternative approaches have been studied—namely, an array of loops and a resonant cavity. For the loop configuration, two columns of four elements are planned for each port. A maximum of approximately 10 MW per array (port) is estimated. Two such ports would suffice for the D-T operation. The resonant cavity is approximately 35 cm wide by 50 cm high and reportedly can handle approximately 20 MW of power. This is a relatively new design developed by F. W. Perkins of PPPL.⁵

Table 8.11. Heating system features

ECRH		LHRH	ICRH
		Function	
Preheating (electron)		Current drive (bulk heating)	Bulk heating
		Launcher	
Type	Horn	Brambilla	Waveguide
Number	8	Two 96-element arrays	4
Size	~6-cm diam	1.1- by 9.6-cm element	30 by 100 cm
Power	~120 kW per horn	~7 MW per array	5 MW per guide
		Transmission	
Type	Circular guide	Rectangular guide	Coax
Number	8	48 (four ways) = 192	4
Size	~6-cm diam	1.1 by 9.6 cm	23.8 cm (9.375 in.)
Power	~140 kW	~400 kW	~6 MW
		Transmitter	
Type	Oscillator	Amplifier	Amplifier
Tube	Gyrotron	Klystron	Triode/tetrode
Number	8	48	16
Power	200 kW	500 kW	~1.5 MW per tube

Fig. 8.27. LHRH current-drive rf port.

Fig. 8.28. ICRH installation.

Fig. 8.29. ICRH launcher parametrics.

8.1.3 MFTF-B Upgrades

In 1982, the FEDC was actively involved in support of LLNL in the definition of a tandem mirror device designated the Technology Demonstration Facility (TDF).⁶ In 1983 the emphasis shifted to a more aggressive physics experiment, coupled with the integration of technologies more reactor relevant than TDF.

In the early part of 1983, three MFTF-B upgrades were studied briefly, with the objective of providing a reasonable cost comparison. In March the Magnetic Fusion Advisory Committee (MFAC) recommended that the MFTF- α +T receive major study emphasis for the remainder of the year.

8.1.3.1 Options for MFTF-B upgrade

Three options were identified as attractive upgrades to the MFTF-B:

- **MFTF-B+T.** A tritium-burning upgrade of the MFTF-B. End cell of the MFTF-B

machine retained, but a new beam-driven center axicell added. Features high neutron wall loading and long pulse.

- **MFTF- α .** Retains solenoidal center cell of the MFTF-B but provides new end-cell physics with new end-cell magnet system. Burns D-T fuel and has large Q .
- **MFTF- α +T.** Introduces a new beam-driven center axicell. Can be operated in either a high- Q mode or a high wall-loading mode.

These options, together with the MFTF-B, are presented schematically in Fig. 8.30. After March 1983, the FEDC, in support of LLNL, concentrated on the MFTF- α +T device. The major device parameters for the MFTF- α +T are presented in Table 8.12 for both the high- Q mode and a high wall-loading mode.

8.1.3.2 Plasma engineering

The emphasis in plasma engineering for tandem mirrors in 1983 was placed on developing

Fig. 8.30. MFTF-B upgrades.

Table 8.12. MFTF- α +T parameters

	High Γ	High Q^a
Plasma radius, m	0.15	0.25
Plasma density	4.75×10^{14}	1.1×10^{14}
Fusion power density, W/cm ³	55.2	1.93
P_{fusion} /unit length, MW	3.9	0.38
Γ , MW/m ²	2.0	0.11
First-wall radius, m	0.25	0.45
Blanket thickness, m	0.5	0.5
Reflector thickness, m	(available)	0.5
	(available)	
B_0 , T	4.5	1.6
Mean coil diam, m	5.0	5.0
Coil spacing, m	5.3	1.25
T_2 production, g/d	0.6	0.06

^aFor this option, we use the central cell parameters because the axicell is not the primary power-producing region in this mode.

a tandem mirror systems code. Major progress was made in implementing two modules of the code. The first model was the plasma physics module. It is essentially the TMRBAR code developed by LLNL. Currently operational at FEDC, this code has been used to perform a number of trade studies.

A second module that is basic to the successful implementation of the systems code is the magnetics module. This module is the TMG code also developed by LLNL.

8.1.3.3 Systems engineering

Development of the system configuration for the MFTF- α +T device was emphasized for the major part of 1983. This development included both the reactor vessel and facilities.

Fig. 8.31. External view of MFTF- α +T.

External arrangement. Figure 8.31 is an external view of the MFTF- α +T; many of the features shown are the direct result of attention given to achieving low capital cost and low operating cost. For instance, it was possible to design the end cell with the same overall diameter, which minimizes tooling and fabrication costs. The device employs the same end-cell concrete support piers as the MFTF-B, which also results in significant cost savings. The water bulk shield in the end cell is integrated with the vacuum vessel, and the resulting double-wall structural vessel represents an efficient use of structurally required material.

Hatches and/or access ports are provided for maintenance in locations that allow maximum direct removal of the major components. Each

end cell incorporates two removable hatches. The small hatch at the end provides access to the halo scraper and direct converter. The large hatch provides access to the end-cell coils. Required access is expected to be infrequent. This large hatch has a welded, single-convolution bellows seal. Separate small access ports are incorporated in the large end-cell hatch for rapid replacement of such items as the drift pump coil and the ICRH and ECRH antennae.

The center cell features two access hatches, one within the other. The test module, a central-cell copper coil, and associated shielding are assembled and installed as a unit. Thus, the smaller hatch is an integral part of the test module. This approach permits relatively simple test module removal. The seal for

the test module hatch is an O-ring type. The large hatch is used to remove the remaining center-cell coils and bulk shield.

Because the coils and bulk shield are lifetime device components, the large hatch vacuum seal is a single-convolution welded bellows. The small hatch structural frame is employed as a precise locating device for the test module.

Internal arrangement. Figure 8.32 shows the installation of the internal components. The overall length of the device vacuum vessel is 65 m, and the outside diameter (OD) is 8.3 m. The specific magnet designations are presented in Sect. 8.1.3.6, "Magnet System."

The arrangement of the D-T center axicell with the test module is illustrated in Fig. 8.33. Neutral beam injection is shown, with beam convergence to one side of the test module. An end view of this configuration is presented in Fig. 8.34. The installation of the D-T center axicell is actually that for the Fusion Power Demonstration (FPD) machine,⁷ but the arrangement was developed for MFTF- α +T. The arrangement features a 2-m-long blanket test module with a wall loading of 5 MW/m². Four neutral beams defined originally for the

TDF are combined in two enclosures, with a total of 16 sources giving 46 MW (trapped) and 50 MW (incident) at 80 keV.

Facilities. The requirements for buildings, structures, and mechanical systems for the MFTF- α +T were identified, and designs were developed. The existing MFTF-B reactor vault requires upgrading to provide for tritium confinement and to add a barrier to the leakage of neutron and gamma radiation through the roof. The vault should be leaktight (leakage not exceeding 1 vol. %/h at 136 kPa internal pressure) to keep tritium leakage to the environment within acceptable limits. To make the vault leaktight, all penetrations through the walls and all the cracks between the concrete blocks of the vault wall must be plugged. To reduce soaking of tritium and to allow decontamination of the internal surfaces, all inside surfaces (walls, floor, ceiling) are required to be grouted and coated with epoxy paint. To provide a barrier to the leakage of neutron and gamma radiation through the roof, additional shielding (about 1 m) is required. This additional shielding may be provided as roof thickness or by welding shielding to the reactor.

Fig. 8.32. Internal arrangement of MFTF- α +T.

Fig. 8.33. Blanket test module—plan view.

Fig. 8.34. Blanket test module—cross section.

Two new hot transfer cells are needed to remotely handle the activated components of the reactor and its support equipment. The remote-maintenance activities will be performed in the existing hot cells. The major components requiring remote maintenance are beamline sources, test modules, beam dumps, and end dumps. The total volume of the hot transfer cells is estimated to be 3800 m³. One cell is located on the south side and one is on the north side of the reactor vault.

A new facility is needed to process tritium in the plasma exhaust and, in general, to handle deuterium and tritium in the plant. The volume of this facility is estimated at 10,000 m³. Facilities that may be upgraded to meet this requirement now exist in proximity to the vault.

Detailed layouts of the MFTF- α +T tritium processing facility were made. This new facility is integrated into the existing MFTF experiment building (Figs. 8.35 and 8.36).

8.1.3.4 Vacuum vessel and shield

A trade study was conducted for the end cell of the MFTF- α +T to determine the optimum combination of vacuum vessel structure and shielding. Six of the options studied were based on the use of a concrete biological shield, and five additional options were based on a water biological shield. Variables in the concrete shield options consisted of the location of the concrete relative to the vacuum vessel, diameter of the end cell, and the use of a steel and water shield to augment the effectiveness of the concrete. The concrete shield options are shown in Fig. 8.37. The five water shield options differed in the relative location of the water to the vacuum vessel (separate water containers), the material used in the container structure, and one option in which the water tanks were integrated with the vacuum vessel. This latter option is shown in cross section in Fig. 8.38. A comparison of the concept costs is shown in Table 8.13 for the concrete shield approaches. The water shield costs are shown in Table 8.14. The concept selected for the baseline was the integral water shield/vacuum

Fig. 8.35. Elevation arrangement—tritium processing facility.

vessel approach because of the simplicity of structural design and low cost.

8.1.3.5 Halo scraper, vacuum pumping, and direct converter

Vacuum pumping. Two vacuum pumping options were identified for the MFTF- α +T

Fig. 8.36. Plan view section at elevation zero.

Fig. 8.37. Concrete shield vacuum vessel options.

Fig. 8.38. Integral water shield/vacuum vessel.

end cell (Fig. 8.39). The configuration shown as "Option 1" divides the end cell into three distinct pumping regions. The neutral gas pressure in the region near the end dump is maintained at 5×10^{-6} torr, with 23 m^2 of cryopanel per end. The neutral gas pressure in the halo scraper channel is maintained at 7×10^{-3} torr, with a 5000-L/s turbomolecular pump. Cryopanel with a surface area of 2.6 m^2 per end are placed in the region between the halo scraper and choke coils to ensure that the pressure in this region is 5×10^{-6} torr.

The configuration shown as "Option 2" combines the halo scraper and end-dump regions into a single vacuum pumping system. Pumping with one 5000-L/s turbomolecular pump at each end keeps the neutral gas pressure at 5×10^{-3} torr. This configuration is a much simpler vacuum pumping system; however, the effect of the 5×10^{-3} -torr pressure in the end-dump region on plasma and direct converter performance is yet to be evaluated.

A leading edge and plate configuration was developed for the halo scraper of the MFTF- α +T device. The scraper leading edge is a water-cooled, tantalum-alloy (Ta-10W) tube with an inside radius of 1.27 cm and a thickness of 0.5 cm. The tube is fabricated in segments welded together to form a 0.5-m-diam

scraper leading edge. The peak temperature is 448°C , and the thermal stress is 350 MPa (50 ksi). Both of these are judged acceptable. The erosion life is 1.6 years at full power—well in excess of the device life. The plates in the scraper duct have a tantalum surface for good erosion life.

Scraper and direct converter. The heat loads and particle fluxes on the end-cell components (i.e., the inner and outer halo scraper and the direct converter) of the MFTF- α +T were evaluated. The electron direct converters have fairly flat heat loads at $\sim 10^{20} \text{ cm}^{-2} \cdot \text{s}^{-1}$. The inner halo scraper has the highest heat load, with a peak value of 3 MW/m^2 and a peak ion flux of $6 \times 10^{20} \text{ cm}^{-2} \cdot \text{s}^{-1}$. Because most of the power is transported out of the end of the device, rather than radially, the outer halo scraper is subject to only $\sim 0.1 \text{ MW/m}^2$ (and a $10^{19} \text{ cm}^{-2} \cdot \text{s}^{-1}$ ion flux). The primary uncertainty in the calculations arises from a lack of knowledge of the radial temperature distribution.

The halo scraper and direct converter configurations have been defined for MFTF- α +T. For this design, the concept represented by "Option 2" (Fig. 8.39) has been employed. The halo scraper consists of an inner halo plate, outer halo plate, scraper housing, pumping ducts, and support frame (Fig. 8.40). The location of the inner halo scraper is at $Z = 27.0 \text{ m}$, which is near optimum from a surface-heat-load standpoint. Peak heat load in the inner halo plate is 280 W/cm^2 .

The direct converter consists of an inner and outer collector plate support frame (Fig. 8.41). The two collector plates are located at $Z = 31.0$ and 31.5 m , respectively. Heat loads on the collector surfaces are approximately 200 W/cm^2 . The support frames provide capability for transferring seismic and dead-weight loads to the vacuum vessel.

To minimize the cost, flat-plate construction will be used for the direct converter plate; its bias potential will be regulated by a variable grounding resistance. The simplest control will be a motor-operated resistance, but other controls using shunt power hubs and inverters are being reviewed.

Table 8.13. Weight and cost summary-shield, vacuum vessel options (concrete shield)

Concept	Vacuum vessel	Vacuum vessel cost (\$ millions)	End-cell support cost (\$ millions)	Stainless steel H ₂ O shield location	Concrete shield thickness and location	Concrete shield weight (kg × 10 ³)	Concrete shield cost (\$ millions)	Shield removable	Total steel H ₂ O cost (\$ millions)	Total steel shield weight (kg × 10 ³)	Total shield cost (\$ millions)	Total end-cell cost (\$ millions)
I	Modify existing	1.7	0.2	All inside vacuum vessel 50 cm	50-cm-thick outside with rebar and supports	2330.9	11.1	Inside and outside	7.3	278.1	18.4	20.3
II	Modify existing	1.7	0.2	All inside vacuum vessel 50 cm	50-cm-thick outside with rebar and self-supports	3536.3	4.8	Inside and top of outside only	7.3	278.1	12.1	14.0
III	Modify existing	2.1	0.7	All inside vacuum vessel 50 cm	50 cm, clad inside and supported by vacuum vessel	835.5	1.42	All	7.3	278.1	8.7	11.5
IV	New 8.3-m diam	5.5	0.5	All inside vacuum vessel 50 cm	50 cm, clad inside and supported by vacuum vessel	653.5	1.12	All	7.3	278.1	8.4	14.4
V	New 5.8-m diam	5.0	0.5	15 cm inside vacuum vessel, 35 cm outside vacuum vessel	50 cm, with rebar and supported by outside vacuum vessel	638.2	0.45	All	33.0	1268.2	33.4	38.9
VI	New 5.8-m diam	5.2	1.3	15 cm inside vacuum vessel	120 cm, with rebar and supported by outside vacuum vessel	1562.6	1.7	All	3.0	116.8	4.7	11.2

Table 8.14. Weight and cost summary--shield vacuum vessel options (water shield)

Shielding options	Weight of container (kg $\times 10^3$)	Weight of water (kg $\times 10^3$)	Cost of container (\$ millions)	Cost of vacuum vessel (\$ millions)	Cost of support structure (\$ millions)	Total shield weight (kg $\times 10^3$)	Total cost per end cell (\$ millions)
I: 160-cm-thick water shield in 304 stainless steel containers located outside vacuum vessel	597	1013	10.5	5.5	0.5	1583.3	16.5
II: Same as option I, except using 5083-0 aluminum water container	265	1013	7.7	5.5	0.5	1273.0	13.7
III: 160-cm-thick water shield in 304 stainless steel containers located inside vacuum vessel	488	422	8.6	5.5	0.5	910.5	14.6
IV: Same as option III, except using 5083-0 aluminum container for the water	216	422	6.3	5.5	0.5	638.6	12.3
V: Integrated 304-L stainless steel vacuum vessel and water container	a	a	a	7.4	0.5	772.2	7.9

*Not applicable.

D-T GAS LOAD:

- END DUMP 90 A = 16 torr - L/s
- HALO SCRAPER 111 A = 20 torr - L/s
- TOTAL 200 A = 36 torr - L/s
- COIL REGION 5% ± TOTAL = 1.8 torr - L/s

Fig. 8.39. Halo scraper/vacuum system options.

Fig. 8.40. Halo scraper and direct converter component.

8.1.3.6 Magnet system

The arrangement of the magnet system for MFTF- α +T is shown in the upper part of Fig. 8.41. In the lower portion of this figure is a plot of the field-on-axis as a function of specific magnets and their location. Table 8.15 presents terminologies for the various magnets, and Table 8.16 shows a summary of the magnet parameters.

Center-cell magnet system configurations were developed for MFTF-B+T and for MFTF- α +T to provide the required field profiles. A trade study was performed to determine the length of the central cell (axial distance between central-cell choke coils) consistent with the configurational constraints imposed by maintenance and neutral beam needs. The center-cell magnet set (choke and background solenoid coils) is identical for the

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Fig. 8.41. MFTF- α +T magnet configuration.

Table 8.15. Magnet terminology

Designation	Description
CC1, CC2	Copper choke coil
CS1	Central solenoid
S	Solenoid
T1, T2	Transition coils
A1, A2	Anchor coils
P1, P2	Plug coils
DC	Recircularizer coils

} C-coils

MFTF-B+T and the MFTF- α +T machines. The location and size of the choke coils and background center-cell coils were determined for a mirror ratio of 2.67. The peak field at the choke coils is 12 T, and the peak field at the solenoid coils is 10 T. The choke coils will probably be a copper normal-conducting type. The background solenoidal coils are the superconducting type.

Generally, the feasibility of designing, constructing, and operating magnets for the MFTF- α +T application has been previously demonstrated. The two exceptions are the

18-T barrier coil CC2 and the 12-T choke coil CC1. These coils are developmental because of the high field and, in the case of CC1, because of severe radiation and configuration constraints. However, it is considered technically feasible to meet these requirements with coils that will function for the life of the MFTF- α +T device. This conclusion is based on the design studies previously completed by GA and M.T during FY 1982 on the TDF project.⁶

Structural support. Three arrangements for support of the anchor and plug coil pairs were studied. Only one of these proved feasible due to the close proximity of one winding to another in each coil pair. The structure consists of the coil cases and four identical collar structures (Fig. 8.42). The concept consists of one coil acting as a "C-clamp" to support the major lobe-opening forces of the other coil, as well as its own minor lobe-opening force. The collar structure carries a portion of the coil bending moment; it also distributes the coil's major lobe-opening force to the complementary coil. Structural analysis has shown that the

Table 8.16. Magnet parameters

Coil	Axial location (m)	Mean diameter ^a or major, minor radii ^b (m)	Sweep angle ^b (deg)	Winding current density (A/cm ²)	MA-turns	Conductor, SC = NbTi, liquid helium at 4.2 K	Approximate peak field in winding (T)
CC1	± 2.0	0.64		2400	22.6	C ^c	12
CS1	± 2.65	5		2400	3.5	SC	10
S1 ^c	± 4.375	5		3090	1.7	SC	3
S2 ^c	± 5.625	5		3140	1.7	SC	3
S3 ^c	± 6.875	5		3140	1.7	SC	3
S4 ^c	± 8.125	5		3140	1.7	SC	3
CC2	± 10.0	1.253		2798	18.9	C ^c	20
T1	± 11.811	1.5, 0.5	80	3473	5.6	SC	7
A1	± 15.611	1.3, 0.5	90	3473	5.6	SC	7
A2	± 15.611	1.3, 0.5	90	3473	5.6	SC	7
P1	± 19.411	1.5, 0.5	80	3473	5.6	SC	7
P2	± 19.411	1.5, 0.5	80	3473	5.6	SC	7
T2	± 23.211	1.3, 0.5	71	3473	5.6	SC	7
DC	± 24.711	0.928		2380	9.2	SC	8

^aSolenoidal coils only.

^bC-coils only.

^cExisting MFTF-B coils, relocated as necessary.

^dWater-cooled copper.

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Fig. 8.42. Anchor and plug coil set support structure.

concept is feasible insofar as stresses at the center of the major coil radius are concerned. A 1/20th scale model of the anchor coil pair and its support structure was made to aid in this study. The concept of structurally coupling magnet pairs was extended to cover the entire C-magnet assembly in the end cell (Fig. 8.43).

Two concepts for cold mass support were investigated. Hanging the coils proved difficult due to the use of a removable hatch and the crane lift capacity. Support from below was studied using two options. Ultimately, the coil weight must be carried to the four existing concrete piers. This may be done by (1) supporting the coils on a 4-K cold table that has support legs at the appropriate axial locations or (2) supporting each coil pair on legs and carrying the load to the piers via the vacuum vessel. For the first approach, coil pair weights were calculated to be approximately 120 tons each. Due to this high weight and the resulting depth of the cold table, a larger diameter vacuum vessel is required. Therefore, the second option was selected (Fig. 8.44). This option features removal of pins that attach the coil pair legs to the support base by installation of a pin-puller mechanism through four reentrant ports. The support base is mounted on four legs in a manner that allows thermal growth. The legs and roller designs are

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Fig. 8.43. Coupling of C-coil pairs.

Fig. 8.44. End-cell magnet support.

taken from the LCP coil support design.⁸ The structure was conservatively sized (including $0.5 \text{ g} \times 4 = 2 \text{ g}$ seismic loading), with a resulting thermal load of approximately 500 W at 4 K (whole machine) for the C-coils.

D-T axicell magnet design. A revision to the D-T axicell magnet configuration is being incorporated into the MFTF- α +T baseline as a result of a design study undertaken to reduce cost.⁹ The original baseline is shown in Fig. 8.45(a), and Table 8.17 is a cost summary. The revised axicell configuration [Fig. 8.45(b)] offers a significant cost advantage in both capital and life-cycle costs. These reduced costs have resulted from the insertion of a relatively small copper coil in the shadow of the test module to more economically provide the 4.5-T field-on-axis in the center of the test region. Incorporation of this coil permits a reduction in total current in the background

superconducting coils. A further reduction in current and total cost of the superconducting coils is made possible by moving them radially inward and axially closer together. A secondary benefit of the version is that the peak field on the superconducting coils, which is 12-T in the original baseline, has been reduced to 10.8 T.

8.1.3.7 Drift-pumping system

Two subsystems of the drift-pumping system have been developed, one for the anchor and the other for the plug. A configuration of 12 channels covering both anchor and plug is shown in Fig. 8.46. Each channel operates at a different center frequency within the required bandwidth. This is illustrated in Fig. 8.47 for the anchor region. In this region, each transmitter channel supplies approximately 55 kW to the drift-pump coil, while only 5 kW is

a) ORIGINAL BASELINE

b) REVISED BASELINE

Fig. 8.45. D-T axicell magnet options.

required for the plug. The characteristics of the drift-pump system are given in Table 8.18. Alternative approaches were considered and include a chopper-inverter transmitter or an energy-recovery technique that allows a low Q with high efficiency.

8.1.3.8 Sloshing ion beam

The sloshing ion beam injector design for MFTF- α +T is being revised. Previously, the design stressed low divergence (approximately 0.32°) but was inefficient. The required 4.2 A

Table 8.17. D-T axicell cost summary
(in millions of dollars)

	Original baseline	Revision
Capital cost		
Superconducting coils	40.4	18.7
Superconducting coils power supply	3.8	1.4
Resistive coils	0.2	0.9
Resistive power supply	0.5	0.8
Subtotal	44.9	21.8
Operating cost		
Cryogenic cooling	1.0	0.7
Resistive coil	3.8	6.4
Subtotal	4.8	7.1
Life-cycle cost	\$49.7	\$28.9

at 200 keV was supplied by two five-beam fans, each having a width of 50 cm [Lawrence Berkeley Laboratory (LBL) source]. Over half of the beam was lost due to collimation in this design. Recently, estimates of the plasma target size were revised upward, and it was determined that the divergence could be increased. Another problem with the old design was that the gas-pumping speed was highly constrained in the neutralizer; this was relaxed for the new design.

The new injector layout is shown in Fig. 8.48. It uses three 50-cm-wide LBL negative-ion-based sources, each supplying about 3.5 A. The beam is transported by a transverse-field-focusing (TFF) system in which the plates are separated by 9 cm (for the 3-cm-high beam). The E -field is about

Fig. 8.46. Drift-pump system schematic.

Fig. 8.47. Anchor cell channel response.

Table 8.18. Drift-pumping system features

	Anchor	Plug
Cell		
Diameter (conductor), cm	2	2
Length, cm	270	270
Width, cm	30	30
Number	12	12
Impedance, Ω	0.0067 +j1.76	0.0179 +j15.08
Cooling	80 GPM at 50 psi and 60°C, water	
Matching network		
Type	Series-parallel tuned transformer	
Number	12	12
Bandwidth, kHz	0.2	6.5
Frequency spacing, kHz	2.5	7.0
Transmission line		
Type	Coax	Coax
Impedance, Ω	50	50
Size (diam), cm (in.)	4.13 (1.625)	4.13 (1.625)
Pressurization, atm	1 (SF6)	1 (SF6)
Efficiency	0.995	0.995
Transmitter		
Type	Tuned amplifier	Tuned amplifier
Number	12	12
Power per channel, kW	42	5
Bandwidth, kHz	28	84
Center frequency, kHz	70	600
Efficiency	0.51	0.45
Tube type	4CW50,000	4CX3000 A

Fig. 8.48. Negative-ion-based sloshing ion neutral-beam injector.

10 kV/cm. About 3 m² of cryopumps at the end of the TFF maintain the pressure. A 3-cm neutralizer cell (1 m long) interfaces with the MFTF- α +T. About 1 torr·L·s⁻¹ of cold gas is dumped into the halo, along with an equal amount from the two ion dumps. The 1-kG stray field—predominantly in the Z direction—performs the bending magnet function for the ion-deposition control.

An alternate design using positive-ion-based beams is being developed. Without benefit of direct recovery, the full energy efficiency is 14%. The power fractions are 840 kW at E , 398 kW at $E/2$, and 169 kW at $E/3$. A molecular-ion separator in advance of the neutralizer is being studied—using a bending mag-

net to deflect these ions away to a dump. This method appears to be efficient because the neutralization efficiency of the positive ion at 200 keV is low; therefore, the gas pressure in the separator region is less critical.

8.1.4 International Tokamak Reactor

The FEDC continues to support the INTOR effort. Personnel from FEDC participated in the INTOR workshop in Vienna, Austria, in August. The objectives of this workshop were (1) to perform a final edit of the draft report of the Phase 2A, Part 1 effort and (2) to plan the workshop activities for the next two years (Phase 2A, Part 2). The editing function was

completed, and the printed document was issued by the International Atomic Energy Agency (IAEA) in late 1983. Detailed plans were developed for the technical work to be done during the next two years for five critical issues and three disciplinary group areas.¹⁰

Part 2 of Phase 2A will last approximately two years. The primary emphasis will be on critical issues and research and development (R&D) assessment from now through October 1984, after which time the primary emphasis will be on updating the INTOR design concept on the basis of the critical-issues work and developments in the worldwide R&D program. It was agreed that the workshop will be organized into five critical-issues groups and three disciplinary groups (Table 8.19).

The identified tasks of each critical-issue group are

- to perform an extensive study of a specific technical issue and
- to assess the data base required for the INTOR design in the areas directly relevant to that critical issue, including an identification of required R&D (i.e., update the Phase Zero assessment).

The tasks of each disciplinary group are

- to keep under continuous review worldwide R&D developments in the respective discipline (excluding areas covered by the critical-issue groups) and to assess their impact on the INTOR design concept and

- to assess the data base required for the INTOR design in the respective discipline (excluding areas covered by the critical-issue groups), including an identification of required R&D (i.e., update the Phase Zero assessment).

The FEDC has primary responsibility for critical issues D and E and support responsibility in critical issues B and C of Table 8.19. The FEDC also has primary responsibility for the engineering disciplinary group.

8.1.4.1 All-remote version of INTOR

Detailed task assignments were developed and implemented dealing with tritium handling, facilities, diagnostics, and remote maintenance. Concepts for an all-remote configuration have been initiated.

Argonne National Laboratory (ANL) has performed thermal-hydraulic calculations for a lithium-cooled limiter for surface heat flux ranging from 2.4 to 13 MW/m² and coolant velocity from 1 to 10 m/s. Results indicate that an upper limit on velocity is ~5 m/s, since further increase in velocity does not decrease the coolant/structure interface temperature significantly. Structure and coating temperatures were also calculated. A guide on the maximum allowable beryllium temperature is needed to determine the cutoff point of surface heat flux.

Work on tritium systems was outlined by ANL. The assumptions to be used include the following:

1. U.S. regulations and guidelines on environmental releases and worker exposures will be the reference case.
2. A coolant system with minimal leakage will be designed, including the cost for both contact and remote maintenance.
3. Decontamination procedures will be listed, including times required, effectiveness, cost, and applicability to remote operations.

Table 8.19. INTOR workshop groups

Critical issues groups	
A.	Impurity control and first wall
B.	RF heating and current drive
C.	Transient electromagnetics
D.	Maintainability
E.	Technical benefit
Disciplinary groups	
F.	Physics
G.	Engineering
H.	Nuclear

4. In-leakage and cost of different buildings to size the atmospheric tritium-recovery (ATR) units will be determined.
5. ATR/ventilation designs will be done, including contact or remote maintenance with associated cost.

Work by ANL on the INTOR shielding systems has started to develop two different configurations. The first configuration is based on hands-on and remote operations for maintaining the external and internal reactor components, respectively. The second assumes all-remote operations for maintaining any reactor components. The results from the work will be a comparison between the two configurations from the point of view of cost and reactor availability.

The effect of plasma disruptions on melting and vaporization of copper and tantalum as a structural or coating material for the limiter/divertor plate has been examined by ANL. The disruption conditions are those assumed for INTOR (with reference energy density of 535 J/cm^2 deposited in 20 ms). The calculation is done parametrically as a function of the energy density for two different disruption times (5 and 20 ms). Copper is shown to develop a large melt-layer thickness (approximately 1 mm for energy density of 1000 J/cm^2 deposited in 20 ms), which is likely to be unstable during the disruption. Tantalum shows smaller vaporization losses for the reference case and much less melting than copper.

A code is developed to include the angular distribution of the sputtered particles as a function of incident particle angle, the angle of exit-sputtered atoms, and the azimuthal angle. Also, the energy distribution of the sputtered particles is included. This calculation may be important in the erosion/redispersion of the sputtered atoms.

8.1.4.2 Partitioning component design and fabrication

The continuation of INTOR into the construction and operation phases will result in

several identifiable benefits to the multinational participants, including generation of information about new fusion scientific and operation knowledge at a cost substantially lower than that required for any single participating nation to undertake alone. These are readily identifiable benefits. A less obvious but critically important aspect of such a large project is the overall design and fabrication of the major systems and components. It is highly desirable to have each participating nation derive the technical benefit associated with all developments that occur during design and manufacture of the hardware. The purpose of this critical issue is to examine the implication of having different manufacturers fabricate some fraction of the components of a major system, for example, three manufacturers each building four TF coils for a 12-coil tokamak device. The most obvious benefits from this approach would be the development of broadened industrial capability for future fusion reactor technology. There are some associated disadvantages, such as administering contracts with many industrial companies. To address these issues, a systematic examination of the probable impacts of contracting several organizations to design and fabricate identical components for a major system is being performed.

Three tasks were completed prior to the INTOR workshop in Vienna (Jan. 16-27, 1984). The first task was to identify those major systems and components to be evaluated during the study. Two criteria were adopted to determine the candidate major systems that are amenable to partitioning the design and fabrication:

1. The system must involve advanced technology.
2. The system must involve multiple units so that production can be partitioned.

Therefore, all systems using standard technology and involving only one (or a few) units are *not* candidate systems for partitioning design or fabrication. The following major systems satisfy both criteria.

Magnets: TF and PF [equilibrium field (EF)]
Nuclear: torus, first wall, divertor plates,
 and test modules
Heating: ECRH and ICRH.

It is recommended that these systems be used in the task evaluation required in the remainder of the study.

The second task was to assess the extent to which the design effort can be assigned to multiple fabricators during the design process and the impact that this would have on conducting the study. It is desirable for the fabricators to be involved as early in the design process as possible, because this would broaden the design base and provide maximum opportunity for innovative and creative input at modest cost.

The third task was to examine the impact of multiple fabricators on the planning and implementation of the project. This task studied the impact on the design control process, preparation of equipment specifications, the nature of procurement, the R&D activities plan, the component verification and test program, the quality assurance (QA) plan, records management, and the project management plan. It was concluded that the impact of developing the plans for various areas just listed would be negligible, with the exception, perhaps, of the component verification and test program. The impact on the implementation of each area would add to the complexity of the project and would likely require additional management administration.

8.2 FUSION ENVIRONMENTAL ASSESSMENT PROGRAM

The Fusion Environmental Assessment Program provides technical assistance to the DOE Office of Fusion Energy (OFE) in coordination and preparation of National Environmental Policy Act (NEPA) compliance documents. The program is administratively part of the Environmental Impact Section of the ORNL Energy Division, but it draws on the technical expertise of staff from the Chemical Technology, Engineering Physics, Environmental Sciences, Fusion Energy, Health and Safety Research, Information, and Metals and Ceramics divisions as well.

Since the program's inception in 1979, its focus has been the development of a generic environmental impact statement (GEIS), which is required by NEPA regulations as the national fusion program advances from basic and applied research to engineering development. In 1983, this work centered on the development of a technical basis document for the GEIS. The following issues were addressed: radioactive inventories, plant effluents, occupational health and safety, reactor safety, radioactive waste management, and availability of basic constituent materials. The technical basis document was issued as a Headquarters report by DOE-OFE.¹¹ It will be used as a major reference for the GEIS, which is expected to be issued in FY 1985.

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Chapter 9

Radiation Materials Testing

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9. RADIATION MATERIALS TESTING

Summary of Activities

The objective of the Fusion Materials Program at ORNL is to develop materials for near-term and commercial fusion reactors. Special emphasis is placed on neutron-irradiation effects arising from deuterium-tritium (D-T) or deuterium-deuterium (D-D) reactions. The helium generated in materials from inelastic collisions of 14-MeV neutrons makes the fusion environment unique. A variety of methods is used to simulate the fusion environment, including helium injection followed by reactor irradiation, irradiation in mixed-spectrum fission reactors for alloys containing nickel, use of "tritium trick" followed by reactor irradiation, and dual- and triple-beam ion irradiation. These methods, combined with rapidly developing theoretical analysis, provide considerable insight into materials response in the fusion environment.

In the Fusion Materials Program, funds are provided for Alloy Development for Irradiation Performance (ADIP), for Damage Analysis and Fundamental Studies (DAFS), and for Insulators and Stabilizers for Superconducting Magnets (ISSM). Alloy development includes irradiation effects and corrosion studies. In conjunction with alloy development, the Basic Energy Sciences Program at ORNL provides support for companion theoretical studies and dual-beam ion irradiation work. Finally, the Fusion Materials Program supports the Oak Ridge Research Reactor (ORR) for use for fusion studies and other DOE and Nuclear Regulatory Commission (NRC) activities.

In the ADIP area, a sufficient data base has been obtained on type 316 stainless steel to conclude that the lifetime is limited to 4 to 5 MW·year/m² by the onset of a high swelling rate for temperatures above 450°C. Titanium-modified alloys such as the prime candidate alloy (PCA) show much better swelling resistance up to 5 MW·year/m², provided the correct starting microstructures are used. Very high fluence tests of the optimum microstructures have been started.

The effort has been increased on the vanadium alloys V-20 Ti, V-15 Cr-5 Ti, and VAN-STAR-7 because of their low activation characteristics. Alloys doped with helium via the "tritium trick" are now being irradiated in the Fast Flux Test Facility (FFTF). These alloys were found to have good properties after gas tungsten arc welding. A serious embrittlement problem has been identified for long-range-ordered (LRO) alloys so that emphasis has been reduced on this alloy class. Extensive irradiation tests revealed that the ferritic alloys 12 Cr-1 MoVW, 9 Cr-1 MoVNb, and 2¼ Cr-1 Mo show better swelling resistance than do austenitic steels. Ferritic steels with high helium contents have different microstructures than the same heats irradiated in Fast Breeder Reactor (FBR) tests. Tensile ductilities of the ferritic steels remain excellent after irradiation. Miniature Charpy-impact test specimens have been irradiated, and testing should begin soon to determine how much the ductile-to-brittle temperature increases with high-fluence, high-helium irradiation. A strategy for the development of ferritic alloys with low-neutron activation characteristics has been proposed, and small heats of several compositions have been prepared for evaluation.

Corrosion studies have shown that vanadium alloys are resistant to 300°C steam. It has also been confirmed that Pb-17 at. % Li is much more corrosive to austenitic and ferritic steels than is pure lithium.

In the ISSM area, the study of the response of different grades of copper to neutron irradiation with intermediate anneals in several neutron spectra has been completed. The results show a strong dependence upon sample purity and degree of cold work. The design and construction of a National Low-Temperature Neutron Irradiation Facility at the ORNL Bulk Shielding Reactor (BSR) is now under way. This facility will make possible improved measurements and tests at higher fluences for superconducting magnet materials.

9.1 ALLOY DEVELOPMENT FOR IRRADIATION PERFORMANCE—ABSTRACTS

A. F. Rowcliffe

M. L. Grossbeck

The following abstracts describe alloy development activities in the area of irradiation performance during 1983.

9.1.1 "The Response of Austenitic Steels to Radiation Damage"¹

A. F. Rowcliffe

M. L. Grossbeck

Austenitic stainless steels are prominent contenders as first-wall and blanket structural materials for early fusion power reactors. Properties affecting the performance of this class of alloys in the fusion irradiation environment, such as swelling, tensile elongation, irradiation creep, fatigue, and crack growth, have been identified. These properties and the effects of neutron irradiation on them are discussed. Emphasis is placed on the present status of understanding irradiation effects.

9.1.2 "Swelling and Swelling Resistance Possibilities of Austenitic Stainless Steels in Fusion Reactors"²

P. J. Maziasz

Fusion reactor helium-generation rates in stainless steels are intermediate to those found in the Experimental Breeder Reactor II (EBR-II) and the High Flux Isotope Reactor (HFIR), and swelling in fusion reactors may differ from the fission swelling behavior. Advanced tritium-modified austenitic stainless

steels exhibit much better void swelling resistance than AISI 316 under both EBR-II (up to ~120 dpa) and HFIR (up to ~44 dpa) irradiations. The stability of fine titanium carbide (MC) precipitates plays an important role in void swelling resistance for the cold-worked (CW) titanium-modified steels irradiated in EBR-II. Furthermore, increased helium generation in these steels can (1) suppress void conversion, (2) suppress radiation-induced solute segregation (RIS), and (3) stabilize fine MC particles, if sufficient bubble nucleation occurs early in the irradiation. The combined effects of helium-enhanced MC stability and helium-suppressed RIS suggest better void swelling resistance in these steels for fusion service than under EBR-II irradiation.

9.1.3 "Improved Swelling Resistance for PCA Austenitic Stainless Steel Under HFIR Irradiation Through Microstructural Control"³

P. J. Maziasz

D. N. Braski

Six microstructural variants of PCA were evaluated for swelling resistance during HFIR irradiation, together with several heats of type 316 stainless steel (316). Swelling was negligible in all the steels at 300°C after ~44 dpa. At 500°C to 600°C, 25% CW PCA showed better void swelling resistance than type 316 at ~44 dpa. There was less swelling variability among alloys at 400°C, but again 25% CW PCA was the best. Microstructurally, swelling resistance correlated with development of fine, stable bubbles, whereas high swelling was due to coarser distributions of bubbles becoming

unstable and converting to voids (bias-driven cavities).

9.1.4 "Microstructural Design of PCA Austenitic Stainless Steel for Improved Resistance to Helium Embrittlement Under HFIR Irradiation"⁴

P. J. Maziasz

D. N. Braski

Several variants of PCA with different pre-irradiation thermal-mechanical treatments were irradiated in HFIR and were evaluated for embrittlement resistance via disk-bend tensile testing. Comparison tests were made on two heats of 20% CW type 316 stainless steel. None of the alloys were brittle after irradiation at 300°C to 400°C to ~10 dpa and helium levels of 3000 to ~3600 at. ppm. However, all were quite brittle after similar exposure at 600°C. Embrittlement varied with alloy and pretreatment for irradiation to 44 dpa at 500°C and to 22 dpa at 600°C. Better relative embrittlement resistance among PCA variants was found in alloys that contained prior grain boundary MC carbide particles that remained stable under irradiation.

9.1.5 "Comparison of Swelling and Cavity Microstructural Development for Type 316 Stainless Steel Irradiated in EBR-II and HFIR"⁵

P. J. Maziasz

Comparison of swelling and cavity microstructures for one heat of 20% CW type 316 stainless steel (316) irradiated at 500°C to 650°C in EBR-II (up to 75 dpa) and HFIR (up to 61 dpa) suggests that void growth and swelling are suppressed by the higher helium generation found in HFIR. Instead of voids, many small bubbles develop in the CW 316 in HFIR and resist conversion to voids. However, similar comparison of solution-annealed (SA) 316 irradiated in EBR-II and HFIR at 500°C to 550°C leads to an opposite conclusion; void swelling is enhanced by helium in HFIR. Many more bubbles nucleate in SA 316 at low fluence in HFIR compared to EBR-II, but

bimodal distributions and rapid coarsening eventually lead to high swelling due to high concentrations of matrix and precipitate-associated voids in HFIR. A key to the swelling resistance of the CW 316 in HFIR appears to be the development of a sufficiently cavity-dominated sink system in the early stages of evolution.

9.1.6 "The Impact of Swelling on Fusion Reactor First-Wall Lifetime"⁶

R. F. Mattas

F. A. Garner

M. L. Grossbeck

P. J. Maziasz

G. R. Odette

R. E. Stoller

Swelling in structural materials is a key issue for the lifetime of fusion components. The dimensional changes associated with swelling can cause a number of problems, including high induced-stress levels, that can lead to premature failure. To assess the impact of swelling on lifetime, it is important to understand the swelling phenomenon, as well as how the swelling interacts with other material properties to affect component operation. The leading candidate as a structural material for both near- and long-term devices is austenitic stainless steel. In this study, the possible swelling behavior of austenitic stainless steel in a fusion environment is first examined, and then the impact of that swelling on first-wall lifetime is assessed.

At this time there is a considerable uncertainty in the actual amount of swelling that will occur in austenitic stainless steel under fusion conditions. For this reason, a range of possible swelling behavior was considered. Three separate forms of swelling, two of which are empirically derived from available data on 20% CW type 316 stainless steel and one of which is based upon a theoretical model, have been used. One form of swelling is based largely on EBR-II data and is representative of fast reactor swelling. The other empirical model is based upon HFIR data and is representative of swelling where large amounts of helium are generated. The theoretical

model predicts swelling for the He/dpa ratio expected in a fusion reactor.

The different forms of swelling have been incorporated into a materials lifetime code that is capable of examining the temperature-stress-strain-radiation effects history of fusion components. The code incorporates the operating and design parameters, the materials characteristics, and the appropriate failure criteria. The code has been applied to the International Tokamak Reactor (INTOR), DEMO, and Starfire first-wall designs, which span the designs from near- to long-term devices. The expected damage levels range from ~50 to 200 dpa, and the expected operating temperatures range from ~100°C to 500°C. The three first-wall designs have each been examined utilizing the three forms of radiation swelling. The predicted impact of swelling on lifetime is described.

9.1.7 "Tensile Properties of Unirradiated PCA from Room Temperature to 700°C"⁷

D. N. Braski

P. J. Maziasz

The tensile properties of PCA austenitic stainless steel after three different thermo-mechanical treatments were determined from room temperature to 700°C. The solution-annealed PCA had the lowest strength and highest ductility, while the reverse was true for the 25% CW material. The PCA containing titanium-rich MC particles fell between the other two heats. The CW PCA had nearly the same tensile properties as CW type 316 stainless steel. Both alloys showed ductility minima at 300°C.

9.1.8 "The Stability of the MC Phase in a Stainless Steel Irradiated in Various Environments"⁸

A. F. Rowcliffe

E. H. Lee

The principal phases formed during heavy ion irradiation of a titanium-stabilized stainless steel at 948 K are the thermally stable MC phase and the radiation-induced G phase. Whereas the G phase continues to grow with

increasing displacement dose, the MC phase eventually dissolves. The dose interval over which MC exists may be altered by cold working, injecting helium, or irradiating in a pulsed mode. It is thought that the dissolution of the MC phase occurs when the matrix titanium concentration is lowered by the incorporation of titanium into the G phase.

9.1.9 "The Effect of Phosphorus on the Swelling and Precipitation Behavior of Austenitic Stainless Steels During Irradiation"⁹

E. H. Lee

A. F. Rowcliffe

L. K. Mansur

Increasing the volume fraction of the needle-shaped iron phosphide phase in austenitic stainless steels tends to inhibit void swelling during neutron irradiation. An earlier analysis showed that this effect could not be accounted for in terms of enhanced point-defect recombination at particle-matrix interfaces. The behavior of the iron-phosphide phase has been further examined using dual-ion-beam irradiations. It was found that the particle-matrix interface serves as a site for the nucleation of a very fine dispersion of helium bubbles. It is thought that since a high number density of cavities lowers the number of helium atoms per cavity, the irradiation time for the cavities to accumulate the critical number of gas atoms for bias-driven growth is correspondingly increased. Although the phosphide phase nucleates rapidly, it eventually undergoes dissolution if either the G or Laves phase develops with increasing dose.

9.1.10 "Wide Area-Beam Averaged AEM of Precipitate Particles Extracted on Replicas from Type 316 Stainless Steel"¹⁰

P. J. Maziasz

G. R. Odette

Extraction replicas are an important complement to in-foil analysis for accurate phase identification and composition measurements in studying precipitation in complex alloys such

as type 316 stainless steel. Analysis of small particles without matrix interference is particularly easy on replicas. Background or in-hole counts on clean replicas are very low compared to in-foil, particularly for reactor-irradiated materials in which intrinsic radioactivity emission interferes with or obscures X-ray detection in-foil. This work introduces another advantage of replicas by demonstrating an analysis in which a wide-area beam is used to blend spectra from many particles into a composite averaged spectrum. Such an averaged spectrum better represents the elemental redistribution from the original matrix to the precipitate microstructure and can yield relative phase fractions upon deconvolution if the individual phase compositions are known. Several prerequisites for meaningful deconvolution of broad-beam measurements are: (1) adequate identification and composition measurement (especially particle-to-particle variations) of all major phases on the replica, (2) thin particles and lack of stacked clusters, (3) lack of extraneous background or artifacts (polishing residue, pieces of matrix) contributed from replica, and (4) extraction of the phases in the same relative proportions found in-foil. In summary, broad-beam measurements on replicas and their potential and convenient use in quantitatively estimating relative phase fractions can be an important complementary tool in the study of complicated precipitation changes in aged and irradiated engineering alloys.

9.1.11 "Identification of Preferential Polishing Effects Using Broad Probe AEM"¹¹

P. J. Maziasz

Many applications of analytical electron microscopy (AEM), X-ray energy-dispersive spectroscopy (XEDS), or electron energy-loss spectroscopy (EELS) in multiphase alloys demand the highest spatial-resolution micro-

analysis, hence minimum probe size and thin (50–75 nm) foils. The quantitative elemental analyses, however, can be misleading if preferential polishing has occurred, causing exaggeration or even removal of microstructural/microcompositional features. In this study, a large-probe or "broad-beam" XEDS technique was employed to detect and identify preferential polishing effects. The broad-beam technique yields a "bulk" analysis, which, ideally, should be equivalent to the bulk chemical analysis. Matrix analyses were made in a spot mode and "bulk" analyses were made with a broad, elliptically stigmated probe ($\sim 10\text{-}\mu\text{m}$ major axis), with the major axis parallel to the foil edge to minimize thickness variations in the analyzed volume. To demonstrate effects of polishing, two different complex microstructures were selected. The first structure, developed by aging the SA steel at 650°C for 10,000 h, contained coarse precipitates of η (M_6C -type), τ (M_{23}C_6 -type), and Laves (Fe_2Mo -type) phases. The broad-beam analysis of the thinner regions consistently revealed an excess of Cr (due to excess τ) and a deficiency of Mo (due to deficient Laves) relative to the conventional bulk analyses of the alloy. The second microstructure was produced by neutron irradiation of the 20% CW material in EBR-II to 69 dpa at 510°C . During electropolishing, voids intersect the surface, and the RIS zones around them can be polished away. Thus, in foil regions that are thinner than the average void diameter, electropolishing produces a matrix "skeleton" that is poor in Ni and rich in Mo and Cr. Both Mo and Ni approach their initial concentrations as the thickness increases and voids and their RIS zones are encompassed in the foil. In conclusion, preferential polishing removes essential microcompositional components in the thinnest foil regions of complex microstructures. Use of broad-beam XEDS techniques provides a convenient method for determining the nature and degree of such polishing aberrations.

9.1.12 "Microstructure of HFIR-Irradiated 12 Cr-1 MoVW Ferritic Steel"¹²

J. M. Vitek

R. L. Kluch

As part of the fusion materials development program in the United States, a 12 Cr-1 MoVW ferritic steel was irradiated in the HFIR to a damage level of 36 dpa at 300°C, 400°C, 500°C, and 600°C. During irradiation in HFIR, a transmutation reaction of nickel results in the production of helium, to a level of 99 at. ppm in the present experiment. The microstructures were evaluated after irradiation, and the results are presented. Cavities were found at all temperatures. Small cavities (3-9 nm) were observed after irradiation at 300°C, 500°C, and 600°C. At 500°C and 600°C, the cavities were found preferentially at dislocations, lath boundaries, and prior-austenite grain boundaries. After irradiation at 400°C, larger cavities (4-35 nm) were observed homogeneously distributed throughout the tempered martensite structure. The maximum swelling was 0.07% after irradiation at 400°C. Comparison of the results with other studies in which helium was not present at such high levels indicated that helium enhances the swelling of 12 Cr-1 MoVW.

9.1.13 "Microstructure of 9 Cr-1 MoVNb Steel Irradiated to 36 dpa at Elevated Temperatures in HFIR"¹³

J. M. Vitek

R. L. Kluch

As part of an effort by the Office of Fusion Energy (OFE) to evaluate the irradiation behavior of ferritic steels, a 9 Cr-1 MoVNb alloy was irradiated in HFIR to a dose of ~36 dpa at temperatures of 300°C, 400°C, 500°C, and 600°C. In addition to the displacement damage produced during irradiation, a transmutation reaction of nickel during HFIR irradiation resulted in the simultaneous production of ~30 at. ppm helium. Electron microscopy disks in the normalized and tempered condition were irradiated, and the microstructures were evaluated as a function of irradiation temperature. A few small cavities

were observed after irradiation at 300°C, 500°C, and 600°C. However, a pronounced cavity microstructure was found after irradiation at 400°C. At this temperature, the cavities had a volume-averaged diameter of 15 nm and a concentration of $1.1 \times 10^{21} \text{ m}^{-3}$, resulting in a void-swelling contribution of 0.19%. The cavities at 400°C were homogeneously distributed throughout the tempered martensite matrix and showed no preference for lath boundaries or precipitate interfaces. The results are compared to those recently reported on a similarly irradiated 12 Cr-1 MoVW ferritic steel.

9.1.14 "Tensile Behavior of Three Commercial Ferritic Steels After Low-Temperature Irradiation"¹⁴

R. L. Kluch

J. M. Vitek

The ferritic (martensitic) steels and the austenitic stainless steels are being considered for use as first-wall and blanket structural components for fusion reactors. Tensile specimens of normalized and tempered 9 Cr-1 MoVNb and 12 Cr-1 MoVW steels, normalized and tempered and isothermally annealed 2½ Cr-1 Mo steel, and 20% CW type 316 stainless steel were irradiated at approximately 50°C to damage levels of up to about 9 dpa in the HFIR. The preirradiated microstructures of the 9 Cr-1 MoVNb and 12 Cr-1 MoVW steels were a tempered martensite; the microstructure of the normalized and tempered 2½ Cr-1 Mo steel was tempered bainite and that of the isothermally annealed 2½ Cr-1 Mo steel was primarily polygonal ferrite. The postirradiation tensile behavior at room temperature and 300°C of all alloys was similar: irradiation hardening was observed as increased yield strength, increased ultimate tensile strength, and decreased ductility (uniform and total elongation). After irradiation, normalized and tempered 2½ Cr-1 Mo and 12 Cr-1 MoVW had similar strengths and were stronger than the 9 Cr-1 MoVNb and type 316 stainless steel, which had similar strengths. The irradiated isothermally

annealed 2% Cr-1 Mo steel hardened to a value considerably below the other four steels, although this material was also much weaker than the other steels before irradiation. With one exception, there was relatively little difference in ductility. At 300°C the ductility of the isothermally annealed 2% Cr-1 Mo steel was substantially better than for the other steels.

9.1.15 "Impact Properties of 12 Cr-1 MoVW Ferritic Steel"¹⁵

W. R. Corwin
R. L. Klueh

J. M. Vitek

The ferritic steel 12 Cr-1 MoVW is a candidate material for use in the first wall of magnetic fusion reactors. One of the primary concerns of materials in this application is service-induced embrittlement from aging and irradiation. Unirradiated Charpy-impact data have been developed on three typical heats of 12 Cr-1 MoVW steel and on heats that have been modified with nickel and chromium additions for subsequent simulation of helium effects of irradiation. The ductile-to-brittle transition temperature and the upper-shelf energy were reduced by nickel additions. The addition of nickel while simultaneously maintaining a constant net chromium equivalent caused the transition temperature to increase. The use of a subsize specimen is mandated by the small volume and high gamma heating in high-flux research reactors used for very high-fluence irradiation experiments. Therefore, an understanding of the behavior of the subsize specimen is important in predicting corresponding irradiation-induced transition temperature shifts and upper-shelf drops of full-size Charpy specimens. Data are reported from subsize Charpy impact specimens, and the full-size and subsize specimens are compared. The effect of specimen size on the upper-shelf energy of this material can be reduced better by volume normalization than by area normalization.

9.1.16 "Microstructure and Bend Ductility of a (Fe,Ni)₃V Ordered Alloy Irradiated in HFIR"¹⁶

D. N. Braski

Disks of a (Fe,Ni)₃V LRO alloy were irradiated in the HFIR to 10, 21, and 42 dpa and helium levels of 1000, 2700, and 6000 at. ppm, respectively. The irradiation temperatures were 300°C, 400°C, 500°C, and 600°C. The alloy remained ordered under all conditions. Swelling of the alloy was low, with a peak of 1.3% occurring at 500°C. Severe embrittlement and intergranular fracture occurred after 10 dpa at 600°C and extended to lower temperatures as the damage level increased. Helium bubbles and a thin, continuous film of VC observed in the grain boundaries may be the cause of the embrittlement.

9.1.17 "Weld Microstructure of (Ni,Fe)₃(V,Ti) Long-Range-Ordered Alloy"¹⁷

D. N. Braski

S. A. David

The microstructure of gas tungsten arc (GTA) welds of a (Ni,Fe)₃(V,Ti) LRO alloys has been investigated. Crack-free welds were produced in which the heat-affected zone (HAZ) and fusion zone were disordered and softened. A postweld heat treatment increased the hardness of both zones by reordering the structure. The reordering treatment produced additional hardening in the fusion zone due to precipitation of small VC particles on grain boundaries and matrix dislocations.

9.1.18 "Copper and Copper Alloys for Fusion Reactor Applications: Summary Report of a DOE-OFE Workshop"¹⁸

F. W. Wiffen
T. C. Reuther

R. E. Gold

DOE-OFE convened a workshop in April 1983 to review the needs for copper and copper alloys in fusion device applications. The adequacy of the data base on these materials was

examined, and recommendations were developed for experimental programs needed to fill identified data gaps. The workshop results are available in a conference proceedings.

9.1.19 "Low-Activation Materials for Fusion Applications"¹⁹

E. E. Bloom
R. W. Conn
J. W. Davis
R. E. Gold

R. Little
K. R. Schultz
D. L. Smith
F. W. Wiffen

Lower-activation materials for fusion reactors are technically possible, may be important to the public acceptance of fusion energy, and should be a main goal of the fusion program. Actual levels of radioactivation in a reactor will depend on the material itself and on its alloying constituents and impurity content. The equilibrium activation level and post-shutdown decay rates affect three primary areas: long-term waste material disposal, reactor maintainability (specifically, the prospects for limited hands-on or contact maintenance), and reactor safety. Goals relating to each of these three areas are proposed and used to develop four particular categories that classify both reactors and materials.

It is recommended that, as a minimum, one goal of the fusion program should be a Reference Reactor that (1) meets Class C requirements of the Code of Federal Regulations (10CFR61) for near-surface disposal of radioactive waste, (2) permits limited hands-on maintenance outside the reactor shield within two days of shutdown, and (3) meets all requirements for engineered reactor safety. A higher-level goal could lead to a Low-Activation Reactor that would meet Class B requirements for waste disposal in 10CFR61 and the same criteria for maintenance and safety as the Reference Reactor. A Very Low Activation Reactor would meet Class A requirements in 10CFR61, would permit limited hands-on maintenance behind the reactor blanket, and would meet criteria for both

engineered and intrinsic reactor safety. A fourth classification, the Standard Reactor, is one that will meet requirements for engineered safety and may meet requirements for limited-contact maintenance outside the reactor shield but does not meet the minimum requirements for near-surface burial of waste (Class C) as presently provided for in federal regulations. A reactor constructed of type 316 stainless steel will be a Standard Reactor. More generally, it is necessary to avoid the use of highly activating materials such as nickel, molybdenum, or niobium (often even as low-percentage alloying constituents).

Very Low Activation Reactors would have to be constructed almost entirely of ceramic materials, examples of which include graphite and silicon carbide. Selective use of metal alloys such as aluminum is possible. All materials, whether ceramic or metallic, in a Very Low Activation Reactor must have an extremely low impurity content, lower in fact than is considered reasonably probable for practical engineering materials. Even then, it is not possible to achieve limited hands-on maintenance within the plasma chamber.

With more reasonable impurity levels, use of these materials would lead to a reactor in the Low-Activation class. Quality commercial vanadium and titanium alloys are examples of metal alloys that can also potentially lead to a Low-Activation Reactor. A definitive judgment on the engineering practicality of such reactors, especially when using ceramics, could not be reached, but we note that essentially all components must be constructed of these materials.

Reference Reactors can be achieved with metal alloys, provided care is taken to control the elemental composition of the alloy and its impurity content. Elemental tailoring of stainless or ferritic steel to avoid the use of natural nickel, molybdenum, or niobium is an example. A more speculative alternative is isotopically tailored molybdenum or nickel for use as low-percentage alloying constituents.

9.1.20 "Control of Activation Levels to Simplify Waste Management of Fusion Reactor Ferritic Steel Components"²⁰

F. W. Wiffen

R. T. Santoro

Activation characteristics of a material for service in the neutron flux of a fusion reactor first wall fall into three areas: waste management, reactor maintenance and repair, and safety. Of these, waste management is the most likely to impact the public acceptance of fusion reactors for power generation. The decay of the activity in steels within tens of years could lead to simplified waste disposal or possibly even to materials recycle. Whether or not these can be achieved will be controlled by (1) selection of alloying elements, (2) control of critical impurity elements, and (3) control of cross-contamination from other reactor components. Several criteria can be used to judge the acceptability of potential alloying elements in iron and to define the limits on content of critical impurity elements. One approach is to select and limit alloying additions on the basis of the activity. If material recycle is a goal, then N, Al, Ni, Cu, Nb, and Mo must be excluded. If simplified waste storage by shallow land burial is the goal, regulations limit the concentration of only a few isotopes. For first-wall material that will be exposed to 9-MW·year/m² service, allowable initial concentration limits include (in at. ppm) Ni < 20,000, Mo < 3650, N < 3650, Cu < 2400, and Nb < 1.0. Other constituent elements of ferritic steels will not be limited. Possible substitutes for the molybdenum normally used to strengthen the steels include W, Ta, Ti, and V.

9.1.21 "Irradiated Tensile Properties of a U.S.S.R. Austenitic Stainless Steel"²¹

R. L. Klueh

M. L. Grossbeck

An agreement has been reached between the program management for the fusion programs

of the United States and the U.S.S.R. to develop common points of reference in materials and tests to which irradiated effects research and development studies may be related. The first step in this agreement was the exchange of a stock of the austenitic stainless steels that are being considered as first-wall and blanket structure candidate materials; type 316 stainless steel was exchanged for the U.S.S.R. steel designated EP-838. The objective of this exchange was for each country to irradiate the respective material of the other country and compare the results to their own material.

The EP-838 steel is a high-manganese, low-nickel steel that also has lower chromium and molybdenum than type 316 stainless steel (EP-838 is 11.6% Cr, 4.2% Ni, 13.5% Mn, 0.9% Mo, and 0.02% C; type 316 stainless steel is 17.3% Cr, 12.4% Ni, 1.7% Mn, 2.1% Mo, and 0.06% C). Tensile specimens of the two steels were irradiated in the HFIR at the coolant temperature (~50°C). A displacement-damage level of 5.2 dpa was reached for the EP-838 and up to 9.5 dpa for the type 316 stainless steel. Tensile tests at room temperature and 300°C on the two steels indicated that the irradiation led to increased strength and decreased ductility compared to the steels in the unirradiated condition. Although the 0.2% yield stress of the type 316 stainless steel in the unirradiated condition was greater than that for EP-838, after irradiation there was essentially no difference in strength or ductility. Investigators in the U.S.S.R. also compared the effect of low-temperature irradiation on the two steels, but the steels were in the solution-annealed condition. In agreement with the results for the cold-worked steels, essentially no difference in strength or ductility was observed. The results of these two studies indicate that the replacement of the majority of the nickel by manganese and a reduction of chromium and molybdenum in an austenitic stainless steel of composition near that for type 316 has little effect on the irradiated and unirradiated tensile properties.

9.1.22 "Fatigue Performance of HFIR-Irradiated Nimonic PE-16 at 430°C"²²

M. L. Grossbeck

K. C. Liu

Miniature hourglass specimens of Nimonic PE-16 in the precipitation-hardened condition were irradiated in the HFIR at 430°C. The specimens attained damage levels up to 9 dpa and helium levels as high as 1000 at. ppm resulting from transmutation of nickel.

Following irradiation, the specimens were tested in a servo-hydraulic testing machine equipped for remote elevated-temperature testing in a high vacuum. A fully reversed ramp function providing a strain rate of $4 \times 10^{-4} \text{ s}^{-1}$ was used. Strain control was employed for all strain ranges above 0.35% using a diametral extensometer with its signal converted to axial strain. For strain ranges of 0.35% and below, strain control was used until a stable hysteresis loop was attained. At this point, control was shifted to load and the strain rate was increased by a factor of 10. Testing was done at the irradiation temperature, 430°C, in a vacuum of 10^{-7} to 10^{-4} Pa.

The fatigue life of the irradiated material was found to be lower than the unirradiated by about a factor of 10. In addition, unlike type 316 stainless steel, which exhibits a 10^7 cycle endurance limit, irradiated PE-16 specimens failed at a strain range as low as 0.3% at only 1.5×10^6 cycles. However, unirradiated specimens of PE-16 displayed a 10^7 cycle endurance limit at 0.35%.

High-nickel alloys often fail by intergranular separation in tensile tests following HFIR irradiation. However, despite the high-helium content of the specimens in this investigation, preliminary results reveal only transgranular separation.

9.1.23 "In-Reactor Uniaxial Fracture Strain of 20% Cold-Worked Type 316 Stainless Steel"²³

M. L. Grossbeck

E. E. Bloom

In-reactor creep strain and fracture strain were determined for type 316 stainless steel at

430°C, 550°C, and 625°C. Rod-type specimens were stressed by means of a swelling-driven holder. Each specimen was surrounded by a driver tube of high-swelling material to provide a tensile stress. The specimens were irradiated in the EBR-II to a fluence of $5 \times 10^{26} \text{ n/m}^2$ ($E > 0.1 \text{ MeV}$), and strain rates of 10^{-10} to 10^{-9} s^{-1} were achieved.

It was found that fracture strain decreases with increasing temperature in the range of 550°C to 625°C, attaining values of 6% at 550°C but only 1% at 625°C independent of fluence in the range of $2\text{--}5 \times 10^{26} \text{ n/m}^2$. The presence of a notch reduces fracture strain to <1% at 550°C and ≈ 0 at 625°C, but strain is >1.6% at 430°C. All fractures were intergranular, with some evidence of ductility for a notched specimen at 550°C, where fracture probably occurred rapidly and at a low fluence.

9.1.24 "Use of Subsize Fatigue Specimens for Reactor Irradiation Testing"²⁴

K. C. Liu

M. L. Grossbeck

Irradiation in nuclear reactors limits the size of test specimens for two reasons. The first is to minimize space considerations; the second is to minimize the nuclear heat deposited in the specimens. This nuclear heat, mostly from gamma radiation, provides a convenient source of heat for elevated-temperature radiation but also limits the lowest irradiation temperature available. As specimen size is increased, the heat source is larger and the conduction distance is longer. For these reasons standard ASTM fatigue specimens are not used for reactor irradiation. Fatigue testing is an important part of fusion reactor materials development. Therefore, a subsize fatigue specimen was developed for this purpose.

Some of the features of the specimen are listed.

1. Threads are used to grip the specimen to keep the overall diameter to a minimum to fit the specimen in irradiation vehicles.
2. The ends are made conical to aid in axial alignment, which is more critical in smaller-diameter specimens.

3. Overall length has been minimized to fit more specimens in an irradiation capsule.
4. Two flats at the shoulders are provided to accommodate a wrench for tightening in the grips and to engrave identification numbers.

The specimen has been used for testing up to 650°C for type 316 stainless steel, Nimonic PE-16, 12 Cr-1 MoVW and 9 Cr-1 MoVNb steels, LRO alloys, and vanadium alloys. Total strain ranges as high as 2% are used routinely, and strain ranges over twice as large have been attained without buckling. The resulting data were found to have low scatter, indicating good reliability of the specimen design.

9.2 CORROSION STUDIES—ABSTRACTS

J. H. DeVan

P. F. Tortorelli

9.2.1 "Effects of a Flowing-Lithium Environment on the Surface Morphology and Composition of Austenitic Stainless Steel"²⁵

P. F. Tortorelli

J. H. DeVan

Optical and electron microscopical techniques were used to study the surfaces of type 316 stainless steel following exposure to molten lithium. In nonisothermal flowing systems, the major corrosive attack by lithium occurred through the transport of nickel and chromium from hotter to cooler parts of the systems. At the higher temperatures, surfaces were depleted of nickel and chromium, and porosity formed in the iron-rich, near-surface layer. Small nodules enriched in molybdenum were also observed. At lower temperatures, net deposition of chromium, nickel, and iron from the lithium occurred such that the composition of the deposits varied with time. Qualitative correlations between porosity variations and surface concentrations as a function of temperature indicate that porosity development may be more related to a nickel or chromium reaction with impurities than with the actual nickel-depletion process.

9.2.2 "Mass Transfer Behavior of a Modified Austenitic Stainless Steel"²⁶

P. F. Tortorelli

J. H. DeVan

An austenitic stainless steel developed to resist neutron damage was exposed to lithium in the high-temperature part of a thermal-convection loop for 6700 h. Specimens of this PCA composed of 65.0 Fe-15.9 Ni-14.0 Cr-1.9 Mo-1.9 Mn-0.4 Si-0.3 Ti-0.05 C (wt %) were exposed at 600°C and 570°C in both solution-annealed and cold-worked forms. The dissolution process was found to be similar to other austenitic alloys in flowing lithium; that is, weight losses of PCA eventually became linearly proportional to exposure time with the specimen surfaces exhibiting porous layers depleted in nickel and chromium. However, the measured weight losses and dissolution rates of these PCA specimens were higher than those of type 316 stainless steel exposed under similar conditions and can be attributed to the higher nickel concentration of the former alloy. The effect of cold work on dissolution rates was less definitive, particularly at 570°C. At longer exposure times, the annealed PCA specimen exposed at 600°C suffered greater dissolution than the cold-worked material, while no effect of prior deformation was observed by analysis of the respective surfaces.

9.2.3 "Corrosion of an Fe-12 Cr-1 MoVW Steel in Thermally Convective Lithium"²⁷

P. F. Tortorelli

J. H. DeVan

A thermal-convection loop of Fe-12 Cr-1 MoVW steel circulated pure lithium between 500°C and 350°C for 10,088 h. Periodic weighings of coupons at different temperatures around the loop revealed small weight losses and corrosion rates. Surface analysis showed a relatively thin corrosion layer with an underlying carbide-free zone and some depletion of chromium from the hottest specimen. While some mass transfer of chromium and nickel was detected, this mechanism did not strongly

influence the weight loss process, as it does with austenitic steels. Therefore, it appeared that reactions with carbon and nitrogen must be the dominant corrosion processes such that weight loss was maximized at the lowest temperature (350°C). Overall, the lithium-steel reactions in the temperature range of this experiment were relatively sluggish, and the corrosion was not severe.

9.2.4 "Surface Analysis of Ferrous Alloys Exposed to Static Pb-17 at. % Li"²⁸

P. F. Tortorelli

J. H. DeVan

Molten Pb-17 at. % Li (eutectic composition with a melting point of 235°C) affords attractive neutronic properties for use as a tritium-breeding fluid for fusion reactors. Accordingly, we have studied the compatibility of ferrous alloys with static Pb-17 at. % Li to understand the basic corrosion reactions that occur under isothermal conditions. Specimens of type 316 stainless steel and an Fe-12 Cr-1 Mo steel (HT-9) were exposed to static Pb-17 at. % Li for 1000, 3000, and 5000 h at 300°C, 400°C, 500°C, 600°C, and 700°C (only type 316 stainless steel at the latter two exposure temperatures). Weight-change measurements indicated higher corrosion rates under these exposure conditions than occurred when these alloys were similarly exposed to pure molten lithium.

9.2.5 "Compatibility of Materials for Use in Liquid-Metal Blankets of Fusion Reactors"²⁹

O. K. Chopra

P. F. Tortorelli

A review of corrosion and environmental effects on the mechanical properties of austenitic and ferritic steels for use with liquid metals in fusion reactors is presented. The mechanisms and kinetics of the corrosion processes in liquid lithium and Pb-17 Li systems are examined, and their influence on degradation of structural materials is discussed. Requirements for additional data are identified.

9.2.6 "Chemical Aspects of Fusion Technology—1982"³⁰

P. F. Tortorelli

The latest research results in the areas of tritium-breeding materials properties, coolants, hydrogen isotope interactions with structural materials, tritium-recovery cycles and plasma interactions with the first wall are reviewed. Areas in which required information is currently lacking are identified, and specific recommendations are made for work that should be given priority in order to most rapidly advance the international effort in fusion technology. These areas include liquid-metal/structural-alloy interactions (including magnetic-field effects); analytical techniques for low levels of tritium and impurities in breeder materials; tritium interactions with breeder and structural materials; thermochemistry and thermophysical properties of solid breeder materials; corrosion-product transport and deposition in magnetic fields; hot-water reactions with Li-17 Pb-83 and ceramic breeding materials; tritium-handling and tritium-recovery cycles; chemical reactions at the plasma/wall interface and impurity getters; and in-pile or pilot-scale tests of breeder materials, tritium interactions with structural materials, and discharge cleaning of advanced first-wall materials.

9.2.7 "Materials Compatibility Considerations for a Fusion-Fission Hybrid Reactor Design"³¹

J. H. DeVan

P. F. Tortorelli

The Tandem Mirror Hybrid Reactor is a fusion-reactor concept that incorporates a fission-suppressed breeding blanket for the production of U-233 to be used in conventional fission power reactors. The present paper reports on compatibility considerations related to the blanket design. These considerations include solid-solid interactions and liquid-metal corrosion. Potential problems are discussed

relative to the reference blanket operating temperature (490°C) and the recycling time of fissile materials (<1 year).

9.3 DAMAGE ANALYSIS AND FUNDAMENTAL STUDIES—ABSTRACTS

L. K. Mansur M. T. Robinson

9.3.1 "Mechanisms of Helium Interaction with Radiation Effects in Metals and Alloys: A Review"³²

L. K. Mansur W. A. Coghlan

Helium has been shown to cause major changes in the radiation-effects response of metals and alloys. Examples are described. Physical mechanisms underlying these effects are discussed in terms of the theory of radiation effects. An extended treatment of the critical cavity-radius concept is developed. Several new analytical results are presented. Applications are reviewed covering the temperature extension of swelling by gas, the evolution of bimodal cavity-size distributions, and the necessity for gas as a prerequisite to swelling under some conditions. The effect of helium on the dose dependence of swelling is described in terms of its effects on the balance of point defect sink strengths. Mechanisms underlying the enhanced formation and growth of cavities on precipitates when helium is present are discussed. A proposal is described to explain recently observed large effects of helium on phase stability.

9.3.2 *Helium Effects on Solids—A Reference Manual*³³

N. M. Ghoniem P. J. Maziasz

Helium gas is quite insoluble in most solids; however, once it is introduced (even in the smallest quantities), it is found in some cases to influence the properties in a dramatic way. The interest in helium effects on materials

dates back to the late 1960s for applications in which helium was either generated or implanted by irradiation. Breeder reactor technology has pushed the understanding of helium effects a long way in the 1970s. During the late 1970s and early 1980s, we have been witnessing a great surge of research on helium effects for applications in fusion reactor technology. In this computerized reference manual, we have compiled all available articles on helium interaction with solids. The open-literature articles are grouped in approximate categories that combine them in a coherent way. The subject categories are blistering, microstructure, transport and migration, bubble mobility, cavity nucleation, cavity growth and swelling, creep rupture, precipitation, similarities with noble gases, mechanical properties, helium production, and, finally, helium equation of state.

9.3.3 "Modification of Radiation Damage Microstructure by Helium"³⁴

K. Farrell E. H. Lee
P. J. Maziasz L. K. Mansur

Current experimental findings on the effects of helium on the evolution of radiation damage microstructure in metals at temperatures where vacancies are mobile are reviewed. It is shown that helium concentrations as low as a few parts per million promote the formation of cavities and dislocations, may increase or decrease swelling, and can alter the development of precipitate phases. Mechanisms underlying these processes are discussed in terms of the theory of radiation effects. Helium-vacancy trapping and the stabilization of cavities is seen as the unifying, underlying feature. Promotion of cavities is explained by reduction of critical cavity size by helium. This promotion, and the attendant increase in dislocations, changes the point-defect sink strengths and thereby modifies swelling. Correspondingly, solute segregation at sinks is changed, resulting in alteration of precipitate phases.

9.3.4 "Radiation-Induced Swelling in an Austenitic Alloy: Observations and Interpretation of the Effects of Helium"³⁵

N. H. Packan

K. Farrell

Microstructural damage is measured in a stable austenitic alloy after nickel-ion bombardment to doses of 1 to 70 dpa at temperatures in the range of 840 K to 1100 K. The influence of helium, both preimplanted at room temperature and coimplanted at a rate of 20 at. ppm per dpa, is examined. The helium causes considerable increases in the concentrations of cavities and reductions in cavity size and shifts the peak swelling temperature upward by ~50 K; growth of dislocation loops is delayed. Preimplanted helium has much more pronounced effects than coimplanted helium, including the generation of a large secondary population of small cavities deemed to be helium bubbles and, in some cases, sub-microscopic bubbles. Cavitation is assessed with regard to the concept of a critical size for bias-driven cavity growth. The results of this experiment are attributed to helium-enhanced cavity nucleation and to the influence of such nucleation on the cavity and dislocation sink strengths.

9.3.5 "The Effect of Pulsed Irradiation on Void Swelling of a Pure Austenitic Alloy"³⁶

K. Miyahara
N. H. Packan

N. Igata

Pulsed irradiation at high temperature has been found to exert significant effects on the void swelling of Fe-17 Cr-17 Ni-2.5 Mo alloy. In the present work, these effects are discussed from the point of void growth and shrinkage, using the theory of void growth. In the calculation of void radius change, the cavities rapidly shrink and disappear during the beam-off period for pulsed irradiation by nickel ions at 1023 K. In the slow-pulsed irradiation (60 s on/off), helium bubble sizes obtained by the calculation are in good agreement with the experimental results.

9.3.6 "Temperature Aspects of Pulsed Ion Bombardment in an Austenitic Alloy"³⁷

N. H. Packan

The influence of pulsed ion irradiation to a damage level of 10 dpa at temperatures from 843 K to 1023 K has been studied in a quaternary Fe-17% Cr-17% Ni-2.5% Mo austenitic alloy. Pulsing periods of either 60 s on/off or 1 s on/off were used, together with continuous bombardment as a control. Helium (200 at. ppm) was supplied either by simultaneous or room-temperature preimplantation or was omitted. While most specimens experienced only 2-K to 3-K temperature fluctuations with the beam pulses, certain specimens were deliberately allowed to undergo 15-K to 50-K variations. Pulsed irradiation effects were found to range from little effect at 843 K, through a notable modification in the relationship between helium and cavity parameters at 938 K (near the peak swelling temperature), to a substantial reduction of swelling at 1023 K. The influence of the simultaneous temperature excursions compared with constant-temperature pulsed ion bombardment (mostly compared at 843 K) was small. These results are interpreted in terms of the effects of pulsing and helium on the stability of cavities at high temperatures through the critical size and number of gas atoms needed for a small cavity to begin bias-driven void growth.

9.3.7 "Effects of Pulsed Dual-Ion Irradiation on Phase Transformations and Microstructure in a Ti-Modified Austenitic Alloy"³⁸

E. H. Lee
N. H. Packan

L. K. Mansur

The influence of pulsed 4-MeV nickel-ion bombardment, with and without simultaneous helium injection, has been explored in a low-swelling, Ti-modified austenitic stainless steel. Irradiations were carried out to 70 dpa at 950 K; the pulsing frequencies were either 60 s on/off or 1 s on/off. Compared to continuous irradiation, pulsing caused a decrease

in the interstitial loop diameter at 1 dpa, although at higher doses the overall dislocation density was not affected. Pulsing and helium both promoted the stability of MC precipitates and retarded the subsequent G phase formation; in some cases G phase was suppressed and η phase formed instead. Small bubble-like cavities were observed to grow into large voids after steady dual-beam irradiation to 70 dpa. However, this conversion was suppressed by pulsed irradiation to 70 dpa; furthermore, the sizes of the small cavities were somewhat reduced. The results are explained in terms of current mechanistic understanding of mean-point-defect kinetics and the evolution of microstructure and microcomposition during irradiation with superimposed annealing periods.

9.3.8 "Effects of Pulsed- and/or Dual-Ion Irradiation on Microstructural Evolution in a Ti- and Si-Modified Austenitic Alloy"³⁹

A. Hishinuma
N. H. Packan

E. H. Lee
L. K. Mansur

The influence of pulsed, 4-MeV, nickel-ion bombardment, with and without simultaneous helium injection, at 958 K and damage levels from 1 to 50 dpa has been studied in a low-swelling, Ti- and Si-modified austenitic stainless steel. Compared to continuous irradiation, pulsing caused an increase in the number density of interstitial loops formed during irradiation. Helium also increased the nucleation of interstitial loops. The main precipitates formed were a large number of small TiC particles uniformly distributed in the matrix and a small number of relatively large η and G precipitates. These coarse precipitates were somewhat larger in the pulsed specimens. Pulsing appeared to produce no significant change in swelling (compared to continuous irradiation). However, for one specimen irradiated to 54 dpa, pulsing concurrent with substantial

temperature fluctuations caused by beam heating may have been responsible for a larger swelling (compared to continuous irradiation).

9.3.9 "Swelling Behavior of a Simple Ferritic Alloy"⁴⁰

L. L. Horton

J. Bentley

The swelling behavior that results from simulated fusion-environment irradiation of Fe-10% Cr has been characterized with transmission electron microscopy. Specimens were bombarded at 850 K with a "triple beam" of He^+ , D_2^+ , and 4-MeV Fe^{2+} ions to 0.3, 1, 3, 10, 30, and 100 dpa; a "dual beam" of He^+ and 4-MeV Fe^{2+} ions to 30 and 100 dpa; and a "single beam" of 4-MeV Fe^{2+} ions to 30 dpa. The helium- and hydrogen-injection rates were ~ 10 at. ppm He/dpa and ~ 40 at. ppm D/dpa. Cavities were observed for damage levels of 3 dpa and greater. The swelling was $< 0.1\%$ for damage levels ≤ 30 dpa, but at 100 dpa, there was an increase in the swelling to 2.5% for the triple-beam irradiation and 1.2% for the dual-beam irradiation. The swelling rates between 30 and 100 dpa correlate well with calculated values assuming that a steady-state swelling-rate regime has been reached. Calculations show that the rapid cavity growth associated with this swelling increase cannot be attributed to equilibrium bubble growth. For all of the bombardments, the cavities with a diameter greater than 10 nm had a truncated octahedral morphology with $[111]$ facets and $[100]$ truncations. Measurements indicate that the surface energy relationship was $\gamma_{111} \approx 0.8 \gamma_{100}$ for these cavities. At 30 dpa, the cavities in the specimen irradiated with the single-beam technique were larger and had a lower concentration than the specimens irradiated with dual- and triple-beam techniques. Comparison of the specimens irradiated with the dual- and triple-ion beams suggests that deuterium has an effect on the damage microstructures in Fe-10% Cr.

9.3.10 "Comparison of Damage Microstructures in Neutron-Irradiated Vanadium and Iron"⁴¹

L. L. Horton

K. Farrell

It is known that body-centered cubic (bcc) ferritic materials are more resistant to radiation-induced cavitation swelling than are other bcc materials. In this study the cavity morphology and dislocation loop geometry in vanadium are compared with the previously reported observations for neutron-irradiated iron. The specimens were vanadium and vanadium with boron carbide additions (V-B₄C) that were irradiated to ~1 dpa at 623 K to 923 K in the same ORR capsules as the iron specimens.

While the cavities in vanadium did not appear to have distinct facets, the cavity shape in the V-B₄C specimens was a truncated dodecahedron with [110] faces and [100] truncations. In iron, the shape was a truncated octahedron with [111] faces and [100] truncations—the shape commonly observed in face-centered cubic (fcc) materials. In vanadium the dislocation microstructures varied from clusters of small dislocation loops at 623 K to larger, homogeneously distributed loops at higher temperatures. The loop Burgers vectors were $a/2\langle 111 \rangle$. At the same homologous temperatures, the dislocation loops in iron were near-edge, interstitial loops with $a\langle 100 \rangle$ Burgers vectors. These results appear to contradict a recent calculation showing that the relative probability of $a\langle 100 \rangle$ loop formation is four orders of magnitude higher for vanadium (5.5×10^{-5}) than for iron (5.7×10^{-9}).

9.3.11 "The Temperature Dependence of the Damage Microstructures in Neutron-Irradiated Vanadium"⁴²

L. L. Horton

K. Farrell

Vanadium and vanadium with boron carbide additions (V-B₄C) were irradiated to ~1 dpa in the ORR at controlled temperatures ranging from 455 K to 925 K. The V-B₄C alloy was

enriched in B-10, which produced ~3900 at. ppm helium. In the vanadium specimens, the dislocation microstructures varied from clusters of small (<50-nm-diam) dislocation loops (455 K to 625 K) to larger, homogeneously distributed loops at higher temperatures. Their Burgers vectors were $a/2\langle 111 \rangle$. The V-B₄C specimens contained only tangled dislocation segments. Cavities were observed in all specimens. The cavity concentration decreased and the average diameter increased with increasing irradiation temperature. At 725 K, the maximum swelling was observed in both the vanadium (0.1%) and V-B₄C (1.4%). At comparable temperatures, the cavities in the V-B₄C specimens were smaller and more numerous than those in the vanadium specimens. Helium bubbles were found on the grain boundaries in all of the V-B₄C specimens.

9.3.12 "A Study of Recoil Ranges in Crystalline and Amorphous Media"⁴³

M. T. Robinson

The computer program MARLOWE was used to study the collisions of particles recoiling from lattice sites in crystalline materials of several different structures. Compared to the expectations for structureless media, there is an excess frequency of close encounters between projectiles and lattice atoms in static crystals of high symmetry that can be reduced by lowering the crystal symmetry, either structurally or by introducing thermal displacements of the atoms from their lattice sites. With sufficiently large displacements, the impact parameter and flight distance distributions take on the characteristics expected for structureless media. The excess of close encounters affects the mean range significantly. Higher moments, however, are mainly influenced by channeling effects. Similar calculations were made for rotationally disordered (amorphous) targets. In such targets, the degree of local order depends on the maximum permitted impact parameter. When this is small, the impact parameter and flight distributions

resemble those of a structureless medium, but when the maximum impact parameter is large, there is an excess of close encounters, much as in the case of static crystals. The higher moments show the recoil range distributions to be essentially Gaussian, however. All of these results show the importance of local order in determining recoil ranges and, consequently, its importance for collision cascade development, both in crystalline solids and in amorphous ones.

9.3.13 "Ion Backscattering from Layered Targets"⁴⁴

O. S. Oen

M. T. Robinson

The reflection of hydrogen atoms from amorphous layered targets was studied using a new version of the computer simulation code MARLOWE. Targets with low-Z overlayers on high-Z substrates, and vice versa, were investigated using normally incident atoms in the energy range from 0.01 to 1 keV. For very low energies, the backscattering is characteristic of the surface overlayer; at higher energies, which depend on the overlayer thickness, it becomes characteristic of the underlying substrate. In addition to the particle and energy reflection coefficients, the reflected atom energy distribution and the correlation between the emergent energy and angle have been examined.

9.3.14 "Computer Simulation of Collision Cascades in Monazite"⁴⁵

M. T. Robinson

Collision cascades in the monoclinic mineral monazite have been studied with a modified version of the computer simulation program MARLOWE. Most of the calculations were made for the irradiation of polycrystalline CePO by normally incident 50-eV to 100-keV argon atoms. A few calculations were made for 1-keV copper atoms recoiling from lattice sites in a hypothetical form of copper with the monazite structure. Although there are many fewer replacements and substantially more

channeling in the mineral, collision cascades in monazite are generally similar to those in metals in size and shape. The dimensions of the calculated cascades suggest that the amorphization of monazite by argon-ion irradiation probably commences when collision cascades begin to overlap. The calculations give a detailed view of the structure of the cascades in monazite that should be useful in interpreting radiation effects in proposed nuclear-waste-isolation media.

9.3.15 "Computer Simulation of the Self-Sputtering of Uranium"⁴⁶

M. T. Robinson

The sputtering of polycrystalline α -uranium by uranium ions of energies below 10 keV has been studied in the binary collision approximation using the computer simulation program MARLOWE. Satisfactory agreement of the computed sputtering yields with the small amount of available experimental data was achieved using the Moliere interatomic potential, a semilocal inelastic loss function, and a planar surface binding barrier—all with conventional parameters. The model is used to discuss low-energy-sputtering processes and the energy and angular distributions of the reflected primaries and the sputtered target particles.

9.4 INSULATORS AND STABILIZERS FOR SUPERCONDUCTING MAGNETS—ABSTRACTS

R. R. Coltman, Jr.

9.4.1 "Low-Temperature-Irradiation Study of Flux-Line Pinning in Type-II Superconductors"⁴⁷

H. R. Kerchner
D. K. Christen
C. E. Klabunde

S. T. Sekula
R. R. Coltman, Jr.

Annealed wires of Nb and Nb-20 at. % Ta were irradiated at liquid-helium temperature in two different modes. In one mode, thermal

neutrons produced 75% of the damage, while in the other mode, fast neutrons produced 85% of the damage. The increase in critical current with fluence was measured to determine its dependence on pin type and density and material purity. Damage due to the fast-neutron component of the flux dominated the flux pinning in both modes. The observations were consistent with the collective statistical summation theory and inconsistent with the conventional single-particle theory. The elementary pinning interaction deduced from the data by using the collective statistical theory agreed well with a recent theoretical calculation of the interaction due to the electron scattering mechanism.

9.4.2 "Organic Materials for Fusion Reactor Applications"⁴⁸

G. F. Hurley

R. R. Coltman, Jr.

Organic materials requirements for fusion reactor magnets are described with reference to the temperature, radiation, and electrical and mechanical stress environment expected in

these magnets. A review is presented of the response to gamma-ray and neutron irradiation at low temperatures of candidate organic materials, that is, laminates, thin films, and potting compounds. Lifetime-limiting features of this response, as well as needed testing under magnet operating conditions not yet adequately investigated, are identified, and recommendations for future work are made.

9.4.3 "A National Low-Temperature Neutron-Irradiation Facility"⁴⁹

R. R. Coltman, Jr.

F. W. Young, Jr.

C. E. Klabunde

The Materials Sciences Division of DOE will establish a National Low-Temperature Neutron-Irradiation Facility (NLTNIF) that will utilize the BSR located at ORNL. The facility will provide high radiation intensities and special environmental and testing conditions for qualified experiments at no cost to users. This report describes the planned experimental capabilities of the new facility.

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Chapter 10

Neutron Transport

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10. NEUTRON TRANSPORT

Summary of Activities

The neutron transport program includes both experimental and analytic phases. The experimental program is designed to provide the data necessary for verifying the analytic method and cross-section data used for fusion reactor neutronics design calculations. Experiments are being carried out to determine neutron and photon transport in typical fusion reactor shield materials and configurations and to determine the effects of penetrations in these shields. The analytic program supports the design of the integral experiments and compares calculated data with data obtained experimentally. Work is also performed in the area of nuclear data evaluation and cross-section processing, and the Radiation Shielding Information Center (RSIC) has continued to supply a broad range of services to the fusion energy research community.

10.1 ABSTRACTS

10.1.1 "Monte Carlo Calculations of Neutron and Gamma-Ray Energy Spectra for Fusion Reactor Shield Design: Comparison with Experiment"¹

R. T. Santoro

J. M. Barnes

Neutron and gamma-ray energy spectra resulting from the interactions of ~ 14 -MeV neutrons in laminated slabs of stainless steel (type 304) and borated polyethylene have been calculated using the Monte Carlo code MCNP. The calculated spectra are compared with measured data as a function of slab thickness and material composition and as a function of detector location behind the slabs. Comparisons of the differential energy spectra are made for neutrons with energies above 850 keV and for gamma rays with energies above 750 keV. The measured neutron spectra and those calculated using Monte Carlo methods agree within 5% to 50%, depending on the slab thickness and composition and neutron energy. The agreement between the measured and calculated gamma-ray energy spectra is

also within this range. The MCNP data are also in favorable agreement with attenuated data calculated previously by discrete ordinates transport methods and the Monte Carlo code SAM-CE.

10.1.2 "Integral Experiments for Fusion Reactor Shield Design—Summary of Progress"²

R. T. Santoro

J. M. Barnes

R. G. Alsmiller, Jr.

G. T. Chapman

Neutron and gamma-ray energy spectra from the reaction of ~ 14 -MeV neutrons in blanket and shield materials and from the streaming of these neutrons through a cylindrical duct ($L/D = 2$) have been measured and calculated. These data are being obtained in a series of integral experiments to verify the radiation transport methods and nuclear data that are being used in nuclear design calculations for fusion reactors. The experimental procedures and analytic methods used to obtain the calculated data are reviewed. Comparisons

between measured and calculated data for the experiments that have been performed to date are summarized.

10.1.3 The ORNL Integral Experiment to Provide Data for Evaluating Magnetic-Fusion-Energy Shielding Concepts. Part I: Attenuation Measurements³

G. T. Chapman
J. W. McConnell

G. L. Morgan

Integral experiments to measure the energy spectra of neutrons and gamma rays due to the transport of approximately 14-MeV $T(d,n)^4He$ neutrons through laminated stainless steel and borated polyethylene shield configurations have been performed at ORNL. An NE-213 detector and conventional pulse-shape-discrimination circuitry were used to record the pulse-height distributions from which the energy spectra were derived. Descriptions of the facility and experimental techniques are given in this paper, along with tables and curves showing the results of the measurements.

10.1.4 "Neutronics—Tritium Breeding"⁴

R. T. Santoro

The neutronics of tritium breeding are reviewed. The ramifications of breeding are delineated with respect to overall blanket design. A brief commentary on the one-dimensional (1-D) discrete ordinates method for estimating tritium production is presented. Some examples of the tritium breeding capability of prototypic blanket designs are summarized, along with examples of the influence on calculated tritium breeding ratios of cross-section uncertainties.

10.2 DATA EVALUATION AND PROCESSING FOR FUSION NEUTRONIC DATA NEEDS

D. C. Larson
C. Y. Fu

D. M. Hetrick
R. W. Roussin

Evaluated and processed neutron cross-section data are produced to meet the needs of

fusion reactor designers. The national neutron cross-section evaluation effort in the past has focused on the data needs of the fission reactor community, which are rather different from the needs of fusion reactor designers. The purpose of our evaluation work is to update ENDF/B evaluated cross sections for at least the materials C, F, Si, Ca, Ti, V, Cr, Fe, Ni, Cu, and Pb. Separate evaluations are generally given for the isotopes of these materials. These evaluations cover all reactions of importance to the fusion community, with particular emphasis placed on cross sections for dosimetry and gas production, as well as recoil nuclei spectra, correlated angle-energy spectra, and cross-section uncertainties. The energy range emphasized for the fission community was generally well below 6 MeV, with less emphasis placed on cross sections to the upper limit of 20 MeV. This task concentrates on upgrading cross sections induced by neutrons from 6 to 20 MeV and extending selected evaluations to ~40 MeV where cross sections are required for understanding data to be obtained from the Fusion Materials Irradiation Test (FMIT) facility. This work includes production of evaluations (80%) and development of associated methodology (20%) for producing evaluated cross-section and uncertainty data from existing theory and experimental data. New isotopic evaluations for $^{63,65}Cu$ are completed from 1 to 20 MeV (ref. 5), and work to remove known problems from existing evaluation of nickel and chromium is well under way.

Evaluated cross sections must be processed into forms that can be used in radiation transport computer codes. The focus of this effort has been the development of VITAMIN-E,⁶ a 174-neutron, 38-gamma-ray group cross-section library. It can be used in conjunction with the AMPX-II system⁷ to derive cross-section data suited to a particular application. The initial version of VITAMIN-E is based on ENDF/B-V.⁸

Recent efforts to update VITAMIN-E have focused on ENDF/B-V, Revision 2, which was released in 1983. Several materials of importance to fusion neutronics work were processed

and included in the basic library. Efforts are under way to place VITAMIN-E and the relevant AMPX-II computing technology on the National Magnetic Fusion Energy Computing Center (NMFECC) at Lawrence Livermore National Laboratory (LLNL). The VITAMIN-E data and AMPX-II computing technology are also available from the RSIC at ORNL.

10.3 RADIATION SHIELDING INFORMATION CENTER

R. W. Roussin
D. K. Trubey

J. E. White
J. Bartley

The RSIC serves an international community by responding to inquiries about radiation transport problems. Staff members provide guidance by drawing on a technical data base that includes a computerized literature file, a collection of complex computer programs, and a substantial body of nuclear data libraries pertinent to the solution of such problems.

Acquiring the needed computer-based technology base requires the collaboration of the neutronics community with RSIC staff members to collect, organize, process, evaluate, and package relevant technology developed in the community. This technology is disseminated throughout the community with a mechanism for feedback of experience through usage, which results in an improved product.

The resulting technology base provides an overall advancement of the state of the art.

A selected few of the products of this information cycle process that are relevant to fusion neutronics are listed below. A newly documented version of a spectrum unfolding code (PSR-102/FERDO/FERD)⁹ was contributed by ORNL. The new general-purpose Monte Carlo code (CCC-200/MCNP)¹⁰ and an updated version of the 1-D discrete ordinates code (CCC-266/ONETRAN)¹¹ were contributed by Los Alamos National Laboratory (LANL), a new system for cross-section data (D-69/ACTL82)¹² was provided by LLNL, and a new system for computing activation and transmutation of alloys in fusion facilities (CCC-443/REAC)¹³ was contributed by Hanford Engineering Development Laboratory (HEDL). An updated version of the CCC-372/TRIPOLI-2 Monte Carlo code system¹⁴ was contributed by the CEA, Saclay, France, and the EIR, Wurenlingen, Switzerland, provided a Cyber-174 version of the LANL 1-D discrete ordinates code CCC-428/ONEDANT.¹⁵

This selection represents only a small portion of the total activity of the center. Information processing (including evaluation and packaging) is a daily concern. In addition to a comprehensive literature data base, RSIC-packaged products include 107 data packages (DLC), 450 neutronics and shielding code packages (CCC), and 207 data processing and other miscellaneous code packages (PSR).

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Chapter 11

Management Services

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-
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11. MANAGEMENT SERVICES

Summary of Activities

The sole function of the Management Services Section is to support the programmatic research and development activities of the Fusion Energy Division (FED). Areas of support are: general personnel administration; material and service procurements; subcontracting; national and international agreements coordination; nonprogrammatic engineering services for support systems and equipment; planning and coordination of general plant project and facility requirements; maintenance and machine shop work coordination; labor relations; telecommunications; financial management; automated management information systems; library services and resources; publications services, including editing, word processing, graphics, photography, and reproduction; safety; emergency planning; and quality assurance. This support is provided through interpersonal relations with FED programmatic personnel and through the coordination of support resources from a variety of disciplines outside the division.

11.1 OFFICE OF THE MANAGER FOR GENERAL ADMINISTRATION AND PROCUREMENT

The office of the manager is responsible for most of the general administrative functions of the division.

11.1.1 Personnel Functions

In addition to the usual activities concerning travel, outside assignments, promotions, vacation, and security items, interviews were conducted with 19 prospective permanent employees to fill 10 positions. There were 9 acceptances out of 12 offers. The positions were filled by five transfers from within the UCC-ND complex, and four new employees were hired. Two persons transferred to other ORNL divisions, three retired, and 13 others terminated for various reasons.

The summer program was increased over that of CY 1982 with the employment of eight

technical students, one faculty, and three clerical. In addition, six students and three faculty came from universities under the sponsorship of the Oak Ridge Associated Universities (ORAU) program. Assignments were processed for 80 scientific guests and subcontractor personnel. Of these, 14 were foreign participants, 7 for the Large Coil Program (LCP).

The Laboratory In-House Facilitated Training (LIFT) program was completed. One person was given a permanent assignment and the others accepted positions elsewhere.

11.1.2 Subcontracts

Industrial participation through subcontracting was continued. Contracts for coils for the LCP began to be phased out with the delivery of the General Electric and the General Dynamics-Convair coils. Also, the ELMO Bumpy Torus Proof-of-Principle (EBT-P) Project was placed in abeyance. Subcontracts with industries in other areas [Fusion

Engineering Design Center (FEDC); EBT-Scale] kept the cost of subcontracts at approximately \$15.4 million.

A special contract involving Historical Black Colleges and Universities for upgrading of technical excellence of those colleges and universities was processed.

11.1.3 National and International Agreements

The U.S.-Japan Exchange Program was continued during 1983. Problems arose concerning the assignment of personnel from Japanese universities who came under the auspices of the Monbusho of Japan. Assignment of Japan Atomic Energy Research Institute (JAERI) and JAERI contractor personnel for the LCP went smoothly.

Fusion and plasma physics fields were added to the blanket agreements with Kernforschungszentrum Karlsruhe (KfK).

11.1.4 Procurement

During 1983 the procurement group processed 2138 purchase requisitions, representing a dollar volume of approximately \$7.3 million. Five hundred forty-five shipping requests were issued during this period. Methods to improve the procurement cycle were discussed with Y-12, Engineering, Finance and Materials personnel, and consultants who were contracted to participate.

11.2 ENGINEERING SERVICES

The Engineering Services Group provides a coordinating service for all engineering work performed in the division. This includes providing or directing the engineering for all nonprogrammatic work, coordinating maintenance and machine shop work, supervising the inventory and storage of materials, coordinating telecommunications, and overseeing all General Plant Project (GPP), Multi-General Purpose Facility (MGPF), Line Item, and

General Plant Equipment (GPE) improvements. This group is also responsible for maintaining building facilities and planning future facilities. Some highlights of the 1983 activities follow.

1. Completed computer room expansion in Bldg. 9201-2.
2. Continued work on the recall maintenance program for building equipment.
3. Completed modifications for the Bldg. 9201-2 cooling tower.
4. Completed addition of another cooling tower on existing basin for cooling demineralized water for Bldg. 9204-1.
5. Continued to improve general appearance of division buildings by installing new tile floors, painting, adding plastic trash containers, replacing drop ceilings, hanging pictures, etc.
6. Renovated old drafting area (Room 344) in Bldg. 9201-2 for the Advanced Toroidal Facility (ATF) conference room and display area.
7. Expanded capability of division video system and improved quality of transmission and operation.
8. Coordinated shop fabrication at Y-12, ORNL, ORGDP, and outside shops. This work comprised over 250 jobs requiring 25 personnel-years. Approximately \$2 million of work was coordinated, excluding Large Coil Test Facility (LCTF) fabrication.
9. Title II design was 90% complete on the MGPF Electrical Upgrade. This will tie the No. 2, 161-kV line into a new 50-MVA transformer that will supply Bldg. 9201-2.

11.3 FINANCE

The Finance Office, an integral part of the Management Services Section, provides financial management support for FED administrative, engineering, and research personnel in areas including budget preparation, cost

scheduling, and variance analysis. This office also provides meaningful and appropriate accounting and cost control. Interaction with division management is an essential part of administering the budget, accounting policies, and procedures.

As shown in Table 11.1 and Fig. 11.1, the funding trends for the division and for the Fusion Program continue to exhibit growth. This trend creates a need for greater efficiency and improvement in specific areas of financial control. In this spirit, the Finance Office must be innovative in the development of financial techniques to meet the growing and changing financial needs of the division.

Fig. 11.1. Fusion Program expense funding (B/O).

Table 11.1. Fusion Program expense funding (in thousands of dollars)—budget outlay (B/O)

Activity	FY 1981 actual cost	FY 1982 actual cost	FY 1983 actual cost	FY 1984 funding as of February 1984	FY 1985 budget submission	FY 1986 budget submission
Applied Plasma Physics						
Fusion Plasma Theory	\$ 2,809	\$ 3,031	\$ 3,237	\$ 3,450	\$ 3,570	\$ 3,910
Experimental Plasma Research	1,092	1,129	1,344	1,335	1,270	1,210
National MFE Computer Network	289	332	352	344	400	430
Technical Program Support	0	0	38	0	215	230
	\$ 4,190	\$ 4,492	\$ 4,971	\$ 5,129	\$ 5,455	\$ 5,780
Confinement Systems						
Toroidal Systems						
Research Operations	\$ 9,875	\$ 9,448	\$ 9,639	\$ 7,432	\$ 8,245	\$10,680
Major Device Fabrication	862	0	54	5,300	9,342	5,022
Magnetic Mirror Systems						
Research Operations	8,382	11,050	10,866	15,986	10,400	11,100
	\$19,119	\$20,498	\$20,559	\$28,718	\$27,987	\$26,802
Development and Technology						
Magnetic Systems	\$10,143	\$11,456	\$12,839	\$11,600	\$13,400	\$ 9,830
Plasma Engineering	8,424	9,000	9,348	4,950	8,964	9,493
Reactor Systems	931	765	765	590	625	670
Environment and Safety	667	494	270	200	231	250
Reactor Materials	4,354	4,883	5,615	5,805	7,282	7,836
Fusion Engineering Design Center	3,228	3,756	4,110	5,110	5,731	6,147
	\$27,747	\$30,354	\$32,947	\$28,255	\$36,233	\$34,226
Program Direction						
Contractual Services and Supplies	\$ 20	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0
TOTAL ORNL FUNDING	\$51,076	\$55,344	\$58,477	\$62,102	\$69,675	\$66,808

11.4 LIBRARY

The Fusion Energy Library is part of the ORNL Library System, having a specialized collection in plasma physics and fusion technology. The library collection consists of 2,800 books, 135 journals, and 12,000 technical reports in paper copies and 22,000 in microfiche. It provides library and information services, such as reference assistance, interlibrary loans, and document delivery. Computerized information retrieval is another specialized service provided by the library. With on-line access to over 200 topical data bases, including Nuclear Science Abstracts, Energy Research Abstracts, Physics Abstracts, Engineering Index, Citation Index, and American Men and Women of Science, in DOE RECON, DILOG, SDC, and BRS, a computerized literature search can provide a comprehensive bibliographic review of a subject, an author, or a cited reference, as well as verify a specific publication.

During 1983, a Minolta microfilm microfiche reader-printer, a circulation desk, and terminals for LION (Library Information On-line Network) were installed. In the upcoming year, the library is moving to the LION automated catalog and circulation system, which will provide immediate on-line access to books, journals, and reports in the entire ORNL library system.

11.5 PUBLICATIONS OFFICE

More than 27,900 pages of reports, articles, proceedings papers, and graphics were edited, composed, drawn, and processed in the Fusion Energy Division Publications Office (FEDPO) during CY 1983. The editors, compositors, and graphic artists processed nearly 125 pages every working day (based on an average 225-day work-year). As shown by Table 11.2, this achievement required a collective effort on the part of the staff that amounted to some 21,000 work-hours, including about 760 overtime hours

Table 11.2. FEDPO production and work-hours for CY 1983 (≈ 225 work-days)

	Service pages ^a	Work-hours
Editing	5,571	2,441
Composition and word processing ^b	5,363	7,292
Proofreading	3,873	^c
Makeup	2,712	710
Final reading	4,517	^c
Graphic arts	5,946	9,876
	27,982	20,319 ^d

^a"Service pages" indicates the total number of pages handled by each functional group (e.g., editing). Pages corrected or reprocessed as a result of FEDPO error are not counted more than once; pages changed by request of the author are again counted as service pages.

^bAbout 90% of the service pages in the composition category were first converted from TEDI to UNIX by the FEDPO compositors.

^cThese work-hours are included in editing.

^dTotal does not include about 760 hours of overtime.

(mostly contributed by the graphic artists and compositors).

Taking in about 3 new jobs per day from the FED authors, the Publications Office handled some 625 separate jobs during the past year—jobs ranging from journal articles, conference papers, and reports of every description to presentation posters, full-color renderings, and view graphs. See Table 11.3 for a synopsis of the wide range of work handled by the office and the numbers of different types of documents and graphics processed.

Far outnumbering all other types of work handled in the Publications Office were about 270 abstracts processed for clearance during CY 1983. In a separate category are the documents that were submitted for editing, word processing, proofreading, makeup, clearance, and reproduction (among other services). This group included 143 papers, 84 technical reports (such as technical memoranda), 93 journal articles, and 48 other types of documents (e.g., brochures, newsletters, theses and dissertations,

Table 11.3. Synopsis of work processed by FEDPO in CY 1983^a

Editing and Composition		Graphic Arts	
Papers	143	Original drawings	2,250
Journal articles	93	Revised drawings	734
Technical reports	84	Visuals	672
Conference proceedings	9	Camera copies (Pos)	11,442
Newsletters	6	Covers	26
Theses/dissertations	4	Posters	26
Letters	3	Poster titles	64
Books	2	Signs	72
Symposia	2	Nameplates	111
Seminar papers	2	Diazo	121
Others ^b	20	Miscellaneous ^c	838

^aNot listed are about 270 abstracts cleared through the work reception office.

^bIncludes bulletins, brochures, workshop proceedings, proposals, notebooks, and memos.

^cIncludes poster pieces and reports binding.

workshop proceedings, and presentations). A comparison of the volume of services provided by the Publications Office over the past three calendar years shows significant increases in all areas (Table 11.4) but most markedly in the prodigious volume of xeroxed materials, which jumped by a factor of over 1.5 from the previous year.

On another front, the composition (word processing) group in the Publications Office made increasingly efficient use of the IS/1 UNIX^{*} Text Management System instituted in the office last year. An additional benefit of the system was installation of the TEDI-to-UNIX conversion program that allows FED compositors and authors to transfer their files directly to the Publications Office for on-line editing, word processing, and outputting. This utility has already proved its merit in saving time and money. Nearly 90% of all composed textual material processed through the FEDPO last calendar year had been first converted from the TEDI system.

The Graphic Arts (GA) group in the FEDPO produced more than 2000 new original draw-

Table 11.4 Three-year comparison of volume of FEDPO publication services

	1981	1982	1983
Publications ^a	600	450	625
Graphic Arts			
Drawings ^b	3,005	2,873	2,984
Visuals ^c	523	400	672
Camera copies (Pos) ^d	15,000	13,562	11,442
Other ^e	864	668	1,258
Xerox 9400 copies (millions)	2.5	2.6	4.4

^aNumber of individual jobs processed, without regard to size of each job.

^bIncludes original and revised drawings.

^cIncludes original artwork for view graphs and slides.

^dIncludes glossy prints and view graphs.

^eIncludes posters, poster titles, signs, report covers, nameplates, diazo, etc.

ings in the past year (Table 11.3), extending the total volume of work processed by the group over the 16,300 mark [including more than 11,000 camera (Pos) copies]. During the past three years (Table 11.4), the graphics output of presentations (i.e., posters, titles, slides, and view graphs) increased steadily. In addition, the illustrators in the group now produce many

^{*}Trademark of Bell Laboratories.

more original, full-color renderings of FED projects and equipment than they have had time for in past years.

One major reason that GA illustrators have more time to devote to special projects requiring more advanced skills, such as posters and color work, is the computer graphics program brought into full use in the past year. Using the computer has meant increased efficiency and expanded capabilities to produce a large portion of the basic graphs, charts, and drawings needed by the FED staff. These were the initial concepts in planning computer graphics use in the GA group, and they have become a reality. Computer graphics production became fully operational in the last half of 1983. In about 4½ months, the illustrators produced 324 publication-quality drawings and visuals using the MAPPER program. With Tektronix equipment—a 4054 terminal and digitizing tablet, a 4114 terminal, and a 4631 hard-copy unit for proof copies—the illustrators can send raw, digitized, or enhanced data to the FR80 for final black and white or color output. One extremely beneficial feature of the equipment is that color slides can be made inexpensively on the FR80 (for less than the cost of black and white view graphs), and the research staff in FED is being encouraged to use color slides for this reason. In addition to saving money, the quality of presentation visuals is upgraded tremendously.

11.6 SAFETY, EMERGENCY PLANNING, AND QUALITY ASSURANCE

11.6.1 Safety and Emergency Planning

The FED safety program included monthly safety inspections by individual sections; quar-

terly safety inspections by an independent inspection committee comprised of the Division Safety Officer, Y-12 safety representatives, and Y-12 Maintenance supervision; and monthly fire inspections performed by professional fire inspectors. Six safety training sessions were held this year, and attendance at these sessions was mandatory for all division personnel. Two special-emphasis safety meetings were also presented. A safety contest was conducted with good employee participation.

During 1983 the division emergency training program continued. Training in cardiopulmonary resuscitation (CPR) conducted by certified Red Cross instructors resulted in the certification of 16 employees and recertification of 16 employees in CPR. Red Cross training in first aid resulted in the certification of 26 employees in Basic First Aid. Training continued to ensure maximum response to building emergencies.

The division safety program received an outstanding rating from the Y-12 Safety Department.

11.6.2 Quality Assurance

The division's Quality Assurance (QA) Program continued to improve during 1983. The program was effective in ensuring the fabrication and the purchase of reliable and cost-effective experimental equipment. The special power supply committee continued its surveillance of the quality of purchased power supplies.

During the year, QA audits were conducted at vendors' sites. In addition, the Department of Energy conducted QA audits of the ATF and LCP projects.

Publications and Presentations

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K. Audenaerde, D. B. Batchelor, and R. C. Goldfinger, "Absorption of Obliquely Propagating Waves in Fully Relativistic Plasmas"

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- K. C. Shaing, "Status of Neoclassical Transport Theory of Multiple Helicity Stellarators" (invited paper)
- K. C. Shaing, "Transport Associated with Collisionless Detrapping/Retrapping in a Nonaxisymmetric Torus"
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- T. Uckan, "Density Measurements with Microwave Interferometer on EBT-S"
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- K. K. Chipley, B. E. Nelson, L. M. Vinyard, and D. E. Williamson, "Design Description of the Vacuum Vessel for the Advanced Toroidal Facility"
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- W. H. Gray, "An Enhancement to the Tektronix PLOT-10 Terminal Control System for Creation of Graphics Metafiles"
- W. H. Gray, "Structural Analysis of the Large Coil Test Facility Two-Coil Test"

- W. H. Gray and T. V. Baudry, "Using PAFEC as a Preprocessor for MSC/NASTRAN"
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- N. A. Uckan and R. T. Santoro, "EBT Reactor Characteristics Consistent with Stability and Power Balance Requirements"
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- D. B. Batchelor, R. C. Goldfinger, and H. Weitzner, "Propagation and Absorption of Electromagnetic Waves in Fully Relativistic Plasmas"
- J. D. Callen and K. C. Shaing, "A New Long Mean Free Path Resistive MHD Instability"
- B. A. Carreras, W. A. Cooper, L. Garcia, T. C. Hender, H. R. Hicks, J. A. Holmes, and V. E. Lynch, "Equilibrium and Stability Properties of High Beta Toratrons"
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- E. C. Crume, "Simulation of Inertial and Beam-Driven Effects on Impurities in ISX-B"
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- W. B. Downum, "EBT Plasma Performance with Improved Refueling Models"
- A. M. El Nadi, D. A. Spong, and J. C. Whitson, "A Numerical Analysis of the EBT Flute Modes in the Low Poloidal Mode Number Limit"
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- L. M. Hively, "Fast Ion Thermalization and Confinement in TF-Rippled Tokamak Reactors"
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L. L. Lao, W. A. Cooper, R. M. Wieland, and F. J. Helton, "Effects of Toroidal Rotation and Pressure Anisotropy on Tokamak Equilibria"

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K. C. Shaing, "Neoclassical Transport in a Multiple-Helicity Torsatron in the Low Collisionality Regime"

D. J. Sigmar and K. C. Shaing, "Plateau Regime Transport for Plasmas with Strong Toroidal Rotation"

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J. S. Tolliver, E. F. Jaeger, D. E. Hastings, and C. L. Hedrick, "Extensions of the ORNL EBT Monte Carlo Diffusion Code"

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R. C. Goldfinger and D. B. Batcelsor, "RAYS: A Geometrical Optics Code for ELMO Bumpy Torus"

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D. A. Spong, H. L. Berk, and J. W. Van Dam, "Radial Structure of Curvature-Driven Instabilities in a Hot Electron Plasma"

U.S.-Japan Workshop on 3-D MHD Simulations, Nagoya, Japan, March 7-11, 1983 (proceedings to be published as Report IPPJ-632 by the Institute for Plasma Physics, Nagoya)

B. A. Carreras, L. A. Charlton, W. A. Cooper, L. Garcia, J. H. Harris, T. C. Hender, H. R. Hicks, J. A. Holmes, V. E. Lynch, and B. F. Masden, "Equilibrium and Stability Studies for High Beta Plasmas in Torsatron/Heliotron Devices"

B. A. Carreras, L. Garcia, T. C. Hender, H. R. Hicks, J. A. Holmes, V. E. Lynch, and B. F. Masden, "3-D Resistive MHD Calculations for Tokamak Plasmas: Beyond the Simple Reduced Set of Equations"

Fourth Topical Conference on Atomic Processes in High Temperature Plasmas, Princeton, New Jersey, April 13-15, 1983 [abstracts published in *Bull. Am. Phys. Soc.* 28 (1983)]

C. Bottcher, D. C. Griffin, and M. S. Pindzola, "Theory of Electron-Impact Ionization of Ti and Fe Ions"

E. C. Crume, "Dielectronic Recombination Rate Coefficients for Fe XVI-Fe XIX" (invited paper)

D. C. Gregory, "Experimental Electron-Impact Ionization Cross Sections" (invited paper)

J. T. Hogan, "Impurity Thermal Charge Exchange Effects"

R. C. Isler, R. A. Langley, and L. E. Murray, "Measurements of Plasma Rotation Using Spectral Lines from Charge-Transfer Reactions"

F. W. Meyer, "The ORNL ECR Multicharged Ion Source"

D. W. Mueller, T. J. Morgan, G. H. Dunn, D. C. Gregory, and D. K. Crandall, "Measured Electron-Impact Ionization Cross Sections for Ti^{2+} and Fe^{2+} "

R. A. Phaneuf, "Electron Capture in Collisions of Al^{9+} and Fe^{9+} with H and H_2 at $E < 120$ eV/amu"

R. K. Richards, "Analysis of EBT Plasmas and Confinement Including Electron Temperature Measurements from Inner Shell Ionization" (invited paper)

D. W. Swain, "Recent EBT Confinement Experiments" (invited paper)

Spring Meeting of the American Physical Society Division of Plasma Physics, Baltimore, April 18-21, 1983 [abstracts published in *Bull. Am. Phys. Soc.* 28 (1983)]

D. B. Batchelor, "Electron Cyclotron Heating and Ion Cyclotron Heating in the ELMO Bumpy Torus Device"

R. A. Faneuf, "Low-Energy Electron Capture by Multiply Charged Ions from a Laser-Pumped Source" (invited paper)

College on Radiation in Plasmas, Trieste, Italy, May 24-June 17, 1983

A. M. El Nadi, "Plasma Stability in a Bumpy Cylinder with Hot Electron Rings"

A. M. El Nadi, J. C. Whitson, H. A. Hirolous, and H. F. Hassan, "Effect of Magnetic Bending on the High Frequency Stability of the ELMO Bumpy Torus"

American Vacuum Society 30th National Symposium, Boston, November 1-4, 1983

G. M. Fuller, "Design Considerations for Achieving High Vacuum Integrity in Fusion Devices"

Symposium on Energy Removal and Particle Control in Toroidal Fusion Devices

J. R. Haines, "DCT-8 Pumped Limiter Design Considerations"

Seventh International Conference on Structural Mechanics in Reactor Technology, Chicago, August 22-26, 1983

R. J. Barrett, "Safety Considerations in the Design of the Fusion Engineering Device"

R. J. Hooper and B. L. Hunter, "Structural Design Procedures for FED/INTOR Magnet Systems"

NBS-DOE Workshop on Materials at Low Temperatures, Vail, Colorado, October 17-19, 1983

R. J. Hooper, "Use of Crack Propagation Rate Test Data in Establishing Design Allowable Stresses"

Winter Annual Meeting of the American Society of Mechanical Engineers, Boston, November 13-18, 1983

T. E. Shannon, "Engineering of Fusion Reactors" (panel discussion)

Course and Workshop on Mirror-Based and Field-Reversed Approaches to Magnetic Fusion, Varenna, Italy, September 12-17, 1983 (published in the proceedings)

D. W. Swain, "The EBT Concept: Status, Plans, and Reactor Potential"

D. W. Swain, N. A. Ukan, R. T. Santoro, L. W. Owen, and T. Ukan, "EBT Reactor and Concept Improvement Studies"

Workshop: Diagnostics for Fusion Reactor Conditions, Villa Monastero, Varenna, Italy, September 6-17, 1982 [published in the proceedings (EUR8351-II EN)]

J. C. Glowienka, "Diagnostic Protection Techniques in Steady-State, High Power RF and Microwave"

Eleventh European Conference on Controlled Fusion and Plasma Physics, Aachen, West Germany, September 5-9, 1983 (published in the proceedings)

J. F. Lyon, B. A. Carreras, L. A. Charlton, W. A. Cooper, R. A. Dory, R. H. Fowler, L. Garcia, J. H. Harris, T. C. Hender, H. R. Hicks, S. P. Hirshman, J. A. Holmes, W. A. Houlberg, T. C. Jernigan, V. E. Lynch, B. F. Masden, K. C. Shaing, and J. Sheffield, "ATF Torsatron Studies"

S. D. Scott, J. D. Bell, C. E. Bush, A. Carnevali, B. A. Carreras, J. L. Dunlap, G. R. Dyer, P. H. Edmonds, O. C. Eldridge, A. C. England, W. L. Gardner, J. H. Harris, H. C. Howe, D. P. Hutchinson, R. C. Isler, T. C. Jernigan, R. R. Kindsfather, P. W. King, R. A. Langley, E. A. Lazarus, J. F. Lyon, C. H. Ma, P. K. Mioduszewski, M. Murakami, L. E. Murray, G. H. Neilson, V. K. Paré, M. J. Saltmarsh, D. J. Sigmar, J. E. Simpkins, K. A. Stewart, W. L. Stirling, C. E. Thomas, R. M. Wieland, J. B. Wilgen, W. R. Wing, and A. J. Wootton, "Neutral Injection Experiments on the ISX-B Tokamak"

D. W. Swain, R. J. Colchin, F. W. Baity, J. A. Cobble, W. A. Davis, J. C. Glowienka, J. R. Goyer, G. A. Hallock, O. E. Hankins, G. R. Haste, D. L. Hillis, S. Hiroe, D. A. Rasmussen, R. K. Richards, L. Solensten, T. Uckan, T. L. White, and J. B. Wilgen, "The EBT Experiment"

Fourth International Symposium on Heating in Toroidal Plasmas, Rome, March 21-28, 1983 (published in the proceedings)

T. L. White, "Mixed-Mode Distribution Systems for High Average Power Electron Cyclotron Heating"

Third International Symposium on the Production and Neutralization of Negative Ions and Beams, Brookhaven National Laboratory, Upton, New York, November 14-18, 1983 (published in the proceedings by the American Institute of Physics)

W. K. Dagenhart, W. L. Stirling, G. M. Bonic, G. C. Barber, and N. S. Ponte, "Short-Pulse Operation with the SITEX Negative Ion Source"

R. W. McGaffey, P. S. Meszaros, J. H. Whealton, R. J. Raridon, and D. H. McCollough, "End Effects in Slot Extraction for a SITEX Negative Ion Source"

O. S. Oen and M. T. Robinson, "Ion Backscattering from Layered Targets"

W. L. Stirling, W. K. Dagenhart, J. H. Whealton, and J. J. Donaghy, "Normalized Emittance of the SITEX Negative Ion Source"

J. H. Whealton, R. J. Raridon, R. W. McGaffey, D. H. McCollough, W. L. Stirling, and W. K. Dagenhart, "2-D Accelerator Design for the SITEX Negative Ion Source"

1983 International Electronic Device Meeting, Washington, DC, December 5-9, 1983

G. Hu, E. K. Choi, and H. Huey, "Use of Finite Element Technique in Designing Gyrotron Output Windows"

H. Huey, N. Lopez, G. Hu, E. K. Choi, and L. Mundie, "Infrared Monitoring of Gyrotron Windows"

N. Jory, R. Bier, S. Evans, K. Felch, L. Fox, H. Huey, J. Shively, and S. Spang, "First 200-kW CW Operation of the Varian 60-GHz Gyrotron"

T. E. Shannon, "Engineering Considerations in the Selection of the Tokamak to Follow TFTR"

Seventh International Conference on Infrared and Millimeter Waves, Marseilles, February 14-18, 1983

W. J. DeHope, P. E. Ferguson, V. A. Matranga, J. J. Sandoval, and J. J. Tancredi, "250-kW, High Efficiency Gyrotron Oscillator Operating at 60 GHz"

C. H. Ma, D. P. Hutchinson, P. A. Staats, and K. L. Vander Sluis, "A Multichord Submillimeter-Wave Polarimeter/Interferometer for Measurements of Electron Density and Plasma Current Distributions in Tokamak Plasma"

Eighth International Conference on Infrared and Millimeter Waves, Miami, December 12-17, 1983

W. DeHope, P. Ferguson, and M. Schmitt, "Field Analysis and Performance Predictions of Complex Cavity Gyrotrons"

K. Felch, R. Bier, L. Fox, H. Huey, H. Jory, J. Manca, J. Shively, and S. Spang, "Analysis of the Output Mode from a 60-GHz, 200-kW CW Gyrotron"

Workshop on Computational Problems in MHD, Wildhaus, Switzerland, September 12-14, 1983
(proceedings to be published in *Computer Physics Reports*)

H. R. Hicks, R. A. Dory, and J. A. Holmes, "Inverse Plasma Equilibria"

Digital Equipment Computer Users Society, USA, 1983 Fall, Las Vegas, October 24-28, 1983
(proceedings published by Digital Equipment Corporation, Marlboro, Mass., 1984)

D. N. Clark, "Overcoming Computer Shock"

Advanced Bumpy Torus Concepts Workshop, Rancho Santa Fe, July 11-13, 1983 (proceedings published as CONF-830758 by Oak Ridge National Laboratory)

D. B. Batchelor, R. C. Goldfinger, D. A. Rasmussen, and D. W. Swain, "Theoretical Aspects of Throat Launch Microwave Heating in EBT-S"

D. E. Hastings, "Nonresonant Particle Transport for Bumpy Field Line Devices with Arbitrary Shaped Flux Surfaces"

C. L. Hedrick, "Comparison of Magnetic Equilibria and Low Frequency Stability for EBT and EBS"

L. W. Owen, D. K. Lee, and C. L. Hedrick, Jr., "ELMO Bumpy Square"

J. A. Rome, J. H. Harris, B. F. Masden, and V. E. Lynch, "On the Possibility of Rings in a Modular Stellarator"

Thirteenth International Conference on the Physics of Electronic and Atomic Collisions, Berlin, July 27-August 2, 1983 (published in the proceedings)

C. Bottcher, "Numerical Solution to the Few-Body Schrodinger Equation" (invited paper)

C. Bottcher and T. G. Heil, "Charge Capture by Multicharged Ions: Fully Quantal Calculations with Larger Basis Sets"

D. H. Crandall, R. A. Phaneuf, and D. C. Gregory, "Double Ionization Cross Sections for Ar^{4+} , Kr^{4+} , and Xe^{4+} in Single Collisions with Electrons"

S. Datz, P. F. Dittner, P. D. Miller, C. D. Moak, N. Neskovic, P. H. Stelson, and C. Bottcher, "Dielectronic Recombination of B^{2+} and C^{3+} via $1s^2 2s \rightarrow 1s^2 2p$ Excitation"

F. W. Meyer, "Coincidence Measurements of Electron Transfer in an Ion-Atom Crossed Beams Experiment"

D. W. Mueller, T. J. Morgan, G. H. Dunn, D. C. Gregory, and D. H. Crandall, "Absolute Cross-Section Measurements for Electron-Impact Ionization of Twice-Charged Ti^{2+} , Fe^{2+} , Ar^{2+} , Cl^{2+} , and F^{2+} "

Third Annual Tennessee Valley Chapter American Vacuum Society Symposium and Equipment Exhibit, Knoxville, Tennessee, May 9-11, 1983

J. C. Glowienka, W. A. Davis, D. W. Swain, and J. E. Simpkins, "Direct Comparison of Two Pressure Measurement Techniques: A Spinning Rotor Friction Gage and Energetic Particle Decay by Charge Exchange"

D. J. Hoffman, W. R. Becraft, C. W. Blue, S. K. Combs, W. K. Dagenhart, W. L. Gardner, N. S. Ponte, P. M. Ryan, D. J. Taylor, and J. A. Moeller, "The National RF Test Facility at ORNL"

P. K. Mioduszewski, "Pump Limiter Studies on the ISX-B Tokamak"

IEEE International Conference on Plasma Science, San Diego, May 23-25, 1983 (proceedings published by IEEE)

W. K. Dagenhart and R. J. Karidon, "High Resolution Total Beam Magnetic Species Analyzer for a $13 \times 43 \text{ cm}^2$, 50-A Ion Source"

W. J. DeHope, P. E. Ferguson, S. L. Hart, V. A. Matranga, J. J. Sandoval, M. J. Schmitt, and J. J. Tancredi, "60-GHz Gyrotron Oscillator"

A. C. England, "Electron Cyclotron Heating Experiments in Tokamaks and Stellarators"

J. C. Glowienka, W. A. Davis, and D. W. Swain, "Preliminary Neutral Density Measurements in EBT Using a Diagnostic Neutral Beam"

D. J. Hoffman, A. C. England, O. C. Eldridge, R. H. Fowler, T. C. Jernigan, J. H. Harris, and J. F. Lyon, "Ion Cyclotron Heating and Its Effect on Particle Orbits in ATF"

H. E. Huey, G. Hu, E. Choi, and L. Mundie, "Thermal Monitoring of Gyrotron Windows"

T. C. Jernigan, "The Advanced Toroidal Facility (ATF-1)"

M. M. Menon, G. C. Barber, W. K. Dagenhart, W. L. Gardner, H. H. Haselton, N. S. Ponte, P. M. Ryan, D. E. Schechter, W. L. Stirling, C. C. Tsai, and J. S. Whealton, "Experimental Results from the ORNL Positive Ion Source Designed for High Power ($\approx 2 \text{ MW}$) Long-Pulse (30-s) Neutral Beam Injection"

D. A. Rasmussen and D. B. Batchelor, "Measurements of High Frequency Fluctuations in EBT"

D. E. Schechter and C. C. Tsai, "Performance of an Electron Feed Assembly for ORNL/MFTF-B 30-s Ion Sources"

T. Uckan, "Electron Density Measurements with a 9-Channel Microwave Interferometer on EBT-S"

J. H. Whealton, R. W. McGaffey, and P. S. Mezaros, "Expeditious 3-D Poisson-Vlasov Algorithm Applied to Ion Extraction from a Plasma"

J. W. Wooten, R. J. Raridon, J. H. Whealton, D. H. McCollough, and C. C. Tsai, "Energy Straggling and Secondary Ion Optics in Neutral Beam Injectors"

A. J. Wootton, "Particle Confinement in ISX-B"

Symposium on Energy Removal and Particle Control in Toroidal Fusion Devices, Princeton, New Jersey, July 26-29, 1983 (proceedings to be published in the *Journal of Nuclear Materials*)

R. E. Clausing, L. Waelbroeck, J. Winter, P. Wienhold, L. Konen, and N. Noda, "Effects of Wall Conditioning on Plasma Parameters, Impurities, and Hydrogen Recycling in TEXTOR"

G. M. Fuller, B. A. Cramer, and J. R. Haines, "DCT-8 Pumped Limiter Design Considerations"

J. D. Galambos and Y-K. M. Peng, "1-D Flow Model for Divertor Plasmas"

R. A. Langley and H. C. Howe, "Determination of the Global Recombination Rate Coefficient for the ISX-B Tokamak"

E. A. Lazarus, "Confinement Improvement in Beam-Heated ISX-B Discharges with Low-Z Impurity Injection"

J. F. Lyon, V. E. Lynch, B. F. Masden, B. E. Nelson, and J. A. Rome, "Magnetic Limiter/Divertor Studies for ATF-I"

P. K. Mioduszewski, L. C. Emerson, J. E. Simpkins, A. J. Wootton, C. E. Bush, A. Carnevali, J. L. Dunlap, P. H. Edmonds, W. L. Gardner, H. C. Howe, D. P. Hutchinson, R. C. Isler, R. R. Kindsfater, R. A. Langley, E. A. Lazarus, C. H. Ma, M. Murakami, G. H. Neilson, V. K. Paré, S. D. Scott, C. E. Thomas, J. B. Whitley, W. R. Wing, and K. E. Yokoyama, "Particle Removal with Pump Limiters in ISX-B" (invited paper)

Third Topical Meeting on Fusion Reactor Materials, Albuquerque, September 19-22, 1983 (proceedings to be published in the *Journal of Nuclear Materials*)

R. E. Clausing, K. G. Tschersich, H. P. Fleischauer, L. Heatherly, F. Waelbroeck, J. Winter, P. Wienhold, Y. Sakamoto, S. Ishii, and K. Yano, "Surface Composition Changes of Inconel 625 During RG and ECR Discharge Cleaning of TEXTOR at 300°C"

L. C. Emerson, P. K. Mioduszewski, and J. E. Simpkins, "Experience with Zr-Al Getter Pumps in the ISX-B Tokamak"

W. A. Gabbard, J. E. Simpkins, P. K. Mioduszewski, and P. H. Edmonds, "The Fabrication of High Rate Chromium Getter Sources for Fusion Application"

R. A. Langley and J. P. Freshour, "Study of Erosion and Degradation of Titanium Carbide Coatings on Graphite Using High Power Neutral Beam Injectors"

J. Roth, J. B. Roberto, and K. L. Wilson, "Enhanced Sputtering of Graphite at High Temperature"

J. E. Simpkins, L. C. Emerson, and P. K. Mioduszewski, "A Practical Sublimation Source for Large-Scale Chromium Gettering in Fusion Devices"

F. W. Wiffen, "The Fusion Engineering Design Center"

F. W. Wiffen, "FEDC Design of Experimental Fusion Reactors"

J. Winter, F. Waelbroeck, P. Wienhold, H. G. Esser, L. Konen, T. Banno, E. Rota, and R. E. Clausing, "Surface Conditioning of Liners and Limiters of TEXTOR by Plasmachemical Carbon Deposition"

R. A. Zuhr, "Impurity Measurements in the TEXTOR Plasma Edge Using Deposition Probe Techniques"

30th National Symposium of the American Vacuum Society, Boston, November 1-4, 1983
(proceedings to be published in the *Journal of Vacuum Science and Technology* A)

T. B. Cook, "Measurements of the Radial Distribution of Neutral Iron in the Edge Plasma of the ISX-B Tokamak Using Laser-Induced Fluorescence"

T. B. Cook, P. W. King, and J. B. Roberto, "Measurement of the Ionization Length for Neutral Iron Near the Wall in the ISX-B Tokamak Using Laser-Induced Fluorescence"

L. C. Emerson, P. K. Mioduszewski, and J. E. Simpkins, "Performance of Zr-Al Getter Pumps Under Transient Load Conditions"

G. M. Fuller, C. Dillow, J. R. Haines, and C. Trachsel, "Design Considerations for Achieving High Vacuum Integrity in Fusion Devices"

R. A. Langley, "Correction of a Vacuum Design Fault in Leak Detectors"

R. A. Zuhr, "Characterization of the TEXTOR Plasma Edge Using Deposition Probe Techniques"

American Physical Society Meeting, Division of Electron and Atomic Physics, Boulder, Colorado, May 23-25, 1983 [abstracts published in *Bull. Am. Phys. Soc.* 28 (1983)]

P. F. Dittner, S. Datz, P. D. Miller, C. D. Moak, P. H. Stelson, C. Bottcher, and C. M. Fou, "Dielectronic Recombination of B^{2+} via $1s^2 2s \rightarrow 1s^2 2p$ Excitation"

D. C. Gregory, D. H. Crandall, C. Bottcher, D. C. Griffin, and M. S. Pindzola, "Electron-Impact Ionization of Xe Ions"

F. W. Meyer and P. M. Griffin, "Formation of $C^{7+}(2p)$ by Electron Capture and Direct Excitation Collisions with He, H_2 , and Xe"

R. A. Phaneuf, "Electron Capture by Slow Fe^{9+} Ions from H and H_2 "

Eighth International Seminar on Ion-Atom Collisions, Utrecht, The Netherlands, August 4-5, 1983

R. A. Phaneuf, "Electron Capture by Multiply Charged Ions from Hydrogen Atoms at Low Energies" (invited paper)

Meeting of the Southeastern Section of the American Physical Society, Columbia, South Carolina, November 3-5, 1983 [abstracts published in *Bull. Am. Phys. Soc.* 28 (1983)]

R. A. Phaneuf, "Electron Capture by Multiply Charged Ions from Hydrogen Atoms at Low Energies" (invited paper)

Workshop on Electronic and Ionic Collisions Cross Sections Needed in the Modeling of Radiation Interaction with Matter, Argonne, Illinois, December 6-8, 1983

D. C. Gregory, "The Controlled Fusion Atomic Data Center"

Second Inter-University Energy Symposium, Santiago, Chile, November 14-18, 1983 (proceedings published by the University of Santiago)

W. A. Cooper, "The Status of the Magnetic Fusion Energy Programme" (invited paper)

W. A. Cooper, "Technological Requisites of the Magnetic Fusion Energy Programme" (invited paper)

Fall Meeting of the American Geophysical Union, San Francisco, December 3-7, 1983 [abstracts published in *Transactions of the American Geophysical Union* 64 (1983)]

P. H. Diamond, Z. G. An, T. Chiuch, B. A. Carreras, and H. R. Hicks, "Anomalous Tearing Mode Growth and Rapid Magnetic Reconnection in Multiple-Helicity MHD Turbulence"

American Geophysical Union Chapman Conference on Magnetic Reconnection, Los Alamos, New Mexico, October 3-7, 1983

V. K. Paré, "Reconnection in Tokamaks"

Ninth International Conference, Plasma Physics and Controlled Nuclear Fusion Research, Vienna, 1983 (published in the proceedings)

F. W. Baity, L. A. Berry, L. Bighel, J. A. Cobble, R. J. Colchin, W. A. Davis, H. O. Eason, J. C. Glowienka, G. R. Haste, D. L. Hillis, S. Hiroe, R. K. Richards, T. Uekan, T. L. White, J. B. Wilgen, J. D. Barter, W. F. DiVergilio, L. L. Lao, N. H. Lazar, B. H. Quon, T. K. Samec, W. Wuerker, F. M. Bieniosek, J. H. Mullen, T. L. Owens, R. A. Dandl, G. E. Guest, G. A. Hallock, and L. Solensten, "Plasma Properties and Ion Heating in EBT-S and Hot Electron Rings at TRW"

Smoky Mountain Osborne Group Meeting, Oak Ridge, Tennessee, January 19, 1983

R. K. Gryder, "One User's View of dBASE II"

Twelfth Annual Symposium on Applied Vacuum Science and Technology, Clearwater, Florida, February 14-16, 1983

R. A. Langley, "Studies of Hydrogen Recombination and Diffusion in Fusion Plasma Devices Using Glow Discharges"

Fifth Topical Conference on Radio-Frequency Plasma Heating, Madison, Wisconsin, February 21-23, 1983

D. B. Batchelor, "Relativistic Effects in Electron Cyclotron Heating"

D. B. Batchelor, R. C. Goldfinger, and H. Weitzner, "Propagation and Absorption of Electromagnetic Waves in Fully Relativistic Plasmas"

D. J. Hoffman, A. C. England, O. C. Eldridge, R. H. Fowler, J. H. Harris, T. C. Jernigan, J. F. Lyon, and N. S. Ponte, "Ion Cyclotron Resonance Heating for the Advanced Toroidal Facility"

Fifteenth Southeastern Symposium on System Theory, Huntsville, Alabama, March 28-29, 1983

J. M. Bailey, J. M. Googe, and R. W. Wood, "Modeling and Simulation of Energy Removal Systems for Superconducting Magnets"

SOUTHEASTCON 83, Orlando, Florida, April 11-14, 1983

J. N. Anderson, "Description of a Low-Cost Electrically Isolated Analog Instrumentation Channel"

DOE Workshop on Copper and Copper Alloys for Fusion Reactor Applications, Washington, DC, April 14-15, 1983

B. L. Hunter, "Fusion Applications of Copper: Unique Requirements in Resistive Magnets"

Eleventh NASTRAN Users' Colloquium, San Francisco, May 2-6, 1983

W. H. Gray and T. V. Baudry, "Using PAFEC as a Preprocessor for COSMIC/NASTRAN"

ORAU Traveling Lecturer Program, Athens, Georgia, May 12, 1983

E. C. Crume, Jr., "Transport of Impurities in Tokamaks"

Cryogenic Engineering Conference, Colorado Springs, Colorado, August 15-19, 1983

L. Dresner, "Superconductor Stability, 1983: A Review"

L. Dresner, "Transient Heat Transfer in Superfluid Helium—Part 2"

S. H. Kim, J. W. Dawson, D. G. McGhee, and S. S. Shen, "AC Losses of 19-Strand Subcables for the ANL 33-MJ Coil"

J. W. Lue, J. R. Miller, L. Dresner, and S. S. Shen, "Simulation of Quenching of an Internally Cooled Superconducting Magnet"

J. W. Lue, S. S. Shen, J. K. Ballou, T. J. McManamy, and C. T. Wilson, "Single Magnet Test Results for the First EBT-P Development Magnet"

Eighth International Conference on Magnet Technology, Grenoble, September 5-9, 1983

S. L. Ackerman, E. R. Kimmy, and D. W. Lieurance, "The Design and Construction Details of the 7.5-Tesla Superconducting Metastable Magnet for the ELMO Bumpy Torus Proof-of-Principle Program"

R. K. Kibbe, P. N. Haubenreich, C. H. Gerwig, D. S. Hackley, P. A. Sanger, and J. L. Young, "Lessons from Design and Manufacture of U.S. LCT Coils"

J. L. Young, T. L. Vota, and S. K. Singh, "Manufacturing Development of the Westinghouse Nb₃Sn Coil for the Large Coil Test Program"

Workshop on Computational Problems in Magnetohydrodynamics, Lausanne, Switzerland, September 12-14, 1983

H. R. Hicks and R. A. Dory, "Inverse Plasma Equilibria"

Tokamak Fusion Core Experiment Advisory Committee Meeting, Princeton, New Jersey, October 18-19, 1983

J. Sheffield, "Fusion Reactor Cost of Electricity"

U.S.-U.S.S.R. Exchange II.2: Workshop on High Beta Tokamak Theory and Experiment, Moscow, May 23-26, 1983

G. H. Neilson, "High Beta Confinement Studies in ISX-B"

MIT Short Course on Large-Scale Applications of Superconductivity, Cambridge, Massachusetts, July 19, 1983

L. Dresner, "Superconductor Stability, 1983: A Review"

L. Dresner, "Superconducting Magnet Design for MHD and Fusion"

L. Dresner, "Transient Heat Transfer in Superfluid Helium—Part 2"

International Cryogenic Materials Conference, Colorado Springs, Colorado, August 6, 1983

J. F. Quirk, "Void-Free Epoxy Castings for Cryogenic Insulators and Seals"

Tenth Annual National Organization for the Professional Advancement of Black Chemists and Chemical Engineers (NOBCCHE), Knoxville, Tennessee, May 25-28, 1983 (published in the proceedings)

R. L. Johnson, O. B. Adams, B. E. Nelson, T. C. Jernigan, J. F. Lyon, and P. B. Thompson, "Design of the Advanced Toroidal Facility (ATF-1)"

Workshop on International Cooperation in Magnetic Fusion, Washington, DC, December 14-15, 1983

J. Sheffield, "The Joint European Torus (JET) Project"

Japan Atomic Industrial Forum Staff Mission, Fusion Engineering Design Center, Oak Ridge National Laboratory, December 8, 1983

J. Sheffield, "Generic Toroidal Reactor Studies at Oak Ridge National Laboratory"

Topical Conference on Ferritic Alloys for Use in Nuclear Energy Technologies, Snowbird, Utah, June 19-23, 1983 (published in the proceedings, *Ferritic Steels in Nuclear Technologies*, eds. J. W. Davis and D. J. Michel, The Metallurgical Society of AIME, Warrendale, Penn., in press)

L. L. Horton and J. Bentley, "Swelling Behavior of a Simple Ferritic Alloy"

R. L. Klueh and J. M. Vitek, "Tensile Behavior of Three Commercial Ferritic Steels After Low-Temperature Irradiation"

P. F. Tortorelli and J. H. DeVan, "Corrosion of an Fe-12 Cr-1 MoVW Steel in Thermally Convective Lithium"

J. M. Vitek and R. L. Klueh, "Microstructure of HFIR-Irradiated 12 Cr-1 MoVW Ferritic Steel"

F. W. Wiffen and R. T. Santoro, "Control of Activation Levels to Simplify Waste Management of Fusion Reactor Ferritic Steel Components"

41st Annual Meeting of the Electron Microscopy Society of America, Phoenix, Arizona, August 8-12, 1983 (published in the proceedings, ed. G. W. Bailey, San Francisco Press, Inc., San Francisco, 1983)

L. L. Horton and K. Farrell, "Comparison of Damage Microstructures in Neutron-Irradiated Vanadium and Iron"

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ACRONYMS AND INITIALISMS

ADC	analog-to-digital converter
ADIP	Alloy Development for Irradiation Performance
AEM	analytical electron microscopy
AMI	Advanced Mechanical Injector
ANL	Argonne National Laboratory
API	Advanced Pneumatic Injector
ARE	aspect ratio enhancement
ASDEX	tokamak, Max-Planck-Institut für Plasmaphysik, Garching bei München, FRG
ATF	Advanced Toroidal Facility
ATR	atmospheric tritium-recovery unit
BBC	Brown-Boveri Company, Switzerland
BBT	Bumpy Bean Torus
bcc	body-centered cubic
BSR	Bulk Shielding Reactor
CW	cold-worked
cw	continuous wave
CWTX	Coil Winding Test Experiment
CXE	charge-exchange excitation
DIII	Doublet III tokamak
DIII-D	DIII upgrade
D-D	deuterium-deuterium
D-T	deuterium-tritium
DAFS	Damage Analysis and Fundamental Studies
DIA	direct interaction approximation
DKE	drift kinetic equation
DNB	diagnostic neutral beam
DOE	U.S. Department of Energy
EBR	ELMO Bumpy Racetrack
EBR	Experimental Breeder Reactor
EBS	ELMO Bumpy Square
EBT	ELMO Bumpy Torus
EBTEC	EBT with enhanced confinement
EBT-I/S	initial and scaled versions of EBT
EBT-P	EBT Proof-of-Principle
EBT-S	EBT-Scale device and configuration (microwave power is ≤200 kW at 28 GHz; magnetic field is 7.2 kG)
EC	Experiment Coordinator interface
ECH	electron cyclotron heating
ECR	electron cyclotron resonance
EDQM	eddy-damped quasi-Markovian

EF	equilibrium field
EFBT	Electric Field Bumpy Torus
ERD	elastic recoil detection
EST	ELMO Snakey Torus
Euratom	European Atomic Energy Commission
FBR	Fast Breeder Reactor
fcc	face-centered cubic
FED	Fusion Energy Division
FED	Fusion Engineering Device
FEDC	Fusion Engineering Design Center
FEDPO	Fusion Energy Division Publications Office
FFT	fast Fourier transform
FFTF	Fast Flux Test Facility
FIR	far-infrared
FLR	finite Larmor radius
FMIT	Fusion Materials Irradiation Test facility, HEDL
FPD	Fusion Power Demonstration machine
FRG	Federal Republic of Germany
GA	General Atomic/GA Technologies, Inc.
GDC	General Dynamics-Convair Division
GE	General Electric Company
GEIS	generic environmental impact statement
GPE	General Plant Equipment
GPP	General Plant Project
GTA	gas tungsten arc
HAZ	heat-affected zone
HBT	helical bumpy torus
HEDL	Hanford Engineering Development Laboratory
HF	helical field
HFIR	High Flux Isotope Reactor, ORNL
HFTF	High Field Test Facility
HIEP	heavy ion beam probe
HTO	tritiated water
IAEA	International Atomic Energy Agency
IBL	inboard limiter
ICCS	internally cooled cable superconductor
ICH	ion cyclotron heating
ICRF	ion cyclotron range of frequencies
ICRH	ion cyclotron resonance heating
ICS	internally cooled superconductor
ID	inverted D-shaped coils

IEA	International Energy Agency
IGC	Intermagnetics General Corporation
INTOR	International Tokamak Reactor
IPP	Max-Planck-Institut für Plasmaphysik, FRG
IPP/JIPP	Institute of Plasma Physics, Nagoya, Japan
ISSM	Insulators and Stabilizers for Superconducting Magnets
ISX/ISX-B	Impurity Study Experiment tokamak
I&C	instrumentation and controls
JA	Japanese coil for the LCP
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus
JILA	Joint Institute for Laboratory Astrophysics
KFA	Kernforschungsanlage, FRG
KfK	Kernforschungszentrum Karlsruhe, FRG
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley Laboratory
LCP	Large Coil Program
LCT	Large Coil Task
LCTF	Large Coil Test Facility
LHH	lower hybrid heating
LHRH	lower hybrid resonance heating
LIF	laser-induced fluorescence
LIFT	Laboratory In-House Facilitated Training program
LION	Library Information On-line Network
LITE	Long-pulse Ignited Test Experiment, MIT
LLNL	Lawrence Livermore National Laboratory
LRO	long-range-ordered
MDAC	McDonnell Douglas Astronautics Company
METF	Medium Energy Test Facility
MF	multifilamentary
MFAC	Magnetic Fusion Advisory Committee
MFTF- α	MFTF-B upgrade with new end-cell physics and magnet system
MFTF- α +T	MFTF-B upgrade with new beam-driven center axicell
MFTF-B	Mirror Fusion Test Facility expansion
MFTF-B+T	MFTF-B tritium-burning upgrade
MGPF	Multi-General Purpose Facility
MHD	magnetohydrodynamic
MIT	Massachusetts Institute of Technology
M&S	Magnetics and Superconductivity Section

NASA-Lewis	National Aeronautics and Space Administration-- Lewis Research Center
NBI	neutral beam injection (neutral beam injector)
NBT	Nagoya Bul. of Torus
NEPA	National Environmental Policy Act
NICH	National Ion Cyclotron Heating
NLTNIF	National Low-Temperature Neutron Irradiation Facility
NMFECC	National Magnetic Fusion Energy Computing Center
NRA	nuclear reaction analysis
NRC	National Research Council
NRL	Naval Research Laboratory
NSA	normal stochastic approximation
OBL	outboard limiter
ODE	ordinary differential equation
OFE	Office of Fusion Energy, U.S. Department of Energy
OH	ohmic heating
ORAU	Oak Ridge Associated Universities
ORGDP	Oak Ridge Gaseous Diffusion Plant
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Research Reactor
PBX	Poloidal Bean Experiment (also PDX)
PCA	prime candidate alloy
PDX	Poloidal Divertor Experiment
PF	poloidal field
PIG	Penning ionization gage
PLT	Princeton Large Torus
PPPL	Princeton Plasma Physics Laboratory
PY	personnel year
QA	quality assurance
RBS	Rutherford ion backscattering
rf	radio frequency
RFTF	Radio Frequency Test Facility
RGA	residual gas analysis/analyzer
RIS	radiation-induced solute
RSIC	Radiation Shielding Information Center
R&D	research and development
SA	solution-annealed
s.d.	standard deviation
SIMS	secondary ion mass spectrometry

SIN	Swiss Institute for Nuclear Research, Villigen, Switzerland
SITEX	surface ionization transverse extraction
SM	symmetric mirror
SMM	submillimeter
SP	Standard Position
SULTAN	SIN facility (joint collaboration among The Netherlands, Italy, and Switzerland)
SXR	soft X-ray
TARA	tandem mirror machine, MIT
TDF	Technology Demonstration Facility, LLNL
TENTOK	Tennessee Tokamak fusion power reactor
TEXT	tokamak, University of Texas, Austin
TEXTOR	tokamak, KFA, Jülich, FRG
TF	toroidal field
TFCX	Tokamak Fusion Core Experiment
TFCX-CCTF	TFCX continuous copper TF coil concept
TFCX-DCTF	TFCX discrete TF coil concept
TFCX-H	superconducting TF coil device supplemented by copper TF coils
TFCX-S	all-superconducting TF coil device
TFF	transverse-field-focusing system
TFTR	Tokamak Fusion Test Reactor
TMX-U	Tandem Mirror Experiment Upgrade
TRT	twisted racetrack
TSDMS	Thomson Scattering Data Management System
TWT	Traveling Wave Tube
USC	User Service Center
VATF	Verification, Assembly and Test Facility
VF	vertical field
VUV	vacuum ultraviolet
XEDS	X-ray energy-dispersive spectroscopy
0-D	zero-dimensional
1-D	one-dimensional
1½-D	one- and one-half-dimensional
2-D	two-dimensional
3-D	three-dimensional

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