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MAGNETIC FUSION ENERGY QUARTERLY REPORT

January through March 1979

Scientific Editor: M. A. Harrison
General Editor: J. R. Strack

MASTER

May 15, 1979

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LAWRENCE LIVERMORE LABORATORY
University of California Livermore, California 94550

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NOTICE

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Frontispiece. Supervisory Control and Diagnostic System Console. This console is the prototype for seven units that will be used to control the MFTF. The three upper screens display status information, and the two lower screens are covered with touch-sensitive transparent plastic that can give X-Y coordinates to the console computer. In effect, the two lower screens are variable control surfaces that can make an unlimited number of "control panels" available to an operator. All control panels consist of sets of graphically defined multicolored buttons and control information. As the operator touches the screen with a finger, a transparent touch sensor detects where the finger touched, and hence, which button the operator implied. These control consoles will be the primary man-machine interface to the MFTF for control and diagnostics.

PREFACE

Our intent in the *Magnetic Fusion Energy Quarterly Report* is to provide a timely summary of activities within the Magnetic Fusion Energy (MFE) Program at Lawrence Livermore Laboratory. In a given *Quarterly*, not all MFE projects are necessarily represented. Throughout, details are kept to a minimum; readers desiring additional information are encouraged to read referenced documents or to contact the individuals engaged in the projects.

The information in each *Quarterly* is presented in the same sequence as in the Field Work Package Proposal and Authorization System (WPAS) submissions prepared for the U. S. Department of Energy; the three main sections are Confinement Systems, Development and Technology, and Applied Plasma Physics. Each of these sections is introduced by an overall statement of the goals and purposes of the groups reporting in it. As appropriate within each section, statements of the goals of individual programs and projects are followed by articles containing summaries of significant recent activity and descriptive text.

In the last *Quarterly* for each fiscal year, we include an appendix that lists all publications and presentations prepared by MFE personnel during that year.

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MAGNETIC FUSION ENERGY QUARTERLY REPORT

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1. CONFINEMENT SYSTEMS

Lawrence Livermore Laboratory (LLI) has primary national responsibility for magnetic-mirror programs, an approach pioneered here since the early 1950's. A goal of LLI's magnetic fusion energy (MFE) program is to provide the technology to develop a continuously operating fusion reactor. The heart of this reactor will be a plasma confined by magnetic-mirror geometry and continuously sustained by injection of beams of energetic neutral atoms (such as deuterium).

Three confinement systems are now in operation or under construction at LLI: the Tandem Mirror Experiment (TMX), the Beta II (formerly 2XIIIB), and the Mirror Fusion Test Facility (MFTF).

- In 1976, we proposed a new idea: the tandem-mirror concept. A tandem mirror reactor would contain a long solenoidal magnet terminated at both ends by conventional mirror cells. These cells would act as "end plugs" to prevent plasma leakage out the ends of the solenoid. TMX is being constructed to test the principles of this concept.

- Beta II relies on magnetic fields to confine a hot, dense plasma for a short time. It features C-shaped magnetic coils that form the confining magnetic field. Their unique shape (in what is known as a yin-yang geometry) stabilizes the confined plasma by creating a magnetic field (a magnetic well) that increases in every direction from the plasma center.

- MFTF, now being constructed, will bridge the physics and engineering gaps between current experiments and an experimental fusion reactor planned for operation by 1990. MFTF will use a superconducting magnet of yin-yang design (similar to the 2XIIIB experiment). This magnet will be capable of continuous operation.

Tandem Mirror Experiment (TMX)

The Tandem Mirror Experiment (TMX)^{1,2} will test a new principle for improved confinement in mirror systems. The basic idea is to reduce the plasma loss rate by electrostatically plugging the ends of a solenoidal central-confinement region using the high positive ambipolar potential generated in minimum-B end plugs. Each end plug will be driven by the injection of neutral beams from 12 source modules, in a manner similar to that used in the 2XIIIB experiment.

TMX has three fundamental objectives:

- To demonstrate the establishment and maintenance of a potential well between two mirror plasmas.
- To develop a scalable magnetic geometry, while keeping macroscopic stability at high beta.
- To investigate the microstability of the plug-solenoid combination to maximize the plug-density/injection power ratio.

Possible secondary objectives that have important reactor implications include the study of enhanced radial transport in the solenoidal cell and the accumulation of thermalized alpha particles in the central plasma.

The key physics parameters projected for the TMX experiment are listed in Table 1.

TMX Machine Checkout

In March all TMX subsystems were successfully checked out. Physics experiments will begin when the neutral beam power is worked up.

On March 8th, we conducted a TMX system checkout. At that time we operated the magnets, getters, startup plasma guns, neutral beams, interlock,

and diagnostic systems. This checkout verified that all systems function simultaneously, and we identified and remedied minor problems. The neutral-beam power was insufficient for plasma buildup. The remainder of the month was devoted to further increasing the neutral-beam power.

TABLE 1. Key physics parameters for the TMX experiment.

Parameter	Value
Electron	
Temperature, T_e	0.2 keV
Confining potential, ϕ_e	1.1 keV
Plug	
Density (assumed uniform over V_p), n_p	$5 \times 10^{13} \text{ cm}^{-3}$
Average energy, E_p	26 keV
Radius of plasma half-maximum, r_p	7 cm
Central magnetic field, B_p	1.0 T
Confinement product, $(n\tau)_p$	$3 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$
Central cell	
Density (assumed uniform over V_c), n_c	$1.2 \times 10^{13} \text{ cm}^{-3}$
Ion temperature, T_i	0.080 keV
Confining ion potential, ϕ_c	0.29 keV
Length, L_c	5.5 m
Radius, r_c	31 cm
Magnetic field, B_c	0.05 T
Confinement product, $(n\tau)_c$	$3.1 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$

The magnet system was successfully run at full field for the base case (1.0 T in plug and 0.05 T in solenoid) with the master timing system that synchronizes the magnets with other TMX systems. At this time, our measurements show that the TMX startup guns generate a satisfactory target plasma. As we expected from 2X11B experience, diamagnetic loop measurements indicated that hot plasma buildup did not occur when we injected 75-A atom equivalent current. We expect at least 125 A more current to be required.

During the past quarter, the manpower on the neutral-beam system was increased to simultaneously support three activities:

- Dummy-load checkout of north-side 40-kV neutral-beam power supplies.
- Implementation of improvements to the existing system.
- Testing to identify further power-supply improvements.

At the end of March the status was as follows:

- North-side 40-kV arc/filament supply checkout was completed and accel/decel supply checkout was in progress.
- Several improvements were identified and demonstrated in the arc supply, the accel supply, and the controls.
- One beam reached full power of 20 kV at 75 A for 25 ms (on April 3).

The improvements demonstrated in March were to be installed throughout the TMX system in April, and

then the system will be run up in power for the initial TMX experiments we expect to carry out next quarter.

The TMX vacuum system employs 88 titanium getter wires to evaporate a thin titanium film preceding each shot. The Ti-Ta alloy wires are 3 mm in diameter and have an average length of about 2 m. Five spare wires in each position bring the total number of wires to 528. This getter system operated for the first time this quarter and reduced the base pressure from 2×10^{-6} to 2×10^{-7} within a few cycles of gettering. We expect further reduction with sustained operation and with simultaneous cooling of the liquid nitrogen panels.

The TMX machine is lined with stainless steel panels that can be cooled with liquid nitrogen. When coated with fresh titanium surface, these supercooled panels provide an active surface for pumping gas. (The panels divide the TMX tank into several volumes, which makes it possible to pump neutral-beam gas to keep the background gas pressure low in the region of the hot-ion plugs.) We cooled the panels down one at a time this quarter to check for possible cold leaks. We were pleased to detect only one small leak; this indicates that this LN liner system was successfully installed.

Target Plasma Measurements

(J. H. Foote)

Line-density measurements of the target plasma indicate that the TMX startup guns provide a suitable target for neutral-beam buildup.

Fig. 1. Fraction of the neutral beam transmitted through the plasma. Also shown is the period during which the streaming guns were emitting plasma.

We have measured the plasma line density from the startup streaming guns at a plug midplane. This was done with a beam-attenuation detector³ aimed through the plasma at one of the neutral-beam sources. (The reduction in flux of neutral-beam particles reaching the detector when a plasma is present is a measure of the amount of plasma transversed by the beam.)

This measurement is obtained from the signal from the beam-attenuation detector with and without the streaming guns firing. By comparing the background shots (no streaming guns) and the plasma shots (streaming guns fired), we determine that the beam flux to the detector was attenuated during the period that the streaming guns were on. After normalizing the two signals to the same value at a time when the guns were off to account for shot-to-shot beam variations - we obtain the beam absorption fraction shown in Fig. 1.

From the measured attenuation and from cross-section information on beam-plasma particle interactions, we calculate the line integral of the plasma density passed through by the beam ($\int ndl$). This result is plotted in Fig. 2, with the maximum $\int ndl$ value observed of about $2 \times 10^{13} \text{ cm}^{-2}$. These data were reduced with the TMX data processing system described on p. 9. The noise is due to detector noise, beam noise, and fluctuations in plasma density.

Electron-Beam Startup

(D. P. Grubb)

We have designed and are fabricating an electron-beam (E-beam) startup system for TMX.

Fig. 2. Line integral ($\int ndl$) of streaming-gun plasma density.

Experiments in the 2X11B device showed that it was possible to ionize the gas in the stabilization gas box by using a pulsed E-beam (30 A, 20 kV).⁴ The resulting plasma formed a sufficiently large and dense target plasma to allow the buildup of a hot, dense plasma fueled by the 2X11B neutral beams. Vacuum ultraviolet measurements of titanium and carbon impurities showed that the E-beam-created target plasma was significantly cleaner than a target plasma formed by the titanium washer stack guns.⁵ However, similar measurements of the hot, dense, steady-state plasma created by neutral-beam injection indicated that the target plasma was not the dominant source of impurities in the hot plasma. We observed very few differences between the plasmas that were started up with the E-beams and those started with the titanium washer stack guns.

Fig. 3. Electron-beam gun assembly mounted on TMX end flange.

Fig. 4. Electron-beam gun assembly.

In TMX, however, the method of startup may be quite important. High-Z impurities introduced into the plasma during startup may be trapped in the TMX center cell while the end-plug plasmas are built up by neutral-beam injection. These multiply-ionized impurities, which are electrostatically confined in the center cell, would then cause radiation power drain on the electron energy that could limit the electron temperatures achievable in TMX.

For this reason we have designed an E-beam startup system for TMX. In our design, the 2XIIB electron-beam guns⁵ will be housed in vacuum-tight assemblies separated from the main TMX vacuum vessel by a gate valve (Fig. 3). The entire E-beam assembly is mounted at an angle that closely aligns it to the TMX field. This remote placement of the E-beams will allow us to install, test, and repair them without reducing the machine vacuum. Conversely, the E-beams can be maintained at a static vacuum to protect their cathodes while TMX is not under vacuum (Fig. 4). The remote location of the E-beams will also allow us to easily change their alignment under vacuum because they are in a region of low-plasma density that should minimize any plasma-induced shorting problems.

This remote placement of the electron-beams requires that we supply each beam with its own solenoidal magnetic field. The ambient TMX field in the region of the E-beams is approximately 65 G for the base case magnetic field ($B_{\min}^{\text{plug}} = 1.0$ T, $B_{\text{center}} = 0.05$ T). For the E-beams to operate at 20 kV, a minimum solenoidal field strength of

approximately 0.1 T is required to maintain the equilibrium electron orbits within the anode-cathode gap. The addition of the E-beam magnet raised questions about perturbations of the TMX base-case field, particle adiabaticity, and the concentration of the ion flux in the region of the E-beam.

To answer these questions, we have employed the magnetic-field codes EFFI⁶ and MAFCO⁷ and the particle-following code TIBRO.⁸ The effect on the TMX field caused by the addition of the E-beam magnets is shown clearly in Figs. 5 and 6. The dominant effect of the extra coil is to draw the $r = 4$ cm and $r = 5$ cm field lines into the coil around the E-beam. In this field configuration, therefore, the F-beam will pass 4 to 5 cm off centerline at the midplane of the plug. (This alignment is quite similar to that in the 2XIIB experiments, where the E-beam also mapped 4–5 cm above the centerline at the midplane of the mirror.) The perturbation of field lines other than these two is small. However, the E-beam system is being designed so that the E-beam magnetic field can be crowbarred out in a period of 1–3 ms after startup has been achieved, so that even these small perturbations can be avoided.

Results of the particle-following calculations indicate that 20-kV electrons will follow the magnetic field lines through the machine, even when a field alignment error of 5° is assumed. The mapping of the electron beam into the gas box is shown in Fig. 7. The E-beam on the same end of the machine as the gas box creates a thin line near the center of the gas box; an E-beam from the opposite end of the experiment

Fig. 5. Magnetic-field line plots and mod-B contours for TMX base case magnetic field ($B_{\min}^{\text{plug}} = 10$ kG, $B_{\text{center}} = 500$ G).

Fig. 6. Magnetic-field line plots and mod-B contours showing the effects of the E-beam magnet on the base-case field: $r =$ (a) 0 cm, (b) 1 cm, (c) 2 cm, (d) 3 cm, (e) 4 cm, (f) 5 cm, and (g) 6 cm.

center the small ellipse to the right of center. The computer particle-following codes indicate that ions from the center cell are unable to follow the rapid change in field due to the E-beam coil, so that no undue erosion of the E-beam cathode by ions following the 1- to 4-cm through 1- to 5-cm field lines is expected. These calculations indicate that we will be

Fig. 7. Magnetic-field line mapping of two E-beams from opposite ends of TMX into one of the gas boxes.

Fig. 8. Laser-beam input arm: (a) front and (b) rear views.

able to successfully operate the E-beams mounted on the end tanks of TMX.

TMX Diagnostics

The initial set of diagnostics on TMX this quarter⁹ was checked out with plasmas generated during the March system checkout. Diagnostic development activities this quarter centered on plug Thomson scattering, axial light-ion beam probe, transverse heavy-ion beam probe, and low-energy solenoid charge-exchange analyzer.

Thomson Scattering. (R. K. Goodman, J. E. Clauser, A. M. Frank and S. L. Jenkins)

The Thomson scattering system will measure the electron temperature and density in the east plug by measuring the Doppler broadening and intensity of scattered ruby laser light.

We completed the assembly of all of the major mechanical-optical subsystems. The laser-beam input arm (Fig. 8), the laser-beam dump (Fig. 9), and the scattered-light-viewing optics (Fig. 10) were all cleaned and assembled in a "clean room" to prevent contamination of the various optical components. The input arm, with its focusing lens, and the beam dump were then checked and prealigned with a HeNe laser. We also checked the viewing optics for proper focus

Fig. 9. Laser-beam dump: (a) front and (b) rear views.

and imaging from a plane that corresponds to the radial measurement positions in the plasma. These subsystems are now ready for installation.

Fig. 10. Scattered-light-viewing optics subsystem: (a) whole assembly and (b) detail.

The ruby laser beam was aligned and checked through the beam transport optics to where it would enter the input arm. Assembly of the scattered-light-distribution box and its optics (Fig. 11) was completed. This box will mount above the viewing optics and will direct the light from the three radial positions in the plasma to the appropriate polychromator. This box also contains a light source that is used to calibrate the gain of all the photomultiplier (PM) tubes after each plasma shot. (This is automatically performed by our Thomson-scattering controller and the TMX computer.) One of our spectrometers was converted to a ten-channel polychromator, and was then aligned; it is now ready for installation. Assembly began on one of the ten-channel PM boxes and the associated light pipes that connect the PM tubes to the polychromator.

Fig. 11. Scattered-light-distribution box and optics: (a) front and (b) rear views.

Fig. 12. Schematic diagram of the light-ion-beam probe diagnostic used to measure the axial ambipolar potential distribution.

An electronic design was completed to provide remote operation of the laser and also to tie the Thomson scattering system and laser into the TMX shot sequence. Fabrication and installation of the necessary electronic components and cabling also began.

Light-Ion-Beam Probe. (*T. A. Casper and R. S. Hornady*)

The light-ion-beam probe (LIBP) incorporates a helium ion beam and a partial analyzer mounted coaxially on the TMX symmetry axis. It will be used to measure the ambipolar potential along the TMX axis.

A schematic diagram of the system is shown in Fig. 12. The helium beam, developed originally for RTNS-II, runs at 20 kV and produces 30 mA of helium ions (He^+). The collisional ionization rate of He^+ to He^{++} is dependent on the axial line density, while the measured energy depends on the ambipolar potential at the point of the ionization event. Thus, the axial potential distribution can be deduced from current-vs-beam-energy data and knowledge of the axial density.

During this period, we operated the source on the test stand where it was developed and measured the energy distribution of the beam. From these tests, we concluded that the beam has an energy spread on the order of 80 V and is suitable for use as a probing beam.

Following the testing, we moved the beam and the major components of the test stand to TMX and

installed them, as well as the analyzer. The electronics was partially checked out and the system was aligned to the geometric axis of TMX. We expect the system to be operational during the next quarter.

Heavy-Ion-Beam Probe. (*R. S. Hornady, G. Hallock*, and R. Klinkwostein**)

The heavy-ion-beam probe (HIBP) measures the radial distribution of ambipolar potential in the mid-plane of the solenoid of TMX. Taking the radial measurements requires a beam that can be electrostatically deflected and varied in energy during the interval when a stable plasma exists in TMX. These requirements call for a real-time control system. In this design, the control system consists of a micro-processor, three CAMAC crates, and an auxiliary high-speed crate controller. The auxiliary crate controller incorporates hardware multipliers to achieve sufficient processing speed for real-time control of the HIBP.

During this quarter, we began the checkout of the portion of the electronics that was fabricated at LLL. Concurrently, the software drivers were being written and an executive program from the time-of-flight processor was modified for use as the HIBP executive.

We assembled the energy analyzer with its vacuum-compatible electronics and installed the combination. We have conducted noise tests and have found excellent agreement with anticipated behavior.

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The primary beam-line components were cabled together, and preparations were made to begin testing the primary beam with and without the TMX magnetic field. We expect this system to be operational during the next quarter.

Low-Energy Time-of-Flight Analyzer. (*A. L. Hunt*)

The low-energy time-of-flight analyzer provides the energy spectrum of the electrostatically confined deutron ion distribution in the central cell between the two minimum-B end cells. (The installation of the analyzer on TMX has been described.⁹) Three areas of activity remain:

- We must extend the measurements of the relative counting efficiency of the microchannel plate (MCP) detector from the energy range of 200 to 50 eV.
- We must develop an effective way to reduce the saturation effect on the microchannel plate output of ultraviolet or other high-energy radiation transmitted through or reflected around the chopper-gate.
- We must transmit the data from the present LSI-11 configuration to the central TMX computer for storage and processing.

Progress in each of these three areas is reported in the following paragraphs.

The efficiency of the MCP in D^0 detection depends on the energy of the D^0 over the energy range from 200 to 50 eV (See Ref. 10). A calibration of the MCP with D^+ is thought to be of sufficient accuracy to infer a correct velocity spectrum from the MCP detector count as a function of time and to assign a kinetic temperature to the ion-energy distribution. Calibration requires, if not a known current, at least a reproducible current of about 10^{-23} A of D^+ incident on the MCP. This should provide a count rate of 6×10^3 counts per second if the counting efficiency is about 10^{-3} . Because of scattering effects, it is difficult to quantitatively deflect such a beam from a Faraday cup into the MCP; hence, we have collected a portion of the beam on a negatively biased grid placed in front of the MCP. The collected positive grid current appears to be linearly related to the count rate of the MCP. We have found in these preliminary measurements that the efficiencies (counts/ion) for deuterons incident at 100, 150, and 200 eV are in the ratio of 3 to 6 to 16, respectively. We have not yet made reliable measurements below 100 eV because of what we believe to be surface-scattering of perhaps as much as 30% to 50% of the beam from the walls and electrodes.¹¹ This defect in the calibration will be

corrected by an improvement in the geometry, so that the MCP detector is shielded from the terminus of the beam.

Ultraviolet and other high-energy plasma radiation is incident on the microchannel plate when the chopper gate is open. This 2- μ s burst of signal at the MCP marks the start-time for the time-of-flight measurement. If the radiation from the plasma is allowed to reflect around the chopper gate, the MCP suffers charge depletion if the potential difference across the detector is adjusted for highest gain. The resulting loss of sensitivity disables the detector for several milliseconds. (The effect is documented in the literature on the MCP.¹²) It can probably be eliminated by shielding the detector from reflected radiation and by reducing the gain of the MCP. While the effectiveness of these measures awaits further test with the plasma, it is always possible -- by some increase in experimental complexity -- to reduce the potential difference across the MCP for the 2 μ s of irradiation.

The data from the MCP are now collected as counts per selected-time-interval, usually 1 or 10 s, for as many as 4096 sequential time-intervals and stored in the counting circuit memory during the plasma shot. After the shot, this information is transmitted via a Camac system and appears either as a table of numbers or as a graphic display generated by the LSI-11 system on a CRT terminal. A photo-isolated link with the central TMX computer is now under construction to allow time-of-flight data to be archived in the central computer for subsequent processing.

TMX Computer System

(*W. F. Cummins, D. M. Bell, T. N. Haratan, C. P. Parrish, W. W. Thompson, and G. E. Wilcox*)

An initial set of diagnostic data processing routines and an interim intershot processing procedure have been added to the system described in our last report. These routines write processed data to disc, and a separate set of display routines operating either from system commands or from a terminal produces graphics from these files. Although hard-copy output rates are still limited by the available equipment, intershot data processing does not pile up because of this. Also, procedural changes have increased the computer's utilization factor by allowing it to switch programs resident in memory.

Fig. 2 (p. 3) is an example of the output produced from the beam-attenuation diagnostic. (Although the plot and hard copy required about 15 s., the processing ran within 2 s.)

Beta II

Beta II is the name given to the reconfigured 2XIB facility after power supplies and other equipment were transferred to TMX. Beta II will begin to operate in the Summer of 1979, when new power supplies are installed, other supplies reconfigured, and new neutral-beam modules built.

The first experiments to be carried out are with a field-reversed plasma gun to generate a field-reversed target plasma for neutral-beam heating and confinement studies. In addition, Beta II will be capable of continuing physics studies in support of MFTF.

Beta II Experiment

(W. Turner, C. Hartman, D. Prono, B. Stallard, J. Taska, H. Bell, S. Bishop, A. Chargin, D. Mullenhoff, L. Pedrotti, W. Reass, and M. Richardson)

Most Beta II activity this quarter has been directed toward preparation for the field-reversed plasma gun experiment, replacement of components and facilities transferred to the TMX experiment, and installation of the IPINS injector. The first physics experimentation is scheduled to begin with tests of the field-reversed plasma gun this summer.

Beginning in November 1978, shortly after approval of the plasma gun proposal, we began work in each of the major subsystems of the plasma gun and began purchasing equipment for the stand-alone facility. At present, the Beta II activities are organized into six major categories:

- Guide field system.
- Plasma gun design and construction.
- Capacitor banks.
- Machine control system.
- Diagnostics and data acquisition system.
- IPINS installation.

The guide field system requires installation of six 600-kW power supplies. Two of these are already on site and are being installed. The other four are being procured.

The detailed design of the plasma gun is complete and all parts are being fabricated. Figure 13 shows the design of the plasma gun. The solenoid magnet for the outer electrode has been wound, and it is ready for vacuum impregnation. Design of the plasma-gun collector plates is complete, and fabrication has begun for some parts. Design of a mechanical support and retraction system for the plasma gun is in progress.

Designs of all of the capacitor banks required for the plasma gun, main gun bank, inner solenoid bank, outer solenoid bank, and gas-valve bank are complete. Prototype tests of the main gun bank and solenoid banks have been completed. Fabrication of the main gun bank has begun.

The central timing distribution for control of the plasma gun has been worked out. The only new equip-

ment items required are time-delay chassis, which have been ordered. Design of a control system for the new 600-kW guide field-power supplies is complete, and the electronics required are in fabrication. Oscilloscopes for monitoring machine operation have been ordered.

A new diagnostics room is under construction and signal-cable conduit is being installed. All of the data acquisition hardware, computer equipment, and oscilloscopes for the plasma gun and stand-alone facility have been ordered and partial shipments have begun to arrive. Design of magnetic probes and a calorimeter for the plasma gun is complete, and both are in fabrication.

Field-Reversed Plasma Gun Calculations

(J. W. Shearer, J. L. Eddleman, C. W. Hartman, and W. C. Turner)

The plasma gun rundown calculation described in our last report¹³ has been linked to three field calculations.

- The first case was a comparison with a previous measurement of the plasma gun output, which was made at Los Alamos (LASI).¹⁴ The plasma was directed at a solenoidal coil whose axis was aligned with the plasma gun axis. A probe measurement inside this coil indicated the passage of plasma; the CODA code was in qualitative agreement with the timing and magnitude of these probe signals. Time and zoning limitations prevented us from following the plasma further down the solenoid past the other probe locations, but the first probe comparison strengthens our confidence in the CODA code.

- The second guide-field calculations are calculational attempts to create a field-reversed plasma ring from the output of this plasma gun—similar to our early computations.¹⁵ In the two examples calculated to date, the ring did not separate from the gun. These results reemphasize the importance of the magnetic reconnection problem in the region between the ring and the gun. Work is continuing on this problem.

Fig. 13. The Beta II field-reversed plasma gun assembly.

- Finally, calculational studies of small field-reversed rings were produced in the last quarter.¹³ We found the poloidal field diffusion to be faster than classical; this effect was traced to numerical diffusion

in the finite computational grid. The effect was minimized by improving the accuracy of the magnetic-field transport by using second-order difference equations.

Mirror Fusion Test Facility (MFTF)

As a result of major experiment successes in the LLL mirror program on startup and stabilization of plasmas in minimum-B magnetic geometry, a Mirror Fusion Test Facility (MFTF) was proposed. MFTF will be used to bridge the gap between present-day small mirror experiments and future fusion-reactor activity based on magnetic mirrors. MFTF will investigate advanced engineering problems such as those associated with superconducting magnets, neutral-beam injectors, plasma-wall interactions, disposal of neutral particles and ions escaping from the plasma chamber, and high-speed vacuum-pumping techniques.

Construction of the facility began on October 1, 1977, with completion scheduled for September 1981. Related activities include R&D, fabrication and installation of auxiliary components for the first experiments in MFTF. The project is proceeding on schedule.

Technical Support

The objectives of the MFTF Technical Support Group are as follows:

- To monitor the MFTF design for consistency with the physics requirements.
- To provide research leading to improved performance of MFTF auxiliary components such as startup neutral-beam sources, streaming-plasma sources, vacuum accessories, etc.
- To analyze the physics of MFTF to ensure that the completed facility will achieve the stated scientific goals.
- To keep the MFTF system requirements consistent with the current understanding of mirror fusion physics.

Summary. During this report period, we have investigated several different problems:

- We completed a series of measurements on the 1/10-scale magnetic shielding test that confirm our design for the MFTF neutral-beam magnetic shield. The measured interior fields of $50 \mu\text{T}$ are well below the design goal of $\leq 150 \mu\text{T}$.
- We have continued the diagnostic measurements of a prototype plasma stream gun. We have determined that the gun energy is carried by electrons that are closely tied to the field lines from the gun cathode. The target plasma is then created when these high-energy electrons ionize the neutral gas.
- We have initiated a study of the effect of the neutral-beam aiming on the initial plasma length. This study incorporates the ORBXYZ code.
- Finally, we are developing two plasma-flow codes to model the cold plasma flow from the MFTF gas boxes.

Magnetic Shielding of Neutral-Beam Modules.

(J. W. Shearer, G. D. Porter, A. W. Molvik, P. M. Holl, L. W. Dilgard, and J. Fabian)

A series of measurements on the 1/10-scale test experiment has verified the basic design choice of the magnetic shield. A further improvement was obtained by using two nested Hypernik inner shields.

In this quarter, we fabricated more exact 1/10-scale models of the magnetic shield, using both 1020 and 1010 steel ($\leq 0.2\%$ and $\leq 0.1\%$ carbon, respectively). Each model was mounted in the center of eight other shield mockups (3-by-3 array) and tested in the coil setup described previously.¹⁶ One- and two-layer

Fig. 14. Plot of magnetic field vs distance for a coil current of 700 A shows superiority of 1010 steel as a shield.

Fig. 15. Plot of magnetic field vs test coil current supports design choice of 1010 steel with two Hypernik liners.

1/10-scale Hypernik inner shields were then added to the inside, with care being taken to keep them from touching the outer shield.

Some results from these measurements are shown in Figs. 14 and 15. These figures demonstrate that the 1010 steel is a superior shield to the 1020 steel and that two layers of Hypernik are better than one layer when the outer steel thickness is unchanged. We also

note that the arc chamber is just far enough away from the back plate for adequate shielding.

When comparing with the full-scale maximum field MFTF assembly, the nominal comparison current is 700 A; however, there are uncertainties in this value because of the differences in coil geometry and the variations expected from one position to another in the array. For a more exact comparison, we are fabricating a support for the array that duplicates the MFTF spherical aiming geometry (in place of the present Cartesian geometry array). However, note that the curve in Fig. 15 that represents the 1010 shield with two liners remains well below the 0.15-to-0.2-MT limit for the arc chamber throughout the entire test coil current range of 0-900 A. Thus, there are already good grounds for confidence in the present design.

A 1/10-scale model prototype design is now being drawn up to include all of the present requirements on the magnetic-shield design. The biggest change is a greater length (4 inches in the full-scale version) to provide sufficient voltage breakdown protection for the 80-keV modules. Another change is enlarged feedthrough holes in the back plate. This prototype and the cylindrical holder will be tested after a one-month shutdown of the Building 436 test coil area for the installation of BETA-II magnet power supplies.

Fig. 16. In this typical arrangement of the Mo-washer stack gun in its auxiliary magnetic field, the washer is positioned in the magnet center line. The gun is shown in the " " position; all diameters are in inches.

Plasma-Streaming Gun Tests. (*J. Osher*)

Diagnostic measurements of a prototype MTFE startup plasma-streaming gun were continued this quarter. A typical arrangement of the Mo-washer stack gun in its auxiliary magnetic field is shown in Fig. 16 (for this example, the Mo washer is in the magnet center line position). The basic arrangement of the gun and diagnostics in the background magnetic field is shown in Fig. 17. Nominal magnetic-field-enhanced gun-operating conditions include a 2-ms-duration voltage pulse (from a PFN) of ~ 300 V

applied at the gun terminal driving a current of 2500 A; with an auxiliary field of 12.5 kG aiding the background field of 0.5 kG. The gun output in this case is noisy, with a $\pm 20\%$ signal variability, which we assume is due to optically observed breakup of the gun output into a number of filamentary channels.

Initial measurement of the plasma output from this gun identified a phenomenon that requires special consideration for diagnostics: i.e., in this relatively long-pulse mode (~ 2 ms here), the gun effectively

Fig. 17. The basic arrangement of the gun and diagnostics in the background magnetic field.

establishes an arc discharge from the central high-voltage negative "cathode" electrode along the bundle of field lines to the chamber "anode" wall. Floating potential measurements in this arc channel range from -100 to -300 V on-axis rising smoothly to a few volt-positive potentials for radii outside the flux bundle. Net currents and integrated energy deposited on a low-impedance 350-cm^2 target calorimeter located 80 cm from the gun typically show an average negative current of 1700 A (68% of input current) and 290 J deposited during the 2 - to 3 -ms pulse duration. Neglecting any ion contribution, this would imply that the primary output from the gun can be viewed as an 1700 -A electron stream of 60 – 85 eV. A direct local measurement of the ion current and energy was also made at the far wall (shown in Fig. 18) with a retarding grid analyzer. Assuming ion mapping follows the flux bundle, the total ion current calculates to 10 – 15 A, with a mean ion energy, with respect to the chamber wall measured to be 75 eV. Tests for an energetic H^+ component were also positive; i.e., using the analyzer in the mode to observe secondary emission with both the ion and electron stream cutoff yielded $\gamma_e I^+ \approx 0.2 I^+$. This implies an equivalent H^+ current of 20 – 30 A if $\gamma_e \sim 0.1$ is assumed. This energetic ion and neutral flux is also consistent with the gas-input flow into the gun of 30 torr-litre/s. In principle, this could yield up to 330 A of H^+ , but a gas efficiency of 10% is fairly typical of plasma guns. Thus the energetic ion currents and associated energy appear relatively small consistent with the E-beam model we describe above.

Density measurements with a double-Langmuir probe (needed because of the large floating potential), however, show that this picture is incomplete. The primary electron or sum of energetic ion and energetic neutral densities above calculate to 10^{11} cm^{-3} , while the Langmuir probe measurements of the ion saturation current yield $n_e \sim 2 \times 10^{12}\text{ cm}^{-3}$ and $n_e b \sim 2 \times 10^{13}\text{ cm}^{-2}$. Thus, the gun-output stream of energetic primary electrons appears to carry along (or produce locally from the background gas) the denser secondary plasma that is of major interest here as a plasma target. Further tests on this gun are continuing.

Additional notable features under study include a dramatic change of gun output energy that occurs with shifts in Mo-washer position relative to the auxiliary field. For example, the energy deposited on the 350-cm^2 target increases from 290 J to over 1100 J with an 8 -cm displacement back ($\sim$ optimum) of the centerline position used in the measurements

Fig. 18. Number of modules accessible to radial aiming point η for the different axial aiming points: (a) $\zeta = 0$, (b) $\zeta = 20$, (c) $\zeta = 40$.

discussed above. Unfortunately, this reduces the magnetic field at cathode and yields undesirable mapping for MFTF, hence some compromise of mapping and output energy efficiency appears necessary.

Neutral-Beam Access. (*J. W. Shearer, R. H. Buhner, J. R. Ferguson, and B. M. Johnston*)

Detailed neutral-beam-aiming calculations using the revised magnet design¹⁷ are being combined with orbit calculations in the vacuum magnetic field to estimate initial plasma length in the MFTF experiment.

The initial aiming calculations indicate which parts of the plasma volume are accessible to each

neutral-beam module, taking into account the magnet entrance aperture, the magnet exit aperture, and the locations of the beam dump. These same results are shown in Fig. 18 in a different way—the number N of codes that have access to each part of the plasma (the top pod). The variable ϵ is given by

$\epsilon = 1/Z$ for the top and bottom pods

$\epsilon = 1/2Z$ for the side pods.

The allowed aimings are then kept and used for the orbit calculations. The direction angles of the neutral beam determine the initial velocity vector of charge-carrying ions produced along the trajectory of the neutral beam in the plasma. The "ORBNYZ" code¹⁸ is then used to follow the orbit of such ions in the MFE magnetic field until two "bounce points" have been reached. Repetition of many such calculations for various modules are then used to rough out the plasma shape. These calculations are in progress.

Gas Box Theory, (G. L. Gruczkowski)

Stabilization of DCLC instabilities in MFE requires the use of gas boxes to generate a cold-ion current in the plasma. Due to the high ambipolar potential generated by the hot plasma, there is some question about the efficiency of such a system and, thus, about the effectiveness of the cold plasma in stabilizing the hot plasma. A time-dependent, Eulerian explicit code was developed by T. Rognlien to measure the efficiency of a single gas box for the 2XtB experiment. In applying this code to MFE criteria, we discovered that the cold-ion current flowing through the plasma could not be satisfactorily determined because of the much higher ambipolar potential hill associated with MFE and the artificial viscosity required to dampen the numerical shocks in this time-dependent code. Thus it was necessary to develop new codes better suited to MFE requirements.

Two new codes now under development will better model the cold plasma flow in MFE. The first is a steady-state code that eliminates the need for an artificial viscosity, and the second is a time-dependent implicit code. Both codes include the effects of dual gas boxes situated symmetrically about the midline. Due to the stagnant velocity condition inside the mirror, the artificial viscosity term eventually vanishes between the gas boxes in the implicit code, thus enhancing numerical convergence. Thermal conduction of the cold plasma component is also included

in these codes since this term is of added significance when dual gas boxes are employed. The cold plasma flow is followed by solving the particle, momentum, and energy conservation equations in one dimension. The cold plasma is assumed to be a collisional fluid tied to the field lines. The hot plasma component is modeled by employing a time-independent, Gaussian, axial density profile. Although the hot plasma is assumed to have a constant temperature, the cold plasma and electrons are heated by drag on the hot plasma. The electron density is determined by quasi-neutrality. The electron mean free path is assumed to be large compared with the length of the system, thus the electrons must be confined by the ambipolar potential and the electron energy can be assumed to be isothermal. The electrons interact with the cold ions through the ambipolar potential and through collisions.

MFE Design and Construction

General Progress. *(E. P. Dixon and E. A. Karpenko)*

During this quarter (the sixth of the MFE project), our design and construction efforts moved ahead as planned without significant deviations. Technical and schedule difficulties encountered previously in the magnet system were reduced by problem-specific actions that we took. Progress—measured by a revised magnet system plan—was encouraging.

Fusion chamber system (FCS) subcontract efforts proceeded through preliminary and final design reviews for the three FCS systems: vacuum vessel and cryopanels, external vacuum, and cryogenic.

We completed a preliminary design review of the power supply subcontract for the sustaining-neutral-beam injectors. The arc power supply design was somewhat delayed, but significant progress in design detail was provided for the accel dc, modulator, and suppressor power supplies to complement the progress in preliminary design on the arc power supply.

The MFE control and diagnostic system (CDS) made significant design and development progress. The remaining eight Interdata central processors were accepted and integrated with the first processor into a prototype MFE CDS operating configuration in Building 431. A prototype supervisory console was completed. Development of several software routines was completed and tests were performed with the touch-panel displays and operating control modes for system development. The work added significantly to improved understanding of MFE operating techniques, interfaces, procedures, and overall system

integration for controls and data handling. We also integrated the local controls and instrumentation with the individual system components and interfaces with the supervisory controls and diagnostics to confirm preliminary designs. Hardware component decisions were made on instrumentation, local controls, status monitors, remote operations, TSI-II chassis design, and operation modes. Several software modules were developed.

The system safety efforts moved ahead with publication of a Preliminary Hazards Analysis and improved calculations of neutron shielding around vault wall penetrations. Improved definition of vault interfaces with the system components allowed the neutron calculations to provide more specific source and dose rate estimates for hazard assessment and as inputs to protective shielding designs.

Very significant steps were taken in the MFTI conventional facility tasks. Demolition within the Building 43I High Bay was finished. Realignment of the vault walls and excavation in the vault was then completed.

Movement of the cryolab helium bottles and gas bags from the area north of Building 43I to be occupied by the MFTI control center (Building 439) was completed. The engineering fill and excavation for underground utilities was finished for this site in March.

Excavation in the east end of Building 43I for the helium recovery compressor pit and foundations was accomplished during the quarter.

The vessel foundations were formed, reinforced with a modification in design of the reinforcing steel (rebar) to meet support requirements with increases in weight of the magnet, vessel, and attached components. Figure 19 shows the foundation rebar in place while the concrete pour is underway. For the foundation, over 350 cubic yards of concrete were needed in the first phase pour to form the pit and floor in the center of the vault area.

The completed floor is shown in Fig. 20 with the rebar for the four piers projecting above it. The rebar was then formed to the shape indicated in the south-west vessel footing skeleton shown in Fig. 21. Each

Fig. 19. Vault and pit in Building 43I when the foundation footing concrete was being poured. Concrete from the mixer truck moves by conveyor from the left of the picture into the vault and down to the point of distribution by the crew around the pit forms. The reinforcing bars will be beneath the finished floor, except for the four piers. Three walls of shielding blocks can be seen surrounding the vault.

Fig. 20. The finished vault floor is shown with the pit and rebar framework for the four vessel foundation piers. Over 350 cubic yards of concrete were poured to form the floor and foundations in the first phase of concrete pouring for the MFTF vault.

Fig. 21. Steel framework for the southwest pier of the MFTF vacuum vessel footing is shown. Each of four piers will stand 13 feet above the vault floor and carry the interface baseplate for a leg of the MFTF vacuum vessel. The coil of copper is part of the grounding conductor network for MFTF systems.

pier wall will rise 13 feet above the floor with interfacing steel plates on top as a base for one of the four vessel feet.

The MFTF primary power activity provided utility power from existing 115-kV substations to Building 431 during the quarter. Also, the 230-kV, 250-MW pulsed-power line was approved by the California Public Utility Commission on the basis of

the application submitted by Pacific Gas and Electric, the utility company supplying power to LLNL.

We made an updated evaluation of MFTF overall system availability and reliability. The main systems were considered and integrated to provide an assessment for operation. Attainment of an overall MFTF availability of 0.8 looks encouraging.

Based on the activities briefly outlined above, several areas of more detailed interest could be reported. The following paragraphs indicate some of the MFTF technical progress steps, along with a few points where work is continuing to resolve issues still present during the period covered by this report.

Magnet System. (C. D. Henning and A. J. Hodges)

The magnet winding was started in January and 16 layers were completed in March (See Fig. 22). Some delays were encountered because of slow material deliveries, but round-the-clock winding was started to gain back some of the lost time. Substantial efficiencies in winding were implemented to meet the required winding rates. In addition, the quality has improved, so that few stoppages are encountered for rework or materials rejection.

An analysis of conductor motion effects on stability was completed by General Atomic. They concluded that half of the cooling channels in the conductor would need to be blocked before transient stability would be impaired. In general the conductor motions studied to cause temporary loss of superconductivity were well beyond any credible limit. Also, General Dynamics/Convair completed their study of conductor strain due to winding looseness and motion. The resulting strain was nearly independent of winding looseness for the 0.005- and 0.01-in. gaps per turn studied. A peak conductor force near 4000 pounds was predicted which leaves a better than 2 safety factor.

Fig. 22. Sixteen layers of the first coil for the MFTF yin-yang magnet were completed in March. The magnet jacket (or coil form) is shown with its Kapton and G-11 insulation layers as the next coil conductor layer is being wound. The length of stabilized superconductor is being wound. The length of stabilized superconductor is fed from its shipping spool on the left, passed through an ultrasonic tester, joined with the string of G-11 interturn insulation buttons, and laid on the interlayer G-11 insulation shown in the photograph. To minimize the coil slack the conductor is clamped in position by the magnet-winding tooling as each turn is made.

Measured looseness in the magnet windings is below 0.005 in. so that neither high strains nor instabilities from conductor motion are expected.

The 750,000 pounds of special 304LN stainless steel plate for fabrication of the magnet structure were cast and rolled by ESCO with excellent chemistry and plate integrity. Most of the plates have been shipped to Chicago Bridge and Iron to commence manufacture of the structure. The plates are being cut in Greenville, Pennsylvania, and will then be formed and welded in Salt Lake City, Utah.

Our welding development program has produced several methods to weld the 304LN steel with 316L welding rod. Most trial welds have exceeded the 120 ksi $\sqrt{\text{in.}}$ fracture toughness required when tested by Battelle Columbus Laboratories. In addition, Chicago Bridge and Iron has qualified two large lots of welding wire with traceability per Section III of the ASME/

code. Charpy impact tests at 77K exceeded 35 ft-lb, indicating that the properties at 4K will be good, as well.

General Dynamics Convair has completed the coil-structure failure analysis. Only two welds were found to be critical (i.e., if a crack started it would propagate to produce structural failure). Both welds join the 5-in. thick plates near the magnet minor radius. One weld was prefabricated and available for complete examination. The other closure weld must have careful process control, and we are considering special nondestructive examination techniques.

Fusion Chamber System. (W. H. Stierbentz and P. M. Holl)

During the quarter, system design reviews were held with the subcontractors of the fusion chamber system to bring the design to 90% completion. Fabrication was initiated on the vacuum vessel and on the aluminum extrusions to be used in the "Z-shaped" cryopanel pump system.

A key function of the vacuum vessel system is to provide the interface structure for supporting the neutral-beam injector modules and the thermal absorbers used for intercepting residual high-energy deuterium ions and neutral-beam deuterium particles.

We have made substantial progress in the design of the two principal thermal absorber systems: one for the neutral beams, and the other for the ion beams.

The maximum power deposition on the neutral-beam thermal absorber panels can be as high as 6.65 kW/cm², having a total energy deposition of 40 MW for 0.5 s for each neutral-beam array. The vacuum vessel system contains four neutral-beam module arrays.

To minimize the effects of the peak-power deposition upon the thermal absorber surfaces, the arrays have been designed for a Vee-shaped configuration containing six Vees per array. The slanted surfaces of the Vees have an included angle of 21°. Thus, except at the leading edges, the maximum power deposition has been reduced to approximately 2.5 kW/cm², which is well within the range of successfully demonstrated existing thermal absorbers.

The six-Vee-panel arrays are each 9-by-12 ft and are to be constructed of copper. Cooling water flowing at a rate of 48 gallons per minute per array at 100 psig pressure will remove much of the absorbed heat deposited upon the panel surfaces. Cooling flow channels 0.406-by-0.2 in. will be spaced every 1.813 in. along the surfaces. The leading edges of the Vee panels are to be specially constructed of tungsten to protect

them in the event the neutral-beam modules are aimed to impact the leading edges with the maximum power level of 6.65 kW cm^{-2} .

The ion-beam thermal absorbers are to be attached to each neutral-beam injector module so that they intercept the deuterium ions drawn from the neutral-beam streams. The maximum power level of these ion streams can be as high as 4.25 kW cm^{-2} .

Because of space constraints, these panels must be flat surfaces. As with the neutral-beam thermal absorbers, these panels, which are 2-by-2 ft. will be made of copper. However, the entire surface must be treated with either tungsten or molybdenum to minimize surface sputtering.

During the 0.5-s pulse of the neutral-beam system, the maximum temperature at the surface of the ion thermal absorber is expected to reach 922°C . Cooling water at the rate of 8 gallons per minute will flow through circular channels 0.375 in. in diameter spaced 1.875-in. apart.

Notable progress has been made in the design and development of the neutral-beam modules, and in interfacing with the fusion chamber. A total of up to 48 of these modules are flexibly mounted in

four close-packed clusters around the waist of the fusion chamber. Flexible mounting permits individual aiming of each module $\pm 4^\circ$ about two orthogonal axes perpendicular to a radial line passing through the plasma center. This installation is illustrated in Fig. 23. (For clarity, electrical cables, air, and water piping are omitted.)

The major components in a neutral-beam module are the neutral-beam source, the magnetic shield, the isolation valve, the neutralizer duct, the gimbal mounts, the bellows, and the actuators. External features of some of these components are seen in more detail in Fig. 24, which illustrates a single neutral-beam module. Neutral-beam source details, the isolation valve, and the neutralizer duct within the magnetic shield are not seen.

The rectangular cross-section tapered box is the outer member of the magnetic shield. This thick-walled vacuum box is the principal structure to which all of the other beam module components are assembled. Additionally, the magnetic shield supports the ion dump, which is the rectangular copper plate shown at the left side of Fig. 24. The magnetic shield outer box is pivotally supported by the tapered-beam

Fig. 23. Neutral-beam module installation.

Fig. 24. Detailed view of neutral-beam module.

rectangular frame ("gimbal ring"), which, in turn is pinned to the saw-toothed flange plate structure that is the gimbal base. The ion-dump end of the module projects into the fusion chamber, and the gimbal base is O-Ring sealed and bolted to a chamber flange, as shown in Fig. 23.

The bellows is a Viton single-convolution flexible member with aluminum flanges which provides the vacuum seal between the chamber and the magnetic shield outer box. In Fig. 24, it appears sandwiched between the gimbal members.

Two mutually perpendicular aiming actuators are shown attached to the gimbal members and to the magnetic shield outer box. The actuators are screw-threaded devices that are driven by electric motors.

The key accomplishment that permitted us to complete the design of the neutral-beam modules, their components, and the fusion chamber interfaces was the design and development of a magnetic-shielding assembly within the physical space criteria

SNBPSS (one of 24)

Ion source (one of 24)

Fig. 25. Block diagram of SNBPSS.

imposed. This met the neutral-beam source operational requirement of 1.5 G maximum within the source arc chamber region at a distance of 7 m from the fusion chamber centerline.

As a result of this achievement:

- Fusion chamber interfaces have been established that include module spacing, chamber penetrations, flange details, and tolerances.
- The magnetic-shield design has been defined.
- Preliminary design has been completed for the module-to-chamber mounting and aiming components.
- Neutral-beam module assembly, test, and installation studies have been initiated.

Sustaining Neutral-Beam Power Supply System.

(R. D. Eckard, D. J. Mayhall, and D. W. Shimer)

Recent workshops and discussions at LLNL and LBL about the requirements of the MFTF 80-kV neutral-beam ion sources and the sustaining neutral-beam power supply system (SNBPSS) have resulted

in a number of proposed changes in the SNBPSS components. These changes will reduce the complexity of SNBPSS and make the sources easier to operate and less susceptible to fault induced damage.

Figure 25 shows a block diagram of the major SNBPSS components on the left and a schematic diagram of the ion source on the right. The SNBPSS components are the accel dc power supply, accel modulator, filament power supply, arc power supply, gradient grid network, suppressor power supply, and control and monitor system. The major parts of the ion source are the filament, arc anode, entrance grid, suppressor grid, and exit grid.

The first proposed change is to relax the accel voltage risetime requirement to the sustaining neutral-beam source module, from 20-100 μ s to 20-200 μ s. This slower risetime will simplify the accel modulator design. The second change is to make k , a parameter that is proportional to source perveance, into a variable (instead of a constant value of 4) in the

Fig. 26. SNBPSS arc power supply design proposed by Aydin.

relationship of $I_{arc} = kV_{acc}^{1.5}$. This change will make the ion source more tunable and easier to operate.

The arc power supply requirements were re-examined with two principal goals in mind.

- Incorporation of new requirements for source protection and control.
- Relaxation of existing requirements where possible to simplify the arc power supply circuit designed by Aydin, the LLL subcontractor building SNBPSS (Fig. 26). Treated as a whole, these changes will provide MFTF with a more reliable sustaining neutral-beam system with a minor cost impact.

New experimental data on neutral-beam sources required the following additions to the arc power supply:

- Addition of a "crowbar" to the output of each power supply to protect the arc chamber from localized heating during "spotting."
- Expansion of the control circuitry to permit open-loop tracking of the accel voltage to the rise of the arc current with a variable waveshape and with up to $\pm 100\text{-}\mu\text{s}$ time offset (Fig. 27). This provides the needed flexibility for optional source operation.

Major simplification of the arc power supply resulted from the following experimental results:

- A well-conditioned source will spark-down less than two or three times during a 0.5-s pulse.
- A risetime anywhere from 20 to 200 μs is sufficient for reliable source operation.

Fig. 27. Relationship between arc current and accel voltage.

The reduction in the number of spark-downs enables a substantial savings in the arc power supply. The minimum time between notches can be relaxed from the original requirement of 2.5 ms to 25 ms. This enables the "energy dissipator" and "commutating pulser" hardware of Fig. 25 to be eliminated. This hardware was required to prevent a gradual buildup in arc current whenever several notches occurred in succession spaced only 2.5 ms apart. The new requirement of 25 ms between notches eliminates this hardware and therefore increases the reliability of the power supply.

The slower risetime of the accel voltage mentioned above results in a slower risetime of the arc current and permits a major simplification of the cable between the power supply and the neutral-beam source. With the notcher circuit tuned for a 100- μs risetime, the cable inductance can be raised from 0.35 to 6 μH without greatly affecting the "notcher-charging circuit." The cable can be changed from 126 individual conductors to only 6. The higher cable inductance also makes the notching characteristic less dependent on both the type of gas being used in the source and the individual source characteristics.

Several other changes made in the arc power supply requirements have a minor impact: The minimum open circuit voltage was reduced from 100 to 30 V to reflect new data on arc striking voltage; the minimum arc current was raised from 300 to 600 A; the notching depth was changed from below 300 to 250 A, or 20% of the arc current, whichever is greater; the requirement of 40 μs below 570 A during the notch interval was eliminated; and finally, the arc current maximum ripple requirement of 4% from 300 to 4000 A was changed to a more limited current range from 1500 to 4000 A with the power supply operating into a source module arc load. Changing the minimum open-circuit voltage requirement permitted elimination of an auxiliary supply in parallel with the main arc supply (see Fig. 26). The other changes affect component size but do not permit component elimination.

A frequent source of potentially destructive faults is the formation of localized internal arcs in the arc chamber. These faults usually occur between the arc plasma and the filaments and are fed by the arc power supply. This process is called spotting and the localized arcs are called spots. We will add a detector to sense the occurrence of spotting. A fast arc current crowbar will also be added to protect the source from spotting by shunting the arc current rapidly away from the source arc anode.

The peak output current of the suppressor power supply for 50 μ s after turn-on can be reduced to 40 A, instead of the previously required 50 A. A 40-A current capability for 200 μ s during the pulse can be tolerated. These two changes would reduce both the size and cost of the suppressor power-supply output filter capacitor.

The filament voltage range at the source terminals is changed from 10.5-12.5 V to 9.5-11.5 V, which reduces the maximum system power at the source terminals by 132 kW. A requirement that the filament inrush current be at least 2.5 times the nominal operating value was also eliminated.

Additional Ion-Source Diagnostics and Fault Detectors. We are adding a plasma probe that produces a voltage proportional to the arc chamber ion current density to give a better picture of internal source conditions, detect spotting, and allow easier source-parameter tuning. Also, we are adding a detector to sense the ratio of the gradient grid network voltage to the accel voltage. If this ratio exceeds 0.9, a fault between the entrance grid and the gradient grid is indicated. Such a fault, if uncorrected, can rapidly result in damage to the gradient grid. A detector that ensures connection of the high voltage to the gradient

grid at the source will also be added. This will prevent operation of the source with a floating gradient grid, which results in an unfocused ion beam and possible grid destruction. A list of SNBPSS source fault detectors is shown in Table 2.

Data Channels and Sampling Rates. A number of monitored electrical variables have been carefully analyzed to determine their expected behavior. Data channels for these variables have been classified according to operating potential, range of variation, desired accuracy, and sampling rate. These results are shown in Table 3.

Control and Diagnostic System. (P. R. Goldrick and R. H. Wyman)

Work on the Control System for MFTF proceeded well, with software developments that used system hardware that was delivered to LL during the quarter. The complete control and diagnostic system includes supervisory and local computers with peripherals and interfaces. The supervisory system is outlined in a previous report.¹⁹

Work on software using the actual MFTF processors, a prototype supervisory control console, and peripherals made significant progress. Establishment of protocol and procedures to provide a working system has been demonstrated with software developed during this period. One example of the work is the use of the shared-memory capability of the Interdata 8/32 and 7/32 supervisory central processors for MFTF.

Communication between the nine processors of the MFTF supervisory control and diagnostics system (SCDS) occurs via shared memory. In this report we cover progress on some of the issues and implementation of the SCDS shared memory system.

TABLE 2. SNBPSS ion source fault detectors.

Type	Status
Accel voltage rate ($\frac{dV_{acc}}{dt}$)	previous
Accel overcurrent (I_{acc})	previous
Suppressor overcurrent (I_{sup})	previous
Gradient grid to accel voltage (V_{gg}/V_{acc})	added
Gradient grid HV connection at source (V_{gg})	added
Arc spotting detector	added

TABLE 3. SNBPSS ion source data channels.

Type	Potential	Range	Accuracy	Sampling rate (per sample)
Accel current	Accel	10-100 A, dc	$\pm 3\%$	5 μ s
Accel voltage	Ground	16-100 kV, dc	$\pm 3\%$	5 μ s
Filament current	Accel	500-18 kA, dc	± 180 A	10 ms
Filament voltage	Accel	9.5-13.5 V, dc	$\pm 0.3\%$ V	10 ms
Arc current	Accel	250-5000 A, dc	$\pm 3\%$	10 ms
Arc voltage	Accel	20-100 V, dc	$\pm 3\%$	10 ms
Gradient grid current	Ground	0-5 A, dc	$\pm 3\%$	5 μ s
Gradient grid voltage	Ground	12-80 kV, dc	$\pm 3\%$	20 μ s
Gradient grid voltage	Accel	12-80 kV, dc	$\pm 3\%$	20 μ s
Suppressor current	Ground	0-50 A, dc	$\pm 3\%$	5 μ s
Suppressor voltage	Ground	0-4 kV, dc	$\pm 3\%$	20 μ s
Plasma probe voltage	Accel	0-5 V, dc	$\pm 3\%$	5 μ s
Arc spot detector	Accel	0-5 V, dc	$\pm 3\%$	1 ms

A design criterion of SCDS is that it should function with a single-point hardware failure. Thus, if one of the network processors fails, there must be a method for overcoming the loss. To accomplish this task, the system is considered to be composed of "logical machines" as well as physical machines, and tables are kept in shared memory that associate each logical machine with a physical machine.

A logical machine is, essentially, a collection of software tasks with a common goal, such as control and diagnosis of the external vacuum system.

These tasks use a system of "checkpoints" and whenever a task passes a checkpoint, it records the fact in shared memory. The checkpoints can be thought of as milestones. If a physical machine fails, the network operator can reassign the logical machines that had been assigned to the failed physical machine to one that is operational, the "backup" machine. When the logical machine is then restarted, it can determine how far through its current task it has gone by examining the checkpoint status in shared memory, thus allowing a "graceful" switchover.

The MFTF shared memory consists of two separate modules of 64 kilobytes each. The interface on each half is designed to permit power to be removed from a memory module without affecting the operations on the other half. Further, our software is being designed to allow the network operator to assign buffer space in the shared memory to both logical and physical machines, so that reassignments can be made easily if a shared memory module is lost.

Another problem confronting the system is the integrity of shared-memory processes in the face of undebugged code. A solution is to prevent "users" from having unrestricted write access to shared memory. This control technique is possible by a simple modification of the vendor-supplied operating system.

Thus, a set of robust (well-debugged) subroutines that will allow users restricted write access to the shared memory is being designed. In some cases, these routines will be part of the executive system. They will use locks to prevent multiple assignment of buffer spaces, assign buffers to tasks, write data from user memory to shared memory, and clean-up/consolidate unused buffer space when it is released. Further, use of these subroutines will prevent user access to areas in shared memory outside those assigned by the network operator.

Prototype Supervisory Control and Diagnostic System Console. (*G. C. Speckert*)

This quarter saw the completion of the prototype control console and of a graphics editor, GREDIT, for

creating and modifying graphically defined control panels.

The console system is the primary man-machine interface to the MFTF for control and diagnostics. The console itself is the prototype for five subsystem control consoles, each with three large status-display screens and two touch-panel-equipped smaller control screens. Two supervisor control consoles will also be built, each with six status displays and two control screens (see Ref. 20 for artist's conception of subsystem and supervisor consoles).

All control panels consist of software-defined sets of buttons appearing on the control screens (see Frontispiece, p. ii). When the operator's finger touches the picture of a button, the button lights up and a beep is produced to provide feedback to the operator that the button has been activated. This is made possible by the use of a commercially available transparent touch-sensor that fits over the control screen and reads the position at which the touchpanel is touched.

Since the operator can interact with only two control panels at any one time, a tree-like structure is used to organize the control panels. For instance, the overall root node control panel allows the operator to select a subsystem to control, i.e. vacuum, magnet, cryogenic, etc. For example, after the vacuum system button is touched, a new set of buttons appears that allow the operator to select which function to perform, i.e. valve control, pump control, etc. After touching the valve control button, the set of buttons allowing the individual valves to be opened and closed is presented.

Further button touches cause the console system to issue a command to the appropriate execute module via the supervisory control communications system. This module will perform the indicated action and report back to the console system the results, if any.

The advantage of this type of control structure is that the control panels are entirely software generated and can be modified quickly and easily, given a suitable editing capability. Toward this end, a graphics editor, GREDIT, has been produced to create and manipulate these graphical control panel files. This editor allows buttons, text, circles, and lines to be added, moved, and deleted, while keeping the associated data files consistent with the graphical representation.

The prototype console is currently being evaluated to refine its design before soliciting bids for the production units.

Console system software development is continuing.

2. DEVELOPMENT AND TECHNOLOGY

This program is aimed at developing the technology required for carrying out the mirror-reactor program. Much of this work applies to the national program and fusion in general; it covers the following areas:

- **Superconducting-magnet development:** The mirror program is the only fusion program that has depended on superconducting magnets for major confinement experiments, and the only major confinement experiment presently under construction in the world using a superconducting magnet is the Mirror Fusion Test Facility (MFTF) at Lawrence Livermore Laboratory (LLI). The magnet program developed and tested the conductor design for MFTF. We are now developing, with industry's cooperation, practical high-field materials, e.g., niobium-tin (Nb_3Sn), that will be needed for future experiments. A key feature of this program is the high-field test facility (HFTF) under construction in which the first large multifilament Nb_3Sn coils will be evaluated.

- **Neutral-beam program (including beam direct conversion and vacuum technology):** The neutral-beam program develops injector systems for mirror experiments as well as for the Tokamak Fusion Test Reactor (TFTR) and the Doublet III tokamak. In addition to the development of prototype injectors for near-term experiments, we have a longer range effort aimed at improving reliability, quality, and efficiency of neutral-beam sources in general. A major long-range effort is to develop high-efficiency, negative-ion sources for future high-energy applications. The 200-kV high-voltage test stand (HVTSS), now completed, is a key element in future negative-ion-based development. In conjunction with work on neutral-beam injectors, we are also developing direct energy converters for improving the efficiency of positive-ion-based systems and the advanced cryopumping techniques needed for all large neutral-injector systems.

- **Direct conversion:** In addition to our study of the direct conversion associated with neutral beams, we have a continuing program to develop efficient direct-recovery systems, which are required for reducing power losses from future mirror reactors.

- **Materials program:** We have a unique source of 14-MeV neutrons at the Rotating Target Neutron Source (RTNS-I), an LLI facility used to investigate the effects of fusion neutrons on materials of interest to reactor designers. Specimens are irradiated for evaluation by many laboratories. A new facility dedicated to the fusion program, the RTNS-II, is now completed. The LLI materials program is aimed at characterizing the type of damage effects produced by fusion neutrons and correlating these effects with fission-reactor experiments.

Several key problems on tritium control and handling that must be solved for any large deuterium-tritium (D-T) fusion device are being investigated in the LLI tritium laboratory; emphasis is on cleanup of low tritium concentrations in reactor-containment buildings, vacuum-pump exhaust, etc.

The effects of neutrons on the properties of superconducting materials are being investigated using a unique apparatus in which superconducting properties are measured while the specimen is continuously maintained at liquid-helium temperature.

- **Reactor-design studies:** Design studies of mirror reactors form a basis for evaluating mirror concepts and for guiding our long-range program. Present emphasis is the tandem mirror reactor (TMR) concept, on a fission fusion hybrid reactor based on TMR, and on an engineering evaluation of a small-reactor system based on field reversal. A special class of reactors that are small and candidates for construction in the next decade is being investigated in a program sponsored by the Electric Power Research Institute (EPRI).

Magnetic Systems

Superconducting Magnet Development

(D. N. Cornish, R. M. Scanlan, and J. P. Zbasnik)

The technology of superconductors and superconducting magnets is of vital importance to the building of present-day plasma physics facilities and to the planning and study of future experimental mirror machines and reactors. We have developed a

niobium-titanium (Nb-Ti) conductor for the Mirror Fusion Test Facility (MFTF) winding and are now developing niobium-tin (Nb_3Sn) conductors for future mirror devices. For FY 1979 our main emphasis will be to proceed as quickly as possible with the construction of the High-Field Test Facility (HFTF). Meanwhile, we shall use the system in its present

state (i.e., with two backing coils plus the MFTF test coil) for the following:

- Tests of two different prototype ohmic heating conductors for Los Alamos Scientific Laboratory (LASL).

- Tests of two stabilized prototype Nb_3Sn conductors for the HFTF.

Main emphasis during this period has been on various aspects of the High Field Test Facility (HFTF).

Design. The design of the facility has been re-examined to accommodate, and test at 12 T, a number of insert coils designed to evaluate prototype conductors for 12-T Tokamak toroidal field coils. The main modifications to the coil stack resulting from this requirement are as follows:

- The capability of splitting both the Nb-Ti and the Nb_3Sn coils on the center line to permit the test coils to be inserted.

- The provision of thick end-plates and bracing structure to prevent the large axial magnetic loads of the facility from being applied to the test coil.

- The provision of additional ampere-turns to overcome the field reduction arising from the parting of the coils for the above reasons.

- The ability to operate the coil stack with its axis horizontal.

Preliminary proposals for the redesign have been submitted to the groups supplying the insert coils for their comments concerning the assumptions made about their coils.

Coil Winding. Preparations for winding the second pair of Nb-Ti coils have now been completed and the winding has begun. The development of a new design of interturn insulation and proving the cold-welding technique for joining the conductor permit us to wind this pair of coils in pancakes, rather than layers, which was the method used for the first pair. The pancake arrangement results in a coil stack much better suited to withstand the large axial forces that accumulate on the center pair of coils. The interturn insulation is 0.035 in. thick and permits 70% of the conductor wide faces to be in contact with liquid helium. A special machine to fabricate the insulation incorporating feed, grinding, punching, and reeling stations has been designed and built at LLL for this purpose. Other preparations have included resetting up all the winding facilities that were dismantled while the TMX coils were fabricated and special tooling for making interpancake conductor joggles and insulating ramps and fillers.

Facility Operation. During this period, the facility in its present form, consisting of two Nb-Ti coils

plus the MFTF test coil, was used to test a "long, short sample" of 50-kA Tokamak development pulse conductor for LASL.

Diagnostic and Data Acquisition System. The Modcomp computer and associated hardware, including teletype console, printer, plotter, and graphics terminal, have been delivered and are undergoing checkout. The strength of the stray magnetic field in the existing cryogenics laboratory is too high for this equipment to be installed there, so a trailer has been rented to house it. This has been delivered and is awaiting power hookup.

Helium Recovery System. Stray field considerations from operations of the Facility have resulted in a change in the site of the MFTF control room to the area formerly occupied by our helium recovery plant. It has, therefore, been necessary to reposition this plant and to carry out the exercise in such a way that half the equipment was always available for use. This has been a major undertaking; and although all the equipment has now been moved, plumbing, wiring, leak testing, and recommissioning will continue for some time. (The cost of this work is covered by the MFTF project.)

Short-Sample Testing for MFTF. Special equipment and facilities have been set up for carrying out critical current measurements at 10 kA and 8 T on samples of the conductor to be used for the MFTF magnet. In addition to critical current, the copper-resistance ratio and ratio of copper to superconductor are also being measured. At least 240 samples are expected to require processing. (The cost of this work is covered by the MFTF project.)

HFTF Nb_3Sn Conductor. We worked in three areas:

- **Copper Stabilizer.** New embossing rolls were fabricated by electrical-discharge machining (EDM) to overcome the problems associated with the first set of rolls, which were prepared by etching. The main problem encountered with the first set of rolls was rounding of the embossed strip from the rolls. Samples prepared with the new rolls showed improved flatness and easy release from the rolls, due to a slight taper provided on the vertical surfaces of the embossing rolls. Some additional experiments are in progress to optimize the initial Cu-stock dimensions and to achieve the required combination of hardness and resistivity ratio in the stabilizer.

- **Nb_3Sn Core.** The Nb rods for the first stage extrusion were received (four months late) by Airco early in February. The material was outside specification on grain size and was returned to Wah Chang for

reannealing with documentation of the required time-temperature annealing schedule. Wah Chang reannealed the Nb at a temperature much lower than that suggested by Airco and returned the Nb with documentation showing the grain size still out of specification. Data obtained by Airco showed that extruding the Nb in this condition would most probably lead to the "sausaging" behavior experienced on the previous HFTF billet, so the material was sent to Kawecki Berylleo for annealing. The Nb grain size was within specification after this anneal and was extruded on March 30.

- **Alternate HFTF Core.** There are two potential problems with the present core design: possibly poor recovery characteristics due to the large amount of bronze matrix between the filaments and the Cu stabilizer, and poor yields in processing due to the long, continuous length requirement.

Airco proposed an alternate design that could overcome these problems if they arose. The proposed conductor would be a compacted cable made by a two-stage extrusion process (187 Nb in bronze first stage, followed by approximately 91 first-stage rods in a Ta-Cu billet), followed by cabling. The cable (3-by-6 strand) would be wrapped with a Cu tube and compacted to produce a monolithic core with the same composition and current density as the original design. For this conductor to be seriously considered as an alternate, several questions must be answered in a short time: Can the necessary Cu:Cu bonding be achieved? Can a 3-by-6 strand cable be compacted without excessive distortion of the elements? What are the economic advantages of this approach? This alternative approach is being actively pursued.

Stabilized Prototype HFTF Nb₃Sn Conductor for LLL Evaluation. A 100-foot length of conductor has been shipped from Airco for stability and recovery evaluation in the High Field Test Facility. This conductor contains the core material with "sausaged" filaments and 90 Pb-10 Sn solder has been used for bonding the stabilizer. A better conductor, with uniform filaments and soldered with 50 Pb-50 Sn, will be evaluated at a later date.

Plasma Engineering

High-Voltage Test Stand

(J. C. Davis)

During the second quarter of FY79 we operated the High-Voltage Test Stand (HVTS) as a complete

system for the first time, producing D⁺ beams at 20 kV from the TFTR prototype neutral-beam source. Operation was limited to less than 30 kV on the source by a low-voltage EIMAC tetrode installed in the high-voltage modulator. After these preliminary tests, the EIMAC tube was replaced by the RCA 200-kV tetrode. We have now completed the checkout required for operation up to 120 kV. In the next quarter, the HVTS will begin testing TFTR (120 kV), MFTF (80 kV), and Doublet-III (80 kV) prototype sources to full current for 0.5-s pulses. Following the initial tests, the beam pulse lengths will be extended to determine the operating limits of these sources.

Beam Direct Conversion

(W. L. Barr)

A beam direct converter was successfully tested on a reduced-area TFTR ion beam on Test Stand IIIA at LBL. From one shot to the next the efficiency increased as the electrodes were conditioned and the gas-pressure rise during a 0.6-s beam pulse decreased. After conditioning, the conversion efficiency was over 60% at the beginning of the pulse, decaying to over 50% by the end of the 0.6-s pulse. This decay was due to the rise in pressure of only the primary beam gas and was limited by the pumping speed. The beam was operated with hydrogen and helium at 100 keV with similar efficiencies. The collector voltage was over 90 kV. When magnetic electron suppression was used, rather than electrostatic suppression, the efficiency dropped to 40%. A better designed electron catcher could improve this efficiency. The catcher that was used was intended to control the electric field in the region where the electrons are stopped and to provide a sink to catch the electrons as they drift in the crossed electric and magnetic fields.

A residual gas analyzer in the direct converter tank and one in the beam dump recorded the degassing. New electrode material released mostly H₂ and Co, and in amounts that exceeded the input of primary gas from the beam. The electrodes were all made of 0.020-in. thick molybdenum cooled only by radiation. This allowed them to get hot enough to outgas and to stay hot between shots, thereby avoiding the reabsorption of gas. About one week of running with 0.5-s pulses every 60 s was required to reduce the evolved gas to a tolerable level.

Analysis of the data is in progress.

Fusion Reactor Materials

Rotating Target Neutron Source II (RTNS-II)

(D. W. Heikkinen and C. M. Logan)

Irradiation of samples has begun at RTNS-II

RTNS-II is now irradiating samples for the fusion materials program. Improvements have been made in the rotating seal to attain the design goal of a 1.0-cm spot size. Present operation with 23-cm-diam targets is limited to a source strength of $\sim 10^{13}$ neutrons/s. Initial experiments are all room-temperature exposures of samples for post-irradiation examination. In one of these experiments, we will irradiate stainless steel samples for K. Wilson of Sandia Laboratories, Livermore. The samples have been prepared from the material used to construct the vacuum vessel of TFTR at Princeton. Wilson will later implant the samples with deuterium and measure trapping at neutron-damage sites. The results will help predict tritium holdup and recycle for TFTR.

Fusion Systems Engineering

Reactor Design Studies

Mirror Next Step. (C. C. Danm and G. A. Carlson)

Studies are underway to determine the characteristics of the next major step in the mirror experimental program beyond MFTF.

Our general objective is to develop a design concept for a long-pulse, DT-burning tandem mirror with end plugs suitable for high-Q operation in future reactors. By limiting the length of the central solenoidal cell, the fusion power output of the Mirror Next Step (MNS) device would be reduced below that of a reactor, hence limiting the overall Q to about 2, but all significant physics and engineering aspects of a tandem reactor could be tested.

Parameter studies during this quarter were based on the standard tandem mirror reactor,²¹ augmented by electron-cyclotron heating (ECH) and including use of an auxiliary cell ("A"-cell) to reduce ambipolar losses from the plugs. From these studies, we found that the high-technology characteristic of the tandem reactor would be required to meet our MNS objectives, implying magnetic fields (at the conductor) of ≥ 14 T and neutral-beam energies of 600 keV or more. The time needed for such technology development does not match our desire for a 1985 start-of-construction for MNS.

Toward the latter part of this quarter, new ideas for pump-out-assisted tandem mirror devices appeared.²² We are presently evaluating these ideas for application to MNS, with the expectation of significantly reducing technology requirements compared with the standard tandem designs. Parameter optimization studies for the new configuration will continue during the next quarter.

Parametric Studies of Tandem Mirror Reactors.

(G. A. Carlson, B. M. Boghosian, J. H. Fink, J. O. Myall and W. S. Neef Jr.)

We made significant progress in our tandem mirror reactor studies.²³ Additionally, we have presented new ideas involving thermal barriers.²²

The parametric studies were carried out with an analytic zero-dimensional physics model, which has been in a continual state of development since first presented in the TMX Proposal.²⁴ The development has resulted in more accurate calculations and a more versatile computational tool. A recent major sophistication has been the addition of a controller program for automatic optimization.

The major goal of our tandem mirror reactor studies since the publication of our preliminary design report²⁵ has been to improve reactor performance, while at the same time lowering the level of required technology (principally neutral beams and magnets). Ideas that have been investigated are the addition of "A" cells, direct electron-heating in the central cell, direct electron-heating in the plugs, and thermal barriers to insulate the plug electrons from the central cell electrons.

The "A" cells are auxiliary plasma cells placed at either end of the tandem mirror, outside the plug cells. The purpose of the "A" cell is to reduce the outward potential drop of the plug plasma and thus improve the confinement of the plug plasma. The required injection power for the "A" cell can be very small, and a net benefit can be realized, either as a reduction in plug-injection energy, or improved performance, or both. An additional benefit from "A" cells is that minimum-B "A" cells may magnetohydrodynamically stabilize the entire tandem mirror system, allowing the use of simple mirror plug cells. For equal on-axis field strengths, simple mirror plugs can be designed with lower maximum fields than minimum-B plugs.

Direct electron-heating in the central cell allows a further reduction in injection energy and results in a further improvement in performance. Electron cyclotron heating (ECH) in the central cell could be done at the microwave frequency of gyrotrons under development (110 GHz).

Direct electron-heating in the plugs by ECH would require the development of higher frequency gyrotrons, but would result in another reduction in required injection energy and another improvement in performance. The improvements are due to the significantly higher electron temperature that is established in the plug.

The thermal barrier concept is discussed in detail in Ref. 24. Basically, it involves the maintenance of a mirror cell with depressed plasma potential between the central cell and plug. This depression in the potential serves as an electron thermal barrier between the central cell and plug. Electron heating in the plug can then result in a very much higher electron temperature there and in a large improvement in tandem performance. The effect of the thermal barrier is so strong that large relaxations of technology can be made. Reduced plug-magnetic field and plasma density allow the use of ECH heating in the range 55-110 GHz in the plug region.

Table 4 gives a short list of parameters for three different tandem mirror reactors. The first column is the case previously discussed in Ref. 26. This unoptimized design used "A" cells and direct electron-heating in the central cell. We see that the injection energy is reduced from the 1200 keV specified for our preliminary design,²⁶ but the plug magnetic field strength is very high. (The lower value for $B_{\max}$ refers to a simple mirror plug, i.e., MHD stabilization by the "A" cell; the higher value refers to a yin-yang plug.)

The second column is an optimized design with "A" cells and direct electron heating in the plugs. (This case is discussed more fully in Ref. 22.) In comparison with the first column, there is a significant reduction in neutral-beam energy and maximum

magnetic-field strength. The plasma Q is the same for the two cases, but the first-wall neutron loading Γ is more than twice as high for the second case. However, the reduced first-wall radius for the second case means that the fusion power density volume-averaged over the annular central cell does not increase as the ratio of Γ 's, but rather as $[1.3(0.9 + 0.5 t)]^2 / [0.6(1.9 + 0.5 t)]$, where t is the thickness of the central cell annulus (blanket, shield, and magnet). Taking $t = 2.0$ m as typical, we find the ratio to be 1.4, still greater than unity.

The third column is a preliminary, unoptimized design incorporating the thermal-barrier concept. This case is discussed more fully in Ref. 23. The improvements over the first two cases are striking. The neutral-beam injection energy is reduced to 200 keV, and only 15 MW of beam power is required. The maximum magnetic field is reduced to 12 T. Q is increased to 23 and Γ to 3.6 MW/m². Of course, this wall loading can always be reduced by increasing the first-wall radius, if that proves to be cost-effective from the standpoint of wall lifetime. Doubling the first-wall radius (halving the first-wall loading) would increase the material volume of the annular central cell (~ 2 m thickness) by a factor of 1.5. The reactor is attractively dimensioned—the central cell has a first wall radius of 1.1 m and a length of 50 m. Clearly, the thermal barrier concept can result in a superior reactor.

Our future reactor studies must thoroughly investigate the details for the thermal barrier concept. Our analytic physics model must undergo a major modification to include thermal barriers. Then, we will be able to do more accurate calculations and begin to optimize a design. Equally important, we must investigate fully the technology requirements of the

TABLE 4. Three tandem mirror reactors.

	"A" cells and central cell electron heating	"A" cells and plug-electron heating	Thermal barriers
E_{inj}	600 keV	350	200
$B_{\max}$	19 or 21 T	15 or 17	12
$P_{\text{neutral beam}}$	80 MW	42	15
$P_{\text{electron heating}}$	130 MW	250	50
P_{fusion}	2100 MW	3000	1500
L_c	240 m	320	50
r_{fw}	1.9 m	0.9	1.1
Q	10	10	23
Γ	0.6 MW/m ²	1.3	3.6 ^a

^aThis value can always be reduced by increasing the first wall radius if that proves to be cost-effective from the standpoint of wall lifetime.

thermal barrier, as discussed briefly in Ref. 23. If these studies show that we can achieve (or better) the parameters listed in the third column of Table 4, then

we will have met our goal of significant tandem mirror performance improvement with reduced technology requirements.

3. APPLIED PLASMA PHYSICS

Applied Plasma Physics is a major sub-organizational unit of the Magnetic Fusion Energy (MFE) Program. It includes Fusion Plasma Theory and Experimental Plasma Research.

The Fusion Plasma Theory group has the responsibility for developing theoretical-computational models in the general areas of plasma properties, equilibrium, stability, transport, and atomic physics. This group has responsibility for giving guidance to the mirror experimental program. There is a formal division of the group into theory and computational; however, in this report the efforts of the two areas are not separated since many projects have contributions from members of both.

Under the Experimental Plasma Research Program we are developing a neutral-beam source, the intense, pulsed ion-neutral source (IPINS), for the generation of a reversed-field configuration on 2XIIB. We are also studying the feasibility of using certain neutron-detection techniques as plasma diagnostics in the next generation of thermonuclear experiments.

Fusion Plasma Theory

Effect of Axial Profiles on Ion Confinement in TMX.

(T. D. Rognlien and T. A. Cutler)

Calculations of ion confinement using actual potential and magnetic field profiles instead of a square-well show that the collisional confinement is smaller than previously estimated.

In the last quarterly,²⁷ we reported on the transition from collisional to Pastukhov confinement for the central cell ions in TMX. The conclusion was that TMX should be well into the collisional confinement regime. These results were based on a square-well model with the potential and magnetic fields rising abruptly at the end of the central cell. This quarter we have extended the Monte Carlo calculations to include the actual spatial profiles of the potential and magnetic fields. For reference, the collisional confinement time is

$$\tau_c = \frac{\sqrt{\pi} R L}{v_i} \exp\left(\frac{e\phi}{T}\right) \quad (1)$$

where R is the mirror ratio, L is the effective length, ϕ is the confining potential, T is the temperature, and $v_i = (2T/m_i)^{1/2}$.

Inclusion of the actual spatial profiles of potential and magnetic field have produced two important modifications to our earlier results. First, the effective length of the central cell which comes into the collisional scaling law is only about 3 m, one-half of the

6-m mirror-to-mirror distance. This is because the length comes from calculating the central cell volume, and using the actual spatially varying flux tube area due to the changing magnetic field reduces the volume by one-half over the square-well model. Secondly, the mirror ratio that is relevant to the central cell ions is the ratio measured at the maximum of the potential. For the TMX vacuum magnetic field, this changes the mirror ratio from 40 to 20, since the peak in the potential is at the center of the mirror plug. From Eq. (1), we see that reducing the length and the mirror ratio each by a factor of one-half gives a fourfold reduction in τ_c . Consequently, this results

Fig. 28. Transition from collisional to Pastukhov confinement for TMX uses actual profiles of potential and magnetic fields.

in the collisional confinement time for TMX greater by a factor of about 2 than the Pastukhov time, rather than by the factor of 8 found for the square-well model.

The transition from collisional to Pastukhov confinement is shown in Fig. 28 as the central cell density n_i is varied. The TMX vacuum magnetic field profile is used with a central cell field of 500 G, a mirror peak field of 20 kG, and a plug midplane field of 10 kG. The ion temperature is 80 eV, q and T is other parameters are taken from the TMX proposal. In Fig. 28, the axial profiles are kept the same while all the densities are varied in the same ratio to show the transition from collisional to Pastukhov confinement.

Experimental Plasma Research

The Intense, Pulsed Ion-Neutral Source (IPINS)

(B. W. Stallard and D. S. Prono)

Efforts during this quarter were devoted to further study of ion-beam propagation within a plasma channel and across a void to a target located 250 cm from the diode anode. The ion beam was extracted through a virtual cathode. Reflexing electrons were supplied by a real cathode on the opposite side of the anode. Improvements in the facility included both installation of a solenoid transport magnet extending to 140 cm from the anode that is capable of operation to 6 kG, and plasma sources — both surface discharge and Ti-washer gun type — used to create a preexisting plasma channel for the beam. Added downstream

diagnostics were several Rogowski belts for current monitors and improved calorimeter and ion collector probe arrays for measuring beam profiles.

Experiments on beam propagation into a plasma channel were carried out in the geometry of Fig. 29. The presence of a plasma channel improves beam propagation and also provides a source of electrons to neutralize the ion-beam space charge. The plasma source used was located either at the end of the transport solenoid (surface discharge type) or on the end-flange of a vacuum tank about 1 m downstream from the exit of the solenoid (Ti-washer guns). The delay between firing of the plasma source and the application of anode voltage was varied to optimize the plasma channel.

Three important results were achieved by use of the solenoid field and plasma sources:

- The solenoid increases the plasma current flow, presumably by acting as a guide field for plasma electrons. Currents are substantially reduced at the end of the transport tube with the solenoid off.
- Ion-beam energy as indicated by calorimetry and neutrons created by deuteron impact upon a CD_2 target are increased.
- By allowing prompt flow of plasma current along the transport when the anode voltage is applied, the diode can rapidly reach the low impedance, high current (ion flow mode) state. This "rapid anode strike" capability is important because the ion-flow pulse length can be increased by widening the anode-cathode gap.

Fig. 29. Experiments on beam propagation into a plasma channel were carried out in the geometry shown here.

Ti-washer guns provide a sufficient source of electrons for neutralizing the beam after it exits the transport solenoid (void propagation). Well-defined beam profiles were measured by the calorimeter and ion probe arrays at 250 cm. Typical beam energy delivered was 500–600 J. On one shot, 800 J was achieved. These energies compare with typically ≤ 100 J delivered at 2.2 m under early operation with extraction through a real cathode. The beam profiles at 6 kG solenoidal field are characterized by a beam half-angle $\theta_{1/2} \sim 8^\circ\text{--}10^\circ$, referred to the end of the

pipe. There is some evidence that the angle may be reduced with a lower solenoid field. This has yet to be explored.

IPINS operation ceased March 21 because of clearing of the experimental area for installation of MFTF related equipment. Machine design and site preparations are now underway for installation of IPINS on Beta II. We anticipate further system improvements and the beginning of cross-field injection experiments when operation resumes.

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