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MAGNETIC FUSION ENERGY ANNUAL REPORT July 1975 through September 1976

Scientific Editor: M. A. Harrison
General Editors: C. K. McGregor
A. Gottlieb

December 2, 1976

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LAWRENCE LIVERMORE LABORATORY
University of California Livermore, California 94550

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ANNUAL REPORT
July 1975 through September 1976**

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ABSTRACT

Experimental and theoretical results achieved by the Magnetic Fusion Energy (MFE) program at Lawrence Livermore Laboratory (LLL) during FY 1976 augured well for the earliest possible demonstration of fusion power achieved through the use of the magnetic-mirror principle. The favorable high-beta confinement results obtained from the 2XIIB experiment were consolidated and extended. Definite programmatic commitments were made for two very promising approaches to enhancing mirror confinement: the tandem mirror and the field-reversed mirror. Preparations proceeded for the Mirror Fusion Test Facility, which is to extend investigations of the physics of the tandem mirror and field-reversed mirror into a regime approaching that needed for fusion power plants.

Supporting research activities continued to provide the technical basis for future mirror-confinement experiments. The industrial development of a high-current, high-field, high-current-density Nb₃Sn conductor was the main goal of the superconducting magnet program. Beam direct conversion was being developed as a means of raising the efficiency of neutral-beam production, and plasma direct conversion was shown to work as predicted. Conceptual designs were completed for various types of power reactors. The neutral-beam program progressed in three areas: *experimental work, facility construction, and conceptual design*. Experiments on the 14-MeV Rotating Target Neutron Source (RTNS-II) included participation by experimenters from many different institutions. Methods for processing tritium-contaminated wastes were pursued, as were studies of tritiated methane in stainless-steel vessels, the control of tritium in mirror fusion reactors, and the development of titanium tritide targets for the RTNS.

The report period witnessed a rapid maturation in ability to describe theoretically the behavior of ion-cyclotron noise in the 2XIIB and the influence of that noise on the confined plasma. The high beta values achieved in 2XIIB prompted much theoretical analysis of the properties of high-beta equilibria and stability, including those of a field-reversed state. Excellent progress was made on the development of computer codes applicable to magnetic-mirror problems, with emphasis on three-dimensional, finite-beta, guiding-center equilibria, field-reversal, and Fokker-Planck codes.

Two conferences of note were held at LLL. At the US-USSR Symposium on Fusion-Fission Reactors, considerable progress was reported in understanding the many engineering problems associated with using complex fusion devices as neutron sources for the breeding of fissile fuel. At the Q-Enhancement Workshop, attendees defined appropriate experiments or calculations bearing on Q-related questions.

SECTION 1. CONFINEMENT SYSTEMS

Introduction and Summary

Two major developments dominated the Program picture during the period covered by this progress report. The first of these was the consolida-

tion and extension of the favorable high-beta confinement results obtained in 2XIIB. The second was the emergence in the form of definite programmatic commitments of two very promising approaches to our objective of enhancing mirror confinement,

thereby better to meet our goal of an economic mirror fusion power plant. The first of these, the tandem mirror, represents a new concept for enhancing mirror confinement. The second the field-reversed mirror, aims at exploiting in new ways an older idea related to the Astron concept of Christofilos, previously investigated at LLL.

In the case of major future activities, preparations for the large Mirror Fusion Test Facility (MFTF) (formerly MX) have been proceeding. This facility is aimed at extending investigations of the physics of the tandem mirror idea and that of field reversal into a high-temperature, large-plasma-volume regime more nearly approaching that needed for fusion power plants.

Other developments during the report period, including the culmination and phase-out of the Baseball II experiment, are described in detail in later sections.

In 2XIIB, the technique of warm plasma stabilization, shown to be successful in suppressing loss-cone instabilities, was improved to the point that a two to threefold plasma density increase was eventually achieved, compared to previously achieved levels. The plasma ion temperature achieved at the new higher density (2×10^{16} ions/cm³) was about 10 keV, for a net plasma pressure of about 3 atmospheres. Since the central value of the confining magnetic field was only 0.5 T, this pressure corresponds to a peak beta value at the center of the plasma of order 2.0, an extremely encouraging result. The achievement of such high-beta values encouraged us to begin exploring the possibility of achieving a field-reversed state in 2XIIB. It was reasoned that by re-aiming the existing neutral-beam injectors so as to impart to the ions a net angular momentum with respect to the magnetic axis, the onset of field reversal might be accomplished. First tests of this idea, performed at the end of the report period, were encouraging but nonconclusive. Indications such as neutral yield and electron temperature and plasma diamagnetic signal showed increases, but these data alone do not comprise conclusive evidence. Nevertheless, the obviously high beta values (in excess of 2.0) achieved in these tests encourage us to press on with these investigations.

The above-reported results, coupled with corroborative evidence from theory and with the emergence of our two new lines of attack on the issue of improving confinement, the tandem mirror and the field-reversed mirror, augur well for the future of the Mirror Program. We intend to move as rapidly as possible to exploit these opportunities with the objective of the earliest possible

demonstration of fusion power achieved through the use of the magnetic mirror principle.

2XIIB Experiment

Introduction

During the previous reporting period, we saw the first demonstration of a hot (13-keV mean ion energy), high-density (4×10^{13} particles/cm³) plasma that could be created and sustained by neutral-beam injection into a magnetic mirror. An important element of this demonstration¹ was warm streaming plasma supplied by a pulsed plasma gun to suppress ion cyclotron instability. The streaming-plasma gun used in these early experiments operated for a maximum of 600 μ s. This leads to several issues and unanswered questions about how this stabilized plasma would behave on a longer time scale. For example, the particle-confinement time of these experiments was typically several milliseconds, whereas the experiments lasted only a tenth as long.

- Could the plasma be maintained longer than the confinement time?

- Would vacuum conditions deteriorate on a millisecond time scale leading to rapid plasma loss by charge exchange?

- Would a beta limit be reached with higher beam current or in longer time-scale experiments?

- Could higher densities be reached by increasing the supply of streaming plasma?

These were questions with which the year began. As we shall see, the answers were found. In addition, we developed unanticipated results of plasma start-up and gas stabilization that contributed to making this a very interesting and exciting year for mirror research.

In the past year, we had two experimental runs totaling about 1000 shots. The first run, from October 1975 to January 1976, used long-pulse streaming-plasma gun operation (up to 5 ms) and multiple streaming-plasma guns (up to three). Our most important result during this period was plasma startup by injection of streaming plasma and neutral beams into a quasi-static magnetic field.² Previous experiments³ had used a plasma target trapped by fast-pulsed gate magnets. Thus, a method had been demonstrated that could be used to start up a mirror reactor with a dc superconducting magnet. The principal results obtained during this first period follow:

- Plasma startup by neutral-beam injection into a plasma stream.

- Long-pulse "steady state" operation (5 ms).

- Peak plasma beta, $\beta \approx 0.6$, increasing with streaming-plasma input.
- Peak density, $\hat{n} \approx 5 \times 10^{13}$ particles/cm³, increasing with streaming-plasma input.

The second experimental run, from February to April 1976, used a new gas-feed system just outside one of the mirror throats. The idea was that escaping plasma electrons would ionize the gas. Some of this ionized gas would flow inward to stabilize the hot plasma, much the same as with streaming plasma supplied by a plasma gun. The gas feed did indeed work as a source of streaming plasma, so well in fact that we obtained higher-than-ever plasma particle and energy densities. Of greatest importance, peak plasma beta reached 1.6 and peak density equalled 1.5×10^{14} particles/cm³. The results obtained during this second period follow:⁴

- Peak $\beta = 1.6$, with no evidence of a beta limit.
- Peak $\hat{n} = 1.5 \times 10^{14}$ particles/cm³.
- Peak particle containment, $\hat{n}\tau_p = 1 \times 10^{14}$ particles/cm³·s.
- Peak energy containment, $\hat{n}\tau_E = 6.8 \times 10^{10}$ particles/cm³·s.
- Identification of electron drag as the principal plasma energy-loss mechanism.
- Scaling laws demonstrating increase of energy confinement and plasma beta with injected neutral-beam current.

Throughout the year, measurements of plasma parameters became more extensive and the underlying physical processes governing plasma behavior were elucidated. Achievements in these areas included the following:

- Demonstration of $n\tau_E$ scaling with $T_e^{3/2}$.
- Experimental evidence that the plasma stream stabilizes turbulent ion energy diffusion.
- Measurements of plasma spatial profiles.
- Measurements of streaming-plasma density and energetics.
- Evidence that plasma "near wall" charge-exchange interaction is less detrimental to plasma confinement than previously known.

In addition to the intensive physics activity described above, there have been a number of engineering developments and improvements to the 2XIIIB experiment that will provide essential support for progress in the coming year. These activities included the following:

- Installation of a power crowbar to provide a constant 10-ms confining magnetic field.
- Fabrication of liquid-nitrogen-cooled liners for the neutral-beam injection tanks.
- Development of 40-keV neutral-beam injectors.

- Computer control of neutral-beam operation.
- Expansion of the data-acquisition system.
- Computer automation of the Thomson-scattering laser system.
- Modification of the charge-exchange analyzer to 15 channels and development of a new calibration method.

For detailed discussion of the 2XIIIB device, refer to the two preceding annual reports.^{1,3}

Plasma-Confinement Experiments With Long-Pulse, Gun-Injected Streaming Plasma

Figure 1 shows how the 2XIIIB experiment uses neutral-beam injection and gun injection of streaming plasma. For clarity, we show only half the dc field-coil structure that forms a guide for the streaming plasma. Gun-injected streaming-plasma experiments fall into two categories, depending on the method of startup. Historically, the first category used a dense plasma target ($\leq 5 \times 10^{13}$ particles/cm³ density, 2- to 5-keV mean ion energy, 80- to 150-eV electron temperature, and 0.2- to 0.4-ms confinement time) to trap beam-injected neutral atoms. This target was formed by transit-time magnetic trapping and compression of plasma injected by fast-pulsed guns. Later, we discovered that

Fig. 1. 2XIIIB in its streaming-plasma gun mode.

streaming plasma injected into a quasi-dc field was a suitable target for beam trapping (the second category).

Figures 2 through 4 show plasma line density for three experimental conditions. Figure 2 characterizes the earliest stream-stabilized plasmas. Plasma line density initially decays, even in the presence of 200 A of neutral-beam injection, until the plasma stream is injected. Then the plasma decay reverses and density builds up for 600 μ s until the plasma stream is shut off. Although these experiments were short-lived, it was nevertheless possible to deduce from the initial buildup rates a peak density-confinement time product, $\hat{n}\tau_p = 7 \times 10^{10}$ particles/cm³·s, with mean ion energy, $\bar{E}_i = 13$ keV.³ As mentioned in the introduction, the steady-state behavior of the plasma was left uncertain by these short-pulse experiments.

Figure 3 shows what happened when the plasma-gun pulse was lengthened to 5 ms. The plasma did

indeed reach a steady state that extended for the duration of the stabilizing plasma stream. Operations with two and three long-pulse streaming-plasma guns demonstrated that the steady-state plasma density increased with increasing amounts of streaming plasma, ultimately reaching $\hat{n} = 5 \times 10^{13}$ particles/cm³ and $\beta = 0.6$. This behavior suggested that plasma density was being limited by the amount of streaming plasma supplied. Further evidence that the plasma stream limits confinement appears in the oscillations of density in Fig. 3 and near the peak density in Fig. 2. Bursts of ion cyclotron oscillations accompany these oscillations, indicating the hot plasma loses density by turbulent diffusion.

Figure 4 shows an example of plasma buildup by injection of 310 A of deuterium atoms on streaming plasma. The mean injected atom energy is 14 keV. A steady-state magnetic field is approximated by delaying injection of the plasma stream and neutral beams until the pulsed magnetic field reaches its maximum value. During the 2-ms duration of the streaming plasma, the central magnetic field decays from 0.67 through 0.60 T. There is ample evidence that the density reached in Fig. 4 is not due primarily to trapping of a warm-plasma component. Without beam injection, the streaming plasma only reaches a line density of 5×10^{13} electrons/cm² with an average ion energy less than 1 keV, compared with the maximum line density of 4.8×10^{14} electrons/cm² and mean ion energy of 12 keV in Fig. 4. A maximum $\beta = n\bar{E}_i/B^2 8\pi = 0.4$ is calculated from Fig. 4. This agrees with measurements of neutron production and plasma diamagnetism. The calculated β is corrected for a 10 to 15% warm plasma component estimated from measured streaming-plasma density at the mirrors.

Fig. 2. Plasma line density for startup on a magnetically trapped target and stabilization with a 600- μ s plasma stream.

Fig. 3. Plasma line density for steady-state operation with a long-pulse (5-ms) plasma stream.

Fig. 4. Plasma line density for startup on a streaming-plasma target in a quasi-de magnetic field.

This plasma is in all respects similar to previous plasmas formed by injection on magnetically trapped targets as in Fig. 2, but now the streaming plasma plays the dual role of providing the initial target plasma and stabilizing the built-up plasma.

We interpret the trapped density buildup in Fig. 4 with the injected neutral beam as buildup by ionization and charge exchange on the streaming plasma plus buildup by ionization on the trapped plasma. The trapped plasma includes a warm component from the stream and a hot component from the beam. These considerations lead to the following rate equation:

$$\frac{dn_t}{dt} = \frac{(\sigma_i v + \sigma_{ex} v) n_s f n_s}{v_b e V_t} + \frac{\sigma_i v n_t f n_t}{v_b e V_t} - \frac{n_t}{\tau}, \quad (1)$$

where σ_i and σ_{ex} are the ionization and charge-exchange cross sections and v_b and v are the neutral-beam and relative particle-beam velocities averaged over the measured ion distribution. The neutral-beam trapping efficiency factor, f , is averaged over the profiles of plasma density, n , and beam current, I . Plasma volume is V , plasma diameter is ℓ , and lifetime due to all loss mechanisms is τ . The subscripts s and t refer to the untrapped streaming plasma and to the trapped plasma.

Taking the loss rates to be small and treating the coefficients of n_t as adjustable parameters, we obtain the best fit to Eq. (1), shown by the dots in Fig. 4. Known values for the parameters in this model give calculated coefficients within a factor of two of

the best fit values. From the agreement with the data, we conclude that Eq. (1) furnishes a reasonable description of the observed buildup by neutral-beam injection on the streaming-plasma target.

Initially, with n_i small, the buildup proceeds linearly in time. Then as n_i increases, the buildup becomes exponential and finally saturates. The saturation in density is mainly due to losses during bursts of ion cyclotron fluctuations. We believe the bursts occur when plasma density exceeds a value for which the amount of streaming plasma can provide stability. This model does not include such losses.

The main particle-loss mechanisms of stream-stabilized plasmas, in the absence of bursting, are charge exchange on the background gas and ion losses from the low-energy end of the ion-energy distribution due to electron cooling and low-level wave diffusion.⁶ In the neutral-beam-injected plasma, losses due to electron drag and diffusion are reduced by charge exchange on the neutral beam, which replaces a cooler ion by one at the injected energy.

From Eq. (1), we obtain the condition for exponentiation:

$$I > \frac{v_b e V_t}{(\sigma_1 v) g_t f_t} \left(\frac{1}{\tau} \right). \quad (2)$$

Using measured values $V_t \approx 4.5$ litres and $f_t = 0.55$, we find the condition for exponentiation with 14-keV injection is $I(\text{mpceres}) > 210/\tau(\text{ms})$. Initially, the trapped ion charge-exchange lifetime on cold gas, τ_{ex} , is 4 ms, so that $I > 52$ A. After 2.3 ms of neutral-beam injection, $\tau_{ex} = 1$ ms; then, $I > 210$ A is required for exponentiation. Thus, for the 310-A case of Fig. 4, we have neglected the loss term in buildup calculations.

The advantages of using the streaming plasma produced by a washer gun for startup of a neutral-beam-sustained plasma in a steady-state magnetic field include the following:

- The equipment is relatively simple.
- Target plasma of large cross section can be produced with multiple guns.
- The gas efficiency of plasma production is high.
- Electron temperature is high, so electron drag times for ion energy loss exceed 1 ms.
- The same plasma that provides the target also stabilizes ion cyclotron-frequency instabilities.³

Fig. 5. 2XIIIB in its gas-feed mode.

Plasma-Confinement Experiments With Gas-Feed Stabilization

As described in the preceding subsection, peak plasma-particle and energy densities, although increasing with multiple streaming-plasma gun operation, were limited by periodic bursts of ion cyclotron oscillations. Thus, some of the hot plasma was lost by turbulent diffusion. This suggested, according to quasi-linear theory, that the density of warm streaming plasma penetrating to the center of the confinement region was inadequate.

Accordingly, we installed a gas-feed system (Fig. 5) to attempt to increase the warm streaming-plasma current. A ceramic feed box sat just beyond one mirror throat of the minimum-B field; its elliptical apertures conformed to the flux tube passing through a 12-cm-diam circle at the central midplane. We injected either ordinary hydrogen or deuterium gas into the box above and below the plasma fan with four pulsed gas valves. The gas was injected with a rise time of $\lesssim 1$ ms, and injection continued for the duration of beam injection ($\gtrsim 5$ ms) at a rate controlled by orifices at the valve openings inside the box.

To start ionization of injected gas, we initially created a hot plasma of $\hat{n}_p = 2 \times 10^{13}$ particles/cm³ in the mirror field by neutral-beam injection into the streaming-plasma target. Gas neutrals were ionized in the box by electrons ($T_e \approx 60$ eV) conducted along the field from the beam-injected central plasma. The cold ions formed were presumably driven out of the box at the speed of sound ($v_s = \sqrt{T_e/m_i}$) by ambipolar electric fields. With sufficient density of cold plasma at the mirror, a small fraction of this plasma can penetrate the hot central plasma to provide the stabilizing stream after the streaming-plasma guns are turned off.⁷

During neutral-beam and gas injection, measurements with a microwave interferometer and a Langmuir probe indicated that a dense, cold plasma ($n_c \approx 10^{14}$ particles/cm³) resided near both sides of the gas box. Because the ionization mean-free-path for gas neutrals was short compared with the thickness of the plasma fan, few neutrals leaked out of the box. Measurements of charge-exchange flux with a fast-atom analyzer at the machine center indicated a charge-exchange lifetime on background gas greater than 5 ms. This loss rate was negligible compared to other losses of the hot ions.

The solid trace in Fig. 6(a) shows the central ($r = 0, z = 0$) electron density, n_e , as a function of time for a measured hydrogen gas input of 8000-A atom equivalent, an incident deuterium neutral-beam atom current of 225-A equivalent, and an average beam energy, E_b , of 14.7 keV. The central density is

determined from $\hat{n}_e \bar{r}_p = \int_0^{\bar{r}_p} n_e(r) dr$, where the radial density profile, $n_e(r)$, is obtained by beam-attenuation measurements of $\int n dl$ along 11 chords through the plasma midplane. The mean plasma radius, $\bar{r}_p$, has a nearly constant value of 8 cm. Thus, $\hat{n}_e(t)$ is obtained using neutral-beam attenuation and the phase shift of a 2-mm microwave beam through the plasma diameter to measure $\int n dl$ as a function of time. We obtained the dots in Fig. 6(a) by fitting the observed time dependence of plasma density to a rate equation and accounting for beam attenuation by ionization and charge exchange:

$$\frac{d\hat{n}}{dt} = a(1 - e^{b\hat{n}}) - \frac{\hat{n}^2}{(\hat{n}r)} \quad (3)$$

The coefficient "a" is the beam current trapped per unit volume, with a density dependence calculated for Gaussian plasma and beam profiles. The parameter $b = (\sigma v / (2 \bar{r}_p)) / v_e$ is an attenuation factor averaged over the energy components of the neutral beam. Here, $(\hat{n}r)$ is a density-independent loss parameter appropriate for particle loss by ion-ion scattering and electron drag. For a constant 10% fraction of cold plasma, the best fit of Eq. (3) to the measured density buildup gives a plasma volume $V = 4.5$ litres (defined by $n_e V =$ total number of particles) and $(\hat{n}r) = 1.2 \times 10^{11}$ particles/cm³·s. Averaging over Gaussian radial and longitudinal plasma profiles gives a mean particle-confinement parameter $(n\tau_p) = 4.2 \times 10^{10}$ particles/cm³·s.

Measurements of the energetic charge-exchange neutral flux, deuterium-deuterium (D-D) neutron production, and plasma diamagnetism showed that the observed density buildup [Fig. 6(a)] consisted almost entirely of energetic deuterium ions from beam injection. Charge-exchange neutrals at 11 energies between 0.5 and 39 keV were detected by a mass-selective, fast-atom analyzer that viewed the plasma at 90° in the midplane. Hydrogen was used in the gas feed with deuterium neutral-beam injection so that hot, beam-injected ions could be distinguished from warm ions trapped from the streaming plasma. At the high-density saturation [$t = 4$ ms in Fig. 6(a)], the average charge-exchange neutral energy observed by the analyzer was 13 keV. However, charge-exchange neutrals originating in the plasma center have an energy-dependent attenuation. A lower average ion energy ($\bar{E}_i = 9 \pm 1$ keV) is thus inferred.

The hot deuterium-ion density n_D required to give the measured absolute charge-exchange flux at 90° depends on the ion angular distribution, which was not measured. However, assuming the narrowest ion angular distribution consistent with

Fig. 6. Measurements for gas-stabilized plasma: (a) density, (b) neutron emission, (c) beta.

the angular spread ($\sqrt{\langle \theta^2 \rangle} = 8^\circ$) due to perpendicular beam injection along the plasma length, and accounting for attenuation of the beam and charge-exchange neutrals in the plasma, a lower limit of central deuterium density ($\hat{n}_D \geq 1.0 \times 10^{14}$ atoms/cm³) is estimated for $\hat{n}_e(\text{min}) = 1.2 \times 10^{13}$ electrons/cm³, or $\hat{n}_D \geq 1.7 \times 10^{14}$ atoms/cm³ for $\hat{n}_e(\text{max}) = 1.5 \times 10^{14}$ electrons/cm³. Thus, the maximum fraction of cold ions, hydrogen, and impurities is less than 20%.

Figure 6(b) shows the D-D neutron emission measured by a lead-shielded, plastic-scintillator detector and corrected for background beam-wall target neutrons ($\geq 10\%$). The observed neutrons can originate only from the deuterium plasma component injected by the beams, not from hydrogen ions originating from the gas feed. A similar neutron flux is observed when deuterium is injected in the gas feed. Taking $\hat{n}_D = \hat{n}_e$, the calculated neutron emission is 30% greater than the measured rate. The calculated rate is uncertain by a factor of about two owing to uncertainties in the measured ion energy and density distributions. However, the agreement does support the conclusion that the dominant plasma component is energetic deuterium.

The dashed line in Fig. 6(c) shows the average plasma diamagnetism, $\Delta B/B_{\text{vac}}$, measured by a compensated diamagnetic loop around the vacuum chamber. The excluded flux of the plasma is normalized to the total flux excluded by a field-free metal object ($\Delta B = B_{\text{vac}}$) of the same volume as the plasma, placed for calibration at the position of the plasma. For constant plasma dimensions, the measured diamagnetic flux will be proportional to the average field reduction, $\Delta B/B_{\text{vac}}$, within the plasma. Because of the substantial reduction in field, the mean ion gyroradius is comparable to the plasma radius. Thus, it is not surprising that the frequency of ion cyclotron fluctuations ($\omega \approx \omega_{ci} \pm 10\%$) decreases according to $\Delta B/B_{\text{vac}}$ as indicated by the point labeled $\Delta\omega_{ci}/\omega_{ci \text{ vac}}$ in Fig. 6(c).

The solid line in Fig. 6(c) gives the peak value of $\beta(1)$ obtained from the measured central density, $\hat{n}_D$, and average ion energy, $\bar{E}_D$. Central beta reaches a value well above unity. The indicated error bar is due to uncertainty in peak density and cold-plasma fraction. Because of the short axial length of the plasma ($L_p/\bar{r}_p \approx 3$) and the high plasma pressure, the field lines are likely to have substantial curvature. That is, in the pressure balance relation

$$\nabla (P + B^2/8\pi) = \frac{1}{4\pi} (\bar{B} \cdot \nabla) \bar{B}, \quad (4)$$

the curvature term on the right is comparable in magnitude to $(B_{\text{vac}}^2/8\pi)$ in this experiment. Conse-

quently, a central beta value of roughly 2 is required to depress the field on axis to zero. The average beta, $\bar{\beta}$, would be less than $\bar{\beta}$ because $\bar{n}_D < \hat{n}_D$, averaging over the radial profile.

The average plasma-energy lifetime at high beta can be estimated from the 63% of the incident beam power absorbed in the plasma and from the energy content of a total $\hat{n}_D V$ of ions at $\bar{E}_D = 9$ keV maintained in steady state, with $\bar{E}_e = 14.7$ keV and $I_b = 225$ A:

$$\tau_E = (\hat{n}_D V) \bar{E}_D / (0.63 I_b \bar{E}_e) = 420 \mu\text{s}. \quad (5)$$

At the peak density $\hat{n}_D = 1.5 \times 10^{14}$ cm⁻³, a corresponding energy-confinement parameter $\hat{n}_D \tau_E = 6.8 \times 10^{10}$ particles/cm³·s is obtained. A radial average over a Gaussian density profile indicates a volume-averaged $(n\tau)_e = 3.1 \times 10^{10}$ particles/cm³·s. From Thomson scattering measurements of the central electron temperature $T_e = 60 \pm 15$ eV, an upper limit on energy lifetime of $n\tau_E(\text{max}) = 2.0 \times 10^{10}$ particles/cm³·s $\pm 30\%$ is set by ion energy loss to colder electrons. Thus, the primary ion energy loss can be identified as classical drag on electrons, as is consistent with a quasi-linear theory for marginal stability of the drift-cyclotron-loss-cone mode.⁶

Figure 7 shows the increase of energy confinement and plasma beta with injected neutral-beam current (at constant beam energy $\bar{E}_e = 14.7$ keV). The central value of beta increases with beam current with no apparent saturation. We conclude there is no evidence of a beta limit due to the mirror mode,⁸ Alfvén ion-cyclotron mode,⁹ or non-adiabatic effects,¹⁰ possibly because of the short axial and radial scale lengths of the plasma.

Physical Measurements of Plasma

$n\tau_E$ Scaling with $T_e^{3/2}$. Since the electrons in a mirror machine are much cooler than the ions, one of the important physical processes to understand is the transfer of energy from ions to electrons. In 2X11B, this energy transfer was measured by switching off the neutral-beam input (the energy source thus driving the ions), then observing the decay rate of mean ion energy $1/\tau_E = 1/\bar{E}_e d\bar{E}_e/dt$ while making simultaneous measurements of electron temperature, T_e , by means of Thomson scattering. According to Spitzer, the density $\hat{n}(\text{particles/cm}^3)$, ion slowing-down time $\tau_E(\text{s})$, and electron temperature $T_e(\text{eV})$ are related by $n\tau_E = 4.4 \times 10^{17} T_e^{3/2}$. This formula is valid if all quantities are measured at the same spatial point and if Coulomb collisions govern the energy transfer between ions and electrons.

Fig. 7. Peak values of plasma density, neutron emission rate, and diamagnetic flux (relative units) as functions of neutral-beam current (8000-A atom-equivalent hydrogen gas feed).

Experimentally, the peak density, $\hat{n}$, and electron temperature, $\hat{T}_e$, were measured at the center of the 2XIIIB plasma (measurements of τ_E referred to a spatial average over an ion gyro-orbit). If the analytic form of Spitzer's result is assumed, then one would expect approximately $\tau_E(r=0) = 1/2 \langle \tau_E \rangle_{\text{orbit}}$. The factor one-half was calculated by averaging over a mean ion gyro-orbit, taking into account the radial density profile and variation of electron temperature with radial position. Accordingly, we plotted (Fig. 8) the experimentally measured product, $1/2 \hat{n} \langle \tau_E \rangle_{\text{orbit}}$, versus the electron temperature, $\hat{T}_e$, measured at $r=0$. From the agreement between the Spitzer curve and the plotted data, we concluded that energy transfer from ions to electrons was predominantly by means of Coulomb collisions. At the end of the previous subsection, a power-balance calculation of the gas-stabilized plasma indicated that the bulk of the ion energy loss

could be attributed to classical electron drag using the Spitzer relation.

Experimental Evidence that Plasma Stabilizes Turbulent Ion Energy Diffusion. To scale 2XIIIB stream stabilization to larger experiments, we needed a valid physical model of the stabilization process. The quasi-linear theory of the drift-cyclotron loss cone (DCLC) mode in mirror machines provided such a model.⁶

According to quasi-linear theory, a mirror plasma evolves to a marginally stable state by filling in the ambipolar hole of the ion energy distribution. Warm plasma filling the ambipolar hole can be supplied either by turbulent diffusion from the hot-ion population at the expense of confinement or by an external plasma stream, in which case hot-ion confinement improves. For this stabilization study, we present experimental data and the results of a detailed quasi-linear code calculation. These show

Fig. 8. Ion cooling rate.

that ion energy diffusion increases markedly when the external source of warm plasma is turned off.¹¹ The agreement between the experimental data and the quasi-linear calculation lend confidence to the use of quasi-linear theory to scale 2X11B results to larger experiments.

Figure 9 shows plasma line density versus time as measured by 2-mm interferometry. The density built up in the manner described in a previous subsection ("Plasma-Confinement Experiments With Gas-Feed Stabilization"). The plasma line density reached a steady-state 4.3×10^{14} ions/cm², then the external source of warm plasma was turned off. Neutral-beam injection continued for 0.80 ms after the stream terminated. The plasma line density decayed (with a 0.38-ms time constant) after the stream shut off. These data were taken with 250-A equivalent of injected deuterium-atom current with a mean injected-atom energy of 13.1 keV. The plasma parameters were mean ion energy = 11 keV; electron temperature $T_e = 60$ eV; and mean plasma radius = 7 to 8 cm.

Since neutral-beam input matched the plasma loss rate before the stream was turned off, the 0.38-ms decay rate could be explained by an increase in ion energy diffusion. However, other ion-transport processes that compete with wave diffusion should be kept in mind. Roughly, the time scales for competing processes are (1) ion energy loss by electron

drag, $\tau_{ie} = 1.6$ ms; (2) charge-exchange replacement of a plasma ion by a beam-injected atom, $\tau_{cb} = 0.2$ ms; (3) hot ion loss by charge exchange on cold background gas, $\tau_{cg} = 0.9$ ms; and (4) ion-ion scattering into the velocity space-loss cone, $\tau_{ii} = 8.0$ ms.

The ion energy distribution function was measured by recording deuterium charge-exchange flux at 12 discrete energies: 0.50, 0.70, 1.0, 1.4, 1.8, 2.7, 3.7, 5.9, 9.3, 17, 25, and 39 keV. The fast-atom analyzers viewed the plasma near 90° to the magnetic field lines and consequently measured a perpendicular energy distribution, $f(E_{\perp}, E_{\parallel} = 0, t)$. The measurements were, therefore, sensitive to diffusion by electrostatic waves polarized perpendicular to the magnetic field, such as modeled by the DCLC dispersion relation. Figure 10 presents charge-exchange flux signals for four of the fast-atom channels and compares them to the results from the quasi-linear diffusion code.¹² Calibrations of the absolute flux of the 25- and 39-keV experimental data in Fig. 10 are not available. For this reason, we normalized each of the theoretical curves in Fig. 10 to the experimental data at 3.8 ms.

In Fig. 10, we see that the overall experimental change in the particle distribution is reproduced by the theoretical simulation. In both theory and experiment, we see that at 17 keV and below, the termination of the plasma stream causes an immediate decrease in the distribution function, while above 17 keV there is an increase in the ion distribution. This effect is explained by an enhanced diffusion occurring from an increased turbulence level, which causes a particle flux from the bulk of the plasma

Fig. 9. Plasma line density buildup and decay.

Fig. 10. Ion energy distribution at four energies (when stream injection terminates).

downward into the ambipolar hole and upward into the high-energy tail. The results are particularly dramatic in the 25- and 39-keV channels, which initially show a large absolute increase in magnitude. The subsequent decrease of 0.3 to 0.4 ms after the stream turnoff arises as the loss rate causes the distribution to decay in all channels. Further, both experiment and theory show ~0.10-ms time delay in the increase of the 39-keV signal compared to 25 keV. This is evidence of ion diffusion upward in energy from the bulk of the ion distribution.

The diffusion coefficient, $D(E_1) = (\Delta E \cdot \Delta E) / \tau_D$, matching the data can be obtained from the com-

puter code. For $E_1 \lesssim 1$ keV, we find that the steady-state values of $D(E_1)$ before and after the stream is turned off are given by

$$D(E_1) = \frac{6.6 \times 10^5}{E_1^{1/2}} \text{ keV}^2/\text{s}, \text{ and}$$

$$D(E_1) = \frac{23.0 \times 10^5}{E_1^{1/2}} \text{ keV}^2/\text{s}, \quad (6)$$

with E_1 measured in keV. With the stream on, a finite $D(E_1)$ is needed to heat the streaming plasma so it fills in the region below the ambipolar-hole energy. This is a requirement of marginal stability.

As a consequence of the correlations between the experiment and the theoretical simulation, we conclude that the enhanced turbulent diffusion of particles into the ambipolar hole causes the observed density decay in Fig. 9.

The results of this and a preceding section on gas-fed stabilization give experimental evidence to support the two most important terms in the quasilinear equation describing ion transport.

Measurement of Plasma Spatial Profiles. Plasma volume is an important physical parameter, because it enters the power-balance and density-buildup equations used to determine energy and particle confinement. For our purposes, plasma volume, V_p , is defined by the integrated plasma density

$$\hat{n} V_p = \hat{n} (\pi R_p^2) L_p \approx n(x) \frac{B(x=0)}{B(x)} d^3 x, \quad (7)$$

where $\hat{n}$ is the peak plasma density. V_p is the equivalent cylinder volume the plasma would occupy, if the density was uniform and equal to the peak density and B was uniform and equal to the central value.

At the vertical plasma midplane $z = 0$ in Fig. 11, plasma profiles in the horizontal x -direction were measured by Thomson scattering, microwave interferometers, and a movable charge-exchange analyzer. See Fig. 12(a) for a sample of these data. The solid line is a parabolic fit to interferometer measurements at $x = 0$ and $x = 7$ cm. The dashed curve through the 17-keV charge-exchange data is a Gaussian $\exp[-x^2/(7.35)^2]$. The height of the charge-exchange flux profile was scaled to match the interferometer data. The plasma density profile in the y -direction was calculated from neutral-beam attenuation measurements along 13 chords. We obtained the density profile in Fig. 12(b) by Abel inversion of the line-density data measured directly by the probes. The dashed line is a best-fit Gaussian. From the combined measurements in Figs. 12(a)

Fig. 11. Coordinate system for plasma density profile measurements.

and (b), the transverse dimensions of the plasma at $z = 0$ are nearly equal, and the radius of an equivalent plasma cylinder,

$$R_p = \frac{1}{\pi n} \left[\int_0^\infty n(r) 2\pi r dr \right]^{1/2} = 7.35 \text{ cm} \quad (8)$$

for these data.

We obtained longitudinal density profiles with 2-mm and 4-mm microwave interferometers fixed at $z = 0$, a 4-mm interferometer movable from $z = 0$ to 130 cm, 4-mm and 3-cm interferometers at $z = 160$ cm, and a Langmuir probe at $z = 160$ cm.

To determine the density profile, we assume the plasma cross section follows a magnetic-flux surface. The axial density profile appears in Fig. 13. The data for $z > 0$ have been measured several times, whereas the data for $z < 0$ have been measured only once. For comparison, we show the "Holdren" collisional distribution, which is considerably broader than the measured distribution. We primarily determine measured distribution by the angular distribution of the injected neutral beams. This is expected, because the characteristic time scale for charge-exchange replacement of the plasma ions with beam-injected atoms is short com-

pared to classical ion-ion scattering times. Assuming that the hot-plasma ion distribution is symmetric about $z = 0$, we calculate the length, L_p , of the equivalent plasma cylinder:

$$L_p = \frac{1}{n} \int_{-\infty}^{+\infty} n(z) \frac{B(z=0)}{B(z)} dz = 35 \text{ cm} \quad (9)$$

from the data in Fig. 13. The length of the plasma is therefore considerably less than the 150-cm distance between mirrors, and the velocity distribution is highly peaked perpendicular to the confining magnetic field. The axial measurement of plasma density in Fig. 13 can be used to calculate the hot-ion angular distribution. For the data in Fig. 13, the angular half-width at half maximum is about 14° .

Characteristics of the Plasma Stream. We will now describe the plasma stream, including measurements of its electrical-gun characteristics, electron temperature, density profiles, and end-loss. Figure 14 shows the locations of diagnostics used for these purposes. The streaming-plasma gun is a standard deuterium-loaded, titanium-washer gun driven by either a 20-kV, 2- Ω LC pulse line or a 3-kV, 0.2- Ω LC pulse line.¹¹

For the 20-kV, 2- Ω pulse line, the current to the gun is typically 4750 A at 230 V, giving an electrical power input of about 1 MW. With a 0.2-T guide

Horizontal

Vertical (at high density)

Fig. 12. Horizontal and vertical plasma density profiles at midplane. (a) Horizontal plasma profiles obtained by microwave interferometry, Thomson scattering, and 17-keV charge-exchange flux measurements. (b) Vertical plasma profile obtained by beam attenuation.

field, about 0.3 MW of plasma power has been collected by a calorimeter on the other end of the machine, 7 m away. This streaming-plasma gun output power (mainly into electrons) compares to the

power transfer to plasma electrons by hot ions slowing down.

To determine if the gun alone could heat electrons, we used the 0.2-T dc guide field to measure

Fig. 13. Axial plasma density profile.

the streaming-plasma gun firing at the west mirror. Thomson-scattering measurements made between gun and mirror indicated a 40-eV electron temperature and a density of several times 10^{13} electrons/cm³. In the dc field alone, without the mirror, Langmuir probe measurements indicated a lower electron temperature and lower density. The density and electron temperature increased when a mirror was added; both increased still more when hot plasma was present.

The external plasma density decreased rapidly (Fig. 14) with the increasing magnetic field in the mirror region. The mirror presumably reflected the ions. Ion cyclotron fluctuations (driven by the hot plasma) extending into the end region could aid reflection at the external ion-resonance zone.

The end-loss analyzer measured the total current through the mirrors (end loss plus streaming).

The spread in end-loss ion energy typically was several hundred eV; plasma potential was ~240 eV. From the end-loss measurement, we estimated the central density of isotropic warm plasma to be 3 through 10×10^{11} particles/cm³. For a trapped density of 1×10^{13} particles/cm³, this corre-

sponded to ~3 to 10% of the trapped energetic density.

A picture emerged from our measurements: the streaming-plasma gun generated a stagnant reservoir of plasma outside the mirror with a density of 10^{14} particles/cm³ and an electron temperature of ~40 eV. Ions and electrons were contained for several transit times between gun and mirror. Stream density was attenuated in the mirror throat, allowing an electron temperature in the confinement region between mirrors to exceed that in the external plasma.

Plasma/Wall Charge-Exchange Interactions

The basic process for wall bombardment by energetic charge-exchange atoms^{14,15} appears in Fig. 15(a). Neutral-beam injection into the plasma resulted in energetic charge-exchange products bombarding the wall. Backscatter of primary atoms or gas released from the walls could cause charge-exchange loss on the plasma surface if it were not pumped away. To reduce the amount of particle

Fig. 14. Location of diagnostics used to study the plasma stream.

Fig. 15. Plasma charge-exchange interaction with vacuum-chamber wall. (a) Cold gas penetrates directly to the interior. (b) A boundary layer shields the cold gas from the interior.

reflux and gas release, we gettered the walls before each shot with several monolayers of titanium. This produced a cleaner surface with the ability to adsorb energetic atoms.

Our calculations below show that if hot ions are lost at a rate equal to the charge-exchange loss rate on background gas, the experimental measurements of buildup of hot-plasma density cannot be explained. This suggests that the hot interior is shielded from the cold gas by a region of lower density and lower temperature plasma [Fig. 15(b)]. The required particle confinement in this shield is $\sim 10^9$ particles/cm³·s.

The charge-exchange flux peaks near 90° because the plasma ion distribution peaks near 90° to the magnetic axis as discussed in a previous section ("Measurements of Plasma Spatial Profiles").

The neutral charge-exchange flux from the plasma surface is measured by an 11-channel analyzer from 0.5 through 39 keV. Figure 16 shows the measured increase of flux due to background gas for 260 Å of injected neutral-beam current. The background gas creating the charge-exchange flux in Fig. 16 is produced by wall reflux of plasma ions, which charge exchange on the neutral-atom beam.

To a good approximation, the background gas density, n_0 , increases as

$$V \, dn_0/dt = \Gamma(I_{cx} + \frac{1}{4} n_0 v_0 A_p \sigma_x / \sigma_T) - \frac{1}{4} n_0 v_0 A_{pump} \quad (10)$$

where V is the volume filled by the gas with speed v_0 . The reflux coefficient, Γ , is the number of atoms from the wall per incident energetic charge-exchange atom. The first term in the parenthesis, I_{cx} , is the charge-exchange current from the neutral beam on the hot plasma, whereas the second term is the charge-exchange current from background gas at the plasma surface. The effective pumping area for cold gas is $A_{pump} = A_p + s_w A_w + A_x$. Here A_p , A_w , and A_x are the areas of the plasma surface, wall, and external-pumping opening; and s_w is the wall-sticking coefficient. Charge-exchange and total ionization cross sections for cold gas are σ_x and σ_T . The source of cold gas is wall reflux of energetic charge-exchange neutrals; pumping is by gettered walls and ionization by the plasma. Ionized gas is assumed to flow along field lines and out the mirrors into the end tanks.

We fit the buildup of charge-exchange flux predicted by Eq. (10) to the data with the curve in Fig. 16. In the limit of a perfect beam dump (i.e., untrapped beam current does not cause gas reflux),

we fit the measured data with $\Gamma = 1.5$ and v_0 corresponding to $E_0 = 14$ -eV deuterium.

We estimated the expected reflux coefficient by averaging the backscattering coefficient, which is a function of energy, over the measured energy distribution of the particles bombarding the surface. For a typical 2X11B energy distribution bombarding a clean titanium surface at perpendicular incidence, this coefficient is estimated to be 0.15. The higher values needed to match the experiment are attributed to the angular dependence of backscatter coefficient and to release of gas from the surface.

A radial buildup code¹⁶ (BUILDUP III) computes time-dependent radial density profiles created by injection of neutral beams. This code balances the neutral-beam input with particle losses due to Coulomb losses and erosion of the plasma boundary by background gas.

The dashed curve in Fig. 17 shows a computed radial profile with $\Gamma = 0$. The normalized profile is insensitive to charge-exchange losses, because plasma size is determined by beam geometry and plasma-ion Larmor radius. Also plotted in Fig. 17 is a typical profile measured by neutral-beam attenuation through several plasma chords for similar plasma conditions and a Langmuir probe density measurement at 20 cm. The measured and computed profiles are in agreement.

Loss rates by charge-exchange compare to beam-trapping rates for the value of reflux coefficient inferred from the experiment. Consequently, the calculated time dependence of plasma buildup strongly depends on Γ , as shown in Fig. 18. For these calculations, the computed buildup is insensitive to $n\tau$ for $n\tau > 4 \times 10^{10}$ particles/cm³·s. An important result of the calculation is that good agreement between the experiment and calculation can be obtained only if charge-exchange losses on

Fig. 16. Measured and calculated charge-exchange flux.

Fig. 17. Measured and calculated radial density profile normalized to central density.

cold gas are neglected when beams are on during buildup. The calculated dashed curves appear in Fig. 18 along with the line density measured by microwave interferometry (solid curve). However, if gas losses are included after beams are turned off, agreement is obtained for the plasma decay rate for values of Γ consistent with Fig. 16, as shown in Fig. 18. These calculations suggest that the plasma is shielded from cold-gas losses when beams are on.

Langmuir-probe measurements indicate the presence of a plasma density in the 10^{11} particles/cm³ range with 16-eV electron temperature at a 20-cm radius. To attenuate several-eV energy neutrals, a line density of $\sim 10^{13}$

particles/cm² is sufficient. For a central density, $n(0) = 5 \times 10^{13}$ particles/cm³, the plasma is one mean-free-path thick to the gas at $r = 12$ cm (Fig. 17).

The sources of particles and energy for the shield are not clearly evident. However, the following picture is consistent with our present measurements. The cold gas and the plasma stream supply particles to the shield. With beams on, the residual ion cyclotron turbulence level is sufficiently high to heat and mirror-trap some of these cold ions. Electrons are heated by these ions as well as by neutral-beam-injected ions trapped in the gas shield. When beams are turned off, the turbulence level decreases and

Fig. 18. Measured and calculated plasma line density buildup with 260-A, 14-keV neutral-beam injection.

the lifetime of cold ions in the shield is too short to maintain a sufficient density to attenuate the cold gas. Langmuir-probe measurements indicate that the shield decays rapidly when the beams are turned off. The hot plasma then decays by charge-exchange erosion at the expected rate (Fig. 18).

Neutral-Beam System

The neutral-beam system, consisting of 12 individual modules, has played a central role in obtaining the experimental conditions described earlier. The neutral beams and power supplies, developed at Lawrence Berkeley Laboratory (LBL)¹⁷ have been debugged and improved by a continuing effort by LBL and Lawrence Livermore Laboratory (LLL). The following paragraphs describe the steps taken to improve the neutral-beam system. These steps aim to reach new physical conditions in 2XII-B, improve reliability, reduce replacement cost, and increase the ease of day-to-day operation.

Of the 12 high-voltage power supplies, 6 have been upgraded from 20 kV to operate sources from 30 through 40 kV. One of these six power supplies is a new configuration with components rearranged to provide better voltage holding and reduce cross-talk between modules.

We constructed six new grid sets for operation at 35 through 40 kV by using a simpler and more rugged support structure than before. Machinable glass ceramic insulators replaced the epoxy-fiberglass insulators of the earlier versions. The improved stability of these new grid sets simplified grid assembly and alignment, and consequently reduced the cost of a grid set by a factor of three.

For extraction voltages exceeding 20 kV, the existing air gap between a beam module and its magnetic shield will not hold voltage. To increase the gap dimension would waste space and reduce the number of modules we could install on 2XII-B. Accordingly, we built plexiglass enclosures that

sealed the source in a sulfur hexafluoride atmosphere; these were successfully used up to 38 kV.

The control circuits required for computer control of the neutral beams were developed. Using a simple control algorithm, the computer successfully ran a single-beam module. The algorithm is being improved to control all 12 beams.

Neutral-beam current injected into 2XIBB was measured with a retractable 10-cm $\times$ 25-cm calorimeter. The neutral-beam computer routinely processed calorimetry data, displaying the injected current and the horizontal and vertical beam profiles. A new calorimeter head with nine horizontal and five vertical segments was installed to improve spatial resolution. This allowed operators to accurately aim the beams and minimize beam divergence by adjusting source parameters. We developed a laser alignment technique to further aid beam aiming. For the initial alignment, a laser mounted in a socket on the back of a beam module

projected backward onto a target. This initial step aligned the beams to within ± 1 cm vertically and ± 5 cm horizontally with the machine's centerline. Final alignment with calorimeter measurements, usually accomplished in a single step, eliminated the problem of backlash in the alignment screws.

As an aid to plasma diagnostics, we built a control circuit to modulate all or some of the beam modules on and off simultaneously. This allowed the hot deuterium plasma fraction to be inferred from the change in energetic charge-exchange flux leaving the plasma surface and from the measurement of decaying plasma parameters in brief periods of a few hundred microseconds after beam turnoff.

Plasma Diagnostic Development

The past year has seen continual improvements and additions to the diagnostic system. Figure 19 shows the location of most of the present diagnostic

Fig. 19. 2XIBB plasma diagnostics.

equipment. What follows cites improvements in the charge-exchange analyzer and laser diagnostics. Also, we describe the new beam-attenuation detectors and electrostatic end-loss analyzers.

Charge-Exchange Analyzer. We developed a new method of calibration and added four new channels to the charge-exchange analyzer. The new system comprised a large 15-channel analyzer and a new single-channel calibrated instrument that could be programmed to coincide with any channel of the larger instrument. The calibrated single-channel analyzer and the multichannel analyzer could view the same volume of the 2X11B plasma.

The calibration scheme consisted of taking shots with the single-channel analyzer set to correspond successively to each channel of the multichannel analyzer. We then calibrated the multichannel analyzer from the signal ratios of these shots and the measured calibration curve of the single-channel analyzer. At a modest increase of complexity, this scheme reduced the time required to calibrate the multichannel analyzer. Thus, by using the single-channel analyzer as a standard, we could repeat the calibration on each run rather than once every few years. Furthermore, calibration of the single-channel analyzer was simpler, and the results were believed to be more reliable than the previous scheme of separately calibrating each channel of the multichannel analyzer with an atomic-beam setup. Neutral-beam injection into the high-energy tail of the ion-distribution function necessitated adding the four additional channels to get a more accurate measurement of ion distribution. The 15 channels could be simultaneously set at the following energies: 0.46, 0.65, 0.88, 1.27, 1.81, 2.67, 3.89, 4.84, 5.90, 7.44, 9.72, 13.01, 17.94, 26.98, and 44.46 keV. (The new channels are italicized.) In addition, the 44.46-keV channel was not previously calibrated; so, in effect five new channels were added.

Figure 20 sketches the calibration setup, which shows the single-channel analyzer. The multichannel analyzer consists of a nitrogen-gas stripping cell, an analyzing magnet for momentum analysis, 90° parallel-plate electrostatic analyzers for energy analysis at each magnet output port, and Daly-type secondary electron-scintillator-photomultiplier detectors.

A combined momentum-energy analysis allowed the multichannel analyzer to be tuned for particular mass species. The single-channel analyzer had a similar gas stripping cell and Daly detector; but it was only a single-stage electrostatic analyzer instead of a tandem magnet-electrostatic analyzer. An rf ion source provided a convenient controlled source of charged and neutral atoms for the calibration. We

obtained calibration data for both hydrogen and deuterium.

Neutralization in the streaming gas flowing out of the ion source was sufficiently efficient, so an added neutralization cell was not needed. The ion-source aperture was the same distance from the stripping cell's entrance aperture as from the plasma when we installed the analyzer on 2X11B. Neutral currents incident on the stripping cell were inferred from measurements of secondary-emission coefficient and current on the Faraday cup-gridded analyzer with the stripping cell pumped out. We then measured the calibration factor (specifically, the ratio of detector signal to neutral current entering the stripping cell) by leaking nitrogen into the stripping cell at a regulated pressure. The solid-angle acceptance of the analyzer was measured by pivoting the rf ion source about the entrance to the stripping cell; energy resolution was measured by sweeping the plate voltage on the electrostatic analyzer.

Given a set of voltages $[V_i]$ from the photomultiplier output, with the analyzer set to correspond to energies $[E_i]$, we computed the energy spectrum according to

$$F(E_i) = \frac{1}{(\sigma v)_i} \frac{C(E_i)}{g_i} V_i. \quad (11)$$

Reaction rate $(\sigma v)_i$ is the energy-dependent charge-exchange rate for producing a neutral at the plasma surface. $C(E_i)$ is the analyzer calibration factor, taken at a photomultiplier voltage of 2000 V; g_i is the photomultiplier gain relative to 2000 V. The $C(E_i)$ data for deuterium, obtained from calibration of the single-channel analyzer, appear in Fig. 21. The differential charge-exchange flux leaving the plasma surface is given by

$$\frac{d^2\phi}{dE d\Omega} = \sum_i \frac{C(E_i)}{g_i} V_i. \quad (12)$$

When installed on 2X11B, the lines of sight through the multichannel and single-channel analyzer stripping cells lay in the same vertical plane perpendicular to B. We mounted the analyzer array [~ 1814 kg (~ 4000 lb)] on rails to measure the radial distribution of charge-exchange flux and ion energy.

Improvements in Thomson-Scattering System. Thomson scattering of ruby-laser light has been used for several years to measure electron temperature and density in the 2X11 and 2X11B series of experiments. We infer electron temperature from the Doppler profile of the scattered light and electron density from the intensity of scattered light. The setup in Fig. 19 consists of a 6-J pulsed ruby

Fig. 20. Neutral-analyzer calibration setup.

Fig. 21. Single-channel analyzer calibration factor for detection.

laser and an optical system that views the laser beam at three plasma radial positions ($r = 0, 4$, and 8 cm). Scattered light from the $r = 0$ -cm position is directed through a grating spectrograph. Interference filter polychromators analyze light from the $r = 4$ -cm and 8 -cm positions. Gated photomultiplier tubes detect the scattered light signals; a photodiode monitors laser output.

Although Thomson scattering is a routine plasma diagnostic, the system described above has not been wholly reliable. Several improvements and modifications are currently nearing completion. These include the following:

Ruby Laser. The reliability of the ruby laser has been improved by replacing the oscillator head, more carefully controlling the flash-tube drive risetime, and making several minor modifications. Also, we have developed a technique for optical alignment of the laser with the 2X11B machine under vacuum.

Spectrograph. The surface quality of the grating in the spectrograph deteriorated, causing high background and low-output levels. We replaced this grating with a new one blazed near the ruby wavelength. Also, we coated the internal mirrors with a dielectric.

Data Analysis and Calibration. Probably the biggest improvement to the ruby-laser system involved data-analysis and calibration methods. Previously, oscilloscope photographs recorded the phototube outputs. We then manually measured these and made a graphic analysis. This procedure was laborious, time-consuming, and error-prone. Moreover, we had no reliable error estimates for the results. Phototubes were calibrated only periodically, thus they were possibly subject to drift. We corrected these difficulties with an improved data-handling system (Fig. 22). In this system, a computer analyzed all data; nine calibrations were performed for every shot. The system also automatically determined error estimates for the results. Phototube outputs drove gated integrators, which in turn were coupled to a multiplexer, analog-to-digital converter, computer interface, and HP-2100 computer.

We used two sets of integrators. The first set was gated on for 100 ns during the ruby-laser pulse; the gate pulse for the second set was delayed by 150 ns to sample the ambient plasma-generated background light. A master control system (sequence controller) executed the following sequence: after the laser shot, a 200-ms delay ensured time to allow the plasma light to decay. We again gated the system to measure the system's dark-current backgrounds. Next, a shutter opened

in front of a standard lamp, and the system gated 15 more times to calibrate the photomultiplier sensitivities. The variation between these 15 measurements could be used to derive an error estimator for the laser-shot measurement. Finally, we issued a reset pulse; the shutter closed, and the system was ready for the next 2X11B data shot.

Once the data was transferred to the computer, considerably more data analysis could be done than previously possible. For example, we used more accurate data-fitting algorithms. These detected bulk motion of the electrons and their thermal spread of velocities. Since we measured backgrounds and laser output for each shot, we could properly treat the error analysis. Data processing took only a few seconds of computer time, with most of this involved in plotting and program overlays. The output results included $n_e(r)$, $T_e(r)$, Spitzer drag time, and bulk electron velocity plus error estimates for each of these.

Beam-Attenuation Detectors. At present, accurate measurements of plasma radial profiles can be obtained with an array of beam-attenuation probes. Data from these probes are in an earlier subsection ("Measurement of Plasma Spatial Profiles"). A schematic of a single probe of the 13-channel radial array appears in Fig. 23. The probes are mounted opposite one of the neutral-beam modules. Neutral atoms that penetrate the plasma and pass through the collimators are detected by secondary electron emitter-collector-type detectors. The collimators give the probe resolution function a full-width half-maximum of 8 mm at the plasma. The probes are all aligned to point at a single spot near the center of the neutral-beam extractor; atoms detected by adjacent probes pass through chords of the plasma separated by 2 cm. The entire array is aligned under vacuum by using (1) a probe fitted with a light pipe and photomultiplier detector and (2) a filament lamp that can be popped up in front of the neutral beam.

We obtain radial profiles of plasma density by computing the fraction T of neutral beam transmitted through the plasma from probe currents recorded with and without plasma present. For the i^{th} probe, the beam transmission T_i is related to line density along a chord through the plasma ($\int n dl$), by

$$T_i = \exp \left[-\sigma_{\text{eff}} \left(\int n dl \right)_i \right] \quad (13)$$

The effective cross section $\sigma_{\text{eff}} = 1.54 \times 10^{-15} \text{ cm}^2$ represents plasma conditions. If we plot line density as a function of probe position, we obtain radial density profiles [such as shown in Fig. 12(b)] by Abel inversion.

Fig. 22. Ruby-laser data-handling system.

Fig. 23. Beam-attenuation probe.

In addition to providing plasma density profiles, the beam attenuation probes provided useful measurements of line-density-supplementing microwave measurements. We installed a new axial array of beam-attenuation probes to measure the axial-density distribution from $z = +5$ through -25 cm.

End-Loss Measurements. We developed a gridded retarding-potential analyzer for end-loss measurements. This diagnostic provided measurements of the magnitude and energy distribution of the streaming plasma, which stabilizes the mirror-confined plasma. For an example of data obtained from the end-loss analyzer, see Fig. 24 (where the streaming-current density J_0 , measured by the analyzer, is plotted vs $nT_e^{3/2}/E_p$). The magnitude of this current is consistent with the scaling and magnitude predicted by quasi-linear theory.⁶

Figure 25 has a diagram of the analyzer in simplified form. We designed it to satisfy the following criteria while it operates in an axial magnetic field:

- Entrance grids must have low transmission so that the Debye length inside the analyzer exceeds grid spacing and so that collected current is less than the space-charge limit.
- Angular acceptance must be larger than 25° so that ions lost by small angle-scattering at the loss-cone angle will be collected.
- The radius of the ion- and electron-repeller grids must exceed the radius of the entrance aperture by two ion gyroradii so that all ions reaching the entrance grid have equal probability of passing through the grids to the collector. The present

device satisfies this criterion for deuterons with energy $E \leq 10$ keV.

- The collector must be smaller in radius than the electron repeller grid so that secondary electrons from the grid support cannot reach the collector by following magnetic field lines.

Data-Acquisition System

Our computer system comprises diagnostic data acquisition and processing, neutral-beam control, and machine-control subsystems. The diagnostic subsystem will be described here. The neutral-beam control subsystem got brief mention in a previous subsection ("Neutral-Beam System"); the machine control subsystem was described in last year's annual report.¹

During the first year of 2XIIB operation, the diagnostic subsystem routinely acquired and processed data from 15 through 17 separate measurements using 30 through 35 signal channels. This was a data base of ~ 43 thousand words/shot. However, intershot processing and display was limited to two through four separate diagnostics owing to a rather primitive operating system and a slow data-transfer rate of the available output devices. Bulk data analysis had to be performed at the end of a day's run.

The principle new development during the year was the implementation of a real-time-executive (RTE) operating system and program structure on the diagnostic computer. This involved revision of the data protocols, programs, and file structure, as well as the addition of numerous utility routines.

Fig. 24. End-loss streaming-current density. Measured streaming current is consistent with scaling and magnitude from quasi-linear theory.

The system now has the following features:

Data Acquisition/Processing.

- Data is taken automatically upon shot interrupt, then processed and plotted with minimal operator intervention.

- Intershot processing and graphics operate as a batch job and are independent of data acquisition. Processing continues after a shot interrupt until the current "last shot" data have been dealt with.

- Users may interact directly with the system to reprocess data or to reexamine processed data in a variety of formats.

- The system supports up to 30 different diagnostics on 90 signal channels, a 200-thousand-word/shot data base, and 5 cathode-ray-tube (CRT) user terminals.

- The diagnostic data system is easily modified. Individual processing and command files exist in modular form for quick insertion or deletion from the system.

General System.

- Multiple users (up to five) are allowed. Priorities may be set so that background operations (programming, editing, etc.) are interrupted for shot-data acquisition and processing.

- A data-oriented graphics package allows for flexible interactive or batch output to various devices from one command string.

- A set of system utilities allows the interested user to construct his own processor with the correct system calls and procedures.

- A 1200-Baud CRT link to the MFE program's PDP-10 is installed and operable.

Several improvements are presently being implemented or are planned for next year. A high-speed data link to the PDP-10 should become operable, allowing a good deal of background processing load to be shifted to that machine. The data subsystem should be modified with a 65-thousand-word central processing unit (CPU) acting as diagnostic processor and executive for the whole 2X11B computer system. The present CPU would become dedicated to diagnostic data acquisition and storage. Software will be written to use the present links with the other 2X11B computer subsystems. Recent developments in data manipulation

that use table-driven or signal-addressed schemes plus a reexamination of our disc data-file protocols indicate that intershot processing throughput may be increased by factors of 5 through 20. These changes will have a strong impact on the architecture of future data systems.

Engineering Support

Electrical. Electrical engineering supported improvement of the neutral-beam system, development of the data-acquisition system, and design and construction of a new "flat-top" power supply for the Yin-Yang coil set. Since our work on neutral-beams and data acquisition was described earlier in the subsections on these systems, we will focus on the flat-top power supply here.

Before installation of the flat-top power supply, the power supply for the Yin-Yang coil set consisted of a 20-kV, 17- μ F capacitor bank and a crowbar switch [Fig. 26(a)]. After the capacitor bank triggered the current in the magnet, the coil reached a peak in 600 μ s, at which point the crowbar switch was triggered and the coil current decayed exponentially with a 10-ms inductance/resistance (L/R) time. After 2X11B successfully demonstrated plasma stabilization, it became desirable to do experiments in a continuous field. Accordingly, we replaced the crowbar switch with the flat-top power supply [Fig. 26(b)].

This power supply operates in two modes. In the first mode, the capacitor bank is triggered and the coil current peaks at 600 μ s, as before, then decays with a 24-ms L/R time. In the second mode, the coil current stays constant for 10 ms, then decays with a 24-ms L/R time. A string of 40 diodes across the coil and the capacitor bank replaces the crowbar switch. The string begins to conduct as the voltage across the coil swings through zero, thus clamping the voltage and preventing ringing oscillations between the capacitor bank and coil set. Now, however, added current can be injected into the coil for 10 ms to compensate for the L/R decay. We accomplish this by periodically triggering capacitors connected in parallel with the center diodes of the diode string [Fig. 26(b)]. In the first mode, the capacitors in the flat-top power supply are not charged and the coil current decays with a 20-ms time constant; in the second mode, the capacitors are charged and the coil current stays constant for 10 ms.

Mechanical. Mechanical engineering directed its support toward diagnostic design, neutral-beam injector modifications, and improvements to the vacuum system. Our major diagnostic design effort went into the calibration test stand for the neutral

Fig. 25. This gridded end-loss analyzer measures end loss from dense mirror plasma.

(a) System without flat-top power supply

(b) System with flat-top power supply

Fig. 26. Yin-Yang power supply (a) without flat-top power supply and (b) with flat-top power supply.

analyzer, the modifications required for adding new channels, and the rail support structure required for making radial scans of ion energy (described earlier in the diagnostic subsection, "Charge-Exchange Analyzer"). The major work on neutral-beam injectors concerned development of a new grid structure that used machinable glass-ceramic insulators (described earlier in the neutral-beam subsection).

With the present vacuum system, we anticipate that the confinement time of long-pulse experiments, made possible by the addition of the flat-top power supply described above, will be degraded by charge exchange on deuterium gas streaming in from the neutral-beam injection tanks. So, we designed and fabricated liquid-nitrogen-cooled (LN-cooled) liners for these tanks. The LN-cooled

surfaces should reduce the gas flow reaching the plasma because of increased sticking probability and a higher wall-saturation limit compared with room-temperature surfaces.

Baseball II-T Experiment

Introduction

We developed, installed, tested, and compared two different target plasmas during the reporting period. Early 2XIIB experiments indicated that a streaming plasma created by its standard plasma guns^{13,14} would be sufficient for buildup with high-intensity neutral beams. We therefore installed and operated one of these guns on the Baseball II-T experiment. The result was gun operation similar to

that on 2X11B. This report contains more details of these experiments; complete details will be in a final Baseball II-T report being prepared. It appears that this plasma source is satisfactory for a target. The hot-plasma density achieved with the available 50-A neutral-beam module was relatively low as expected. Some evidence indicates that the hot-plasma density was $\sim 10^{12}$ particles/cm³. Since this is 10% of the streaming-plasma density, it makes an accurate measurement difficult.

Because the additional neutral beams needed to reach higher densities were not yet available, we continued development of the laser-initiated target plasma. During the early part of this period, we successfully completed the development of the ammonia (NH₃) generation-and-guidance system in a side experiment. The early-guidance system¹⁸ was sufficient to reduce the spread in the position of the NH₃ pellets to 0.5-mm radius. This residual spread probably owes to a variation in the charge-to-mass ratio of the pellets. We had intended to study the interaction of the 30-J carbon dioxide (CO₂) laser with NH₃ pellets before moving the system to the vacuum chamber. However, the NH₃ corroded the chrome-plated steel used for thermal ballast in the heat exchanger. This meant extensive repair of the pellet-generator system. So we began installation of a new apparatus on the main chamber in January 1976.

Figure 27 shows the final system. The pellet generator required only relatively minor design changes when moved to the main chamber. We installed a new set of detectors for the guidance system. Furthermore, we modified all the external electronics to use a new, faster, 12-bit computer (LSI-11). This computer was fast enough for us to measure the charge-to-mass ratio of each pellet and include it in the correction voltage. However, this measurement required the installation of a third detector (which made alignment much more difficult). Consequently, we felt that this refinement should not be included in the first experiments.

We initially installed the pellet system on the main chamber, which lacked the magnet. This permitted checkout of both pellet system and laser optical system, and gave us easy access to the main chamber. We identified and corrected several minor difficulties in the system during these tests. The magnet was installed in June and July, and the final experiments with the laser-initiated plasma targets began in August. These experiments were hampered somewhat by laser damage to sodium chloride (NaCl) windows. This delayed the experiments, since the coil had to be warmed to replace the damaged windows. We then operated the laser at a reduced power level to minimize further damage.

Experimental progress was also delayed by a modification made in the guidance system when the

Fig. 27. Target-plasma buildup experiment.

magnet was installed. We changed the guidance plate geometry to improve field uniformity. Unfortunately, we later discovered that these modifications also permitted some insulating material to be charged up whenever the laser beam hit a pellet. These charged surfaces deflected subsequent pellets, thus nullifying the effect of the guidance. Once we identified the problem, a relatively simple modification in the software prevented its reoccurrence. We found that the guidance worked as well as it had on the side experiment; i.e., the final spread was ~ 1 -mm diam. Although this did not guarantee a hit on each pellet, it did permit the coincident firing of both neutral beam and laser.

Experiments in late August and September produced favorable results. It appears that 10 to 20% of input laser energy couples to plasma ions. The pellet completely ionizes and its expansion is nearly isotropic. Data from some experiments in the magnetic field are still being analyzed. More complete results will be included in a final report.

Clearly the plasma rapidly ($\sim 5 \mu\text{s}$) increases to a 20-cm diam and remains that size throughout its decay. These results could not be reproduced in October's experiments. At that time, the pellets were not completely ionized and the plasma expansion was asymmetric. During these October experiments, we completed the triggering system to permit coincident triggering of laser and neutral beam. Because of poor quality hits, the plasma decayed faster than the beam's turn-on time. The time available for experimentation was insufficient to solve this problem.

These laser-pellet experiments have proven that this target-production technique produces a target plasma. Further refinements will perfect the system. However, no major technical difficulties were found. Plasma geometry is sufficiently large for buildup by neutral beams. One feature of this technique overrides all others: it is much more difficult than using the plasma guns developed in the 2XIB experiment.

Ammonia-Pellet System

Ammonia-Pellet Generation. We previously described the details and operation of the solid- NH_3 pellet generator (see p. 28 of Ref. 1; also see Ref. 19). This pellet generator and its transport system were installed and operated as shown in Fig. 28. For these experiments, a 75- μm (inside diameter) nozzle produced charged ($\sim 10^{-12}$ C), 150- μm -diam liquid NH_3 drops at a rate of $\sim 3500/\text{s}$. These drops subsequently froze (by evaporation) into charged, spherical pellets of NH_3 ice as they traversed the low-pressure pumping tank. The mass loss of a drop

in this freezing process was $\sim 25\%$. When the drops passed through the 2.29-mm-diam orifice into the low-pressure region, they accelerated to ~ 32 m/s. However, they also acquired a slight random transverse velocity that gave them a small "shotgun" pattern. Because of this divergence, only ~ 100 pellets/s entered the 3-mm-diam entrance aperture of the first position sensor. About 10% of the pellets that entered this sensor were on trajectories that could be corrected by the computer guidance system. Even with this low efficiency, the pellet delivery rate to the laser focal zone was sufficient for the laser-pellet target experiments.

Pellet Guidance. Our pellet guidance system was extensively upgraded. We designed a system capable of measuring the charge-to-mass ratio of each pellet. This required the installation of three detectors to determine the position of the pellet at three points on its trajectory. The existing microprocessor was not fast enough to permit the calculations necessary for this three-detector system, so we upgraded the system by substituting another microprocessor, one that permitted the use of 12-bit analog-to-digital (A/D) converters to improve the accuracy of the detection scheme. To avoid timing difficulties inherent to the previous system, we installed peak-hold circuits for each detector plate. These circuits held the maximum signals until the computer sampled this voltage. This eliminated the need to carefully time the computer sampling to the signal peak.

We fabricated, debugged, and tested the electronics for the three-detector system. To avoid complexity in system alignment, we decided that the initial experiments on Baseball II-T would use only a two-detector system. This did not allow for trajectory corrections due to variation of the charge-to-mass ratio. The LS-11 unit was easy to operate and effective. When working well, our pellet guidance system reproduced the previous results of a scatter of ± 0.5 mm at the laser focus: the best anticipated for a two-detector system.

Neutral-Beam Development and Diagnostics

Automatic-Timing Sequence Control for Combined Pellet-Generator, Laser, and Neutral-Beam Ion-Source Operation. We set out to fire a 20-kV neutral-beam ion source at the same time as a 300-J CO_2 laser that depended on detection of a properly positioned pellet. This required additions to, modifications of, and interconnections between the various control circuits.

Fig. 28. Ammonia-pellet generator and pellet guidance systems.

Several preliminary conditions had to be established and acknowledged to prepare both laser and neutral-beam source for firing:

- About 1 min had to be allowed to charge the 100-kV Marx bank, which is discharged at 400 kV when the laser fires.

- The neutral-beam source filament power had to be turned on and 1 s allowed for filament warm-up to proper emission temperature.

- The earliest "good pellet trajectory" signal had to be obtained ~60 ms before the pellet reached the laser focal point. The occurrence frequency of these good-pellet-trajectory signals depended on the performance of the pellet-generator system and could vary from 0.5 to as high as 15 signals/s.

- The neutral-beam source pulsed gas valve had to be fired. Adequate gas density conditions existed in the source arc chamber for ~50 ms after gas-valve firing. The maximum repetition rate for pulsing the source gas valve was ~2 to 3/s as limited by the pumping-speed capacity of the source-tank vacuum system.

We obtained the laser-fire trigger from a final pellet-position detector system ~6 μ s before the pellet reached the laser focal point. After the neutral-beam source was fired, it took us ~2 min to recycle it to a ready-to-fire condition.

Our automatic control sequence caused the preliminary conditions to occur in their proper or-

der within the various time constraints. This system also provided for multiple occurrence of a 50-ms "fire enable" time window during the source's arc-chamber "good gas condition" intervals. If a "fire trigger" appeared during these fire-enable time intervals, only then would the neutral-beam source and laser be allowed to fire concurrently.

The neutral-beam source filament "on time" range was extended from the normal 1.5 to ~7 s. With an allowable source-pulsed gas-repetition rate of 3/s, about 21 fire-enable time windows could occur during a 7-s source-filament on-time interval.

During actual operation, this control system proved to be effective and efficient. A coincident laser neutral-beam source fire, with a pellet hit, occurred during practically every operate cycle attempted.

With reference to a typical time histogram of events (Fig. 29), the control sequence progressed as follows:

The operate cycle was initiated by a manual pushbutton that started the charging of the CO₂ laser's 100-kV capacitors. Simultaneously, a "HV charge" time delay, adjustable from 1 to 2 min, started timing out. On time-out (i.e., when time runs out) for this time delay, a pulse that went to the neutral-beam source control turned on the source filament power for a preset time interval of

Fig. 29. Time histogram of neutral-beam firing chassis.

1.5 to 7 s. If the source were to fire during this time interval, the filament power would turn off at the end of the source pulse. At "filament on," a filament warmup time delay of 1 s also started timing out. On time-out, a "good pellet trajectory signal" (GPTS) pass gate opened. This allowed GPTS's, which are randomly occurring, to enter the source-control circuit. These GPTS's sent out from the second pellet detector station signified that a good pellet was on the way and would arrive at the laser focal point in ~ 60 ms. The first GPTS to appear after the pass gate opened started the time-out of a source gas-trigger time delay set for ~ 55 ms. On time-out of this time delay, the source-pulsed gas valve fired. Simultaneously, a laser-fire-enable gate opened to allow a laser fire trigger, were it to occur, to fire the CO_2 laser

and neutral-beam source concurrently. This laser-fire-enable gate time window was set for 50 ms to coincide with the source arc-chamber good-gas-condition time interval.

To limit the source-gas pulse-repetition rate to its allowable range, a gas-trigger-inhibit time delay started timing out simultaneously with the gas-trigger-delay time delay. During time-out of the inhibit time delay, the short gas-trigger delay was inhibited from further triggering by the GPTS's, which could have appeared as frequently as 15/s. Only after the time-out of the inhibit time delay was the gas-trigger time delay again allowed to be triggered by the GPTS's.

If a laser fire trigger did not appear in the first laser-fire-enable time window, then the source-gas pulse cycle was allowed to repeat again and

again until either a laser-fire trigger appeared in a fire-enable time window or the source filament power shut off.

The time histogram shows a laser trigger occurring in the third laser-fire-enable time window.

Paddle-Target Measurements. The neutral-beam profile from a single 50-A, 20-kV LBL source module was measured with a 5×9 multiplexed array of secondary emission detectors inserted at the entrance to Baseball II-T. A typical contour readout from this 5-cm $\times$ 28-cm detector array appears in Fig. 30. The focused beam from this source was adversely affected and systematically deflected by central magnetic fields over ~ 0.8 T (~ 8 kG). This indicated a need for added magnetic shielding around the ion sources and charge-exchange chamber. Using hydrogen, we achieved our best operation at 14 kV; this yielded an average of 22-A equivalent (at full 14 kV) injected for a source drain of ~ 45 A. At 17 kV, the useful neutral-beam output actually declined despite drain increases to 85 A. This happened even with the operating parameters being relatively limited by interrupts for higher arc settings that appeared to have better beam focal properties.

300-J Laser System

We received the 300-J laser and made it operational during July and August 1975. A Faraday cage was constructed to eliminate cross talk between the laser and other systems.

Optical component fabrication and installation, except for the focusing mirrors, was completed in the fall of 1975. The vendor delayed delivery of the focusing mirrors because of the extreme difficulty of achieving both the final figure and surface finish simultaneously. After the vendor made some personnel and corporate responsibility changes, the two mirrors were delivered in November and January.

Full system operation began in May 1976 and continued through October. Several problems occurred during this period, including high-voltage breakdown that went from the laser to the external structure. We modified the structure to eliminate the problem.

Damage to the laser cavity optics occurred as a result of a series of misfires. The suspected mechanisms for the damage included optical feedback from both outside and within the laser cavity and high-voltage discharge to the mirrors. We added absorbing baffles to eliminate any optical feedback and, to reduce misfires, took greater care in presetting the preionizer. Video monitoring of the mirror surfaces gave some indication of occasional discharge to the mirrors. Replacement cavity mirrors were fabricated inhouse by diamond turning, and the NaCl window was replaced by a spare.

The laser, after several hundred shots, broke the upper NaCl vacuum window. Damage to the replacement window isolated the source as a hot spot in the upper return beam. Suitable baffling permitted continued operation to completion of the run without further replacement.

Less serious laser damage was sustained by the upward-facing copper-turning mirrors. Its cause: dust that settled on the mirror face acted as absorption centers. We resurfaced the two mirrors involved and chose more stringent cleaning and inspection procedures. Backup mirrors were also fabricated but not used.

Little or no laser damage occurred to other components. After completing operation in October, we noted some slight burning on the coating of the focusing mirrors.

Multibeam Project

In July 1975, we submitted a proposal to add a multibeam injector line to the Baseball II-T experiment; a revised version of this proposal followed in

Fig. 30. Neutral-beam intensity.

December 1975.²⁰ The principal revisions involved the beam complement, which was based on results from the 2XIIB experiments. Preliminary design continued through June 1976 until funding and approval for part of the project appeared in July 1976. The portion approved consisted of all components needed for the buildup-beam system that, when installed, would permit neutral-beam injection from four LBL-type modules, rated at 20 keV and 50 A each. This beam would be sufficient to generate a high-density, high-temperature plasma in the steady-state Baseball magnet [when used in conjunction with a suitable target such as the laser-pellet plasma or a streaming plasma (as in 2XIIB)].

The multibeam project proposal listed four subsystems: multibeam injector line, beam sources, cryopumping, and magnet heat shield. Existing designs for the 20-keV, 50-A sources and their power supplies enabled these items to be procured immediately; meanwhile, time and need directed an early and intensive design effort on the source tanks and LN-cooled liners. Other main components worked on at this time included those for mounting and shielding the source modules, tank couplings and valves, and the internal and external LN piping (of which the gas separators were a part).

In a parallel effort, another group engaged in site layout and facilities design (including power supply plants). Later, the magnet-chamber helium cryopanel work was added to this group.

At the end of September 1976, we suspended this project pending possible revisions to LLL's confinement studies program. Work continued on the beam modules and beam power supplies, as these units would be useful anyway. At that time, more than half the engineering design had been completed, and the components requiring a long lead time for construction were waiting placement by purchasing for outside fabrication. Fabrication of parts of three 20-keV, 50-A neutral-beam sources, excluding the insulators, was virtually complete; the power supplies for these 10-ms pulsed sources were 85% complete and scheduled for delivery in December 1976. We have since completed the three 20-keV, 50-A sources. The accelerator/decelerator, filament, and arc-pulse-line power supplies are still projected for delivery in December 1976. All other orders for materials and fabrication were cancelled except for the bulk titanium-tantalum getter wire and two LN gas separators that were almost completed.

Diagnostic Development

Time-of-Flight Detectors. Time-of-flight (TOF) detectors are one of the most useful detectors for ion energy analysis of laser-pellet-pulsed plasma

production studies. The common considerations for the design of these detectors include a grid mesh size, $\gtrsim \lambda_{Debye}$; a bias potential sufficient to separate out the electron component of the plasma flux; a combination of transverse magnetic field or biases to suppress secondary electron emission; at the collector plate; and grid transparency or distance from the source such that the ion current signals are not space-charge limited.

We tested several designs, including one through three grids, with and without auxiliary permanent magnets or biases, for secondary electron suppression on an ion-beam test stand with a 1- to 20-kV dc hydrogen ion (H^+) beam. Calibration against a similar aperture calorimetric-reference detector allowed direct measurement of the net transparency of the grid system. This generally indicated no direct problem with secondary electron emission. However, the response for H^+ energies >10 keV typically deviated some 10 through 20% from the simple predicted response. The best explanation for this deviation involves a combination of backscattered energetic neutrals and collected resultant secondary electrons from negatively biased grid structures.

Figure 31 shows a schematic of one of the TOF detector designs used on the 30-J CO_2 laser test stand. (Later in this report, we will discuss the signals from an array of TOF detectors of this type.) In use with 100- to 150- μ m-diam pellets, the detectors were typically operated with a transparency of only $\sim 10\%$ and at a distance ≥ 50 through 100 cm to assure that ion currents were not saturated by space-charge effects. The applicable "monoenergetic" space-charge-limited current density was

$$j \approx \frac{5.44 \times 10^{-5} V^{3/2} [(T/qV + 1)^{3/4} + (T/qV)^{3/4}]^2}{\sqrt{A/q} d^2} \text{ mA/cm}^2, \quad (14)$$

Fig. 31. Time-of-flight detector. We operated the bias around ~ 400 V for the experiments reported here. The sections shown between the electrodes are insulators.

where T is incident ion energy, V the electron suppression voltage, A the ion species mass in amu, q its charge in units of e , and d the effective grid spacing in cm.

2-mm Microwave Interferometer. We measured plasma density with a 140-GHz microwave interferometer. The signal that passed through the plasma underwent two down-conversions in a balanced-mixer-receiver to 60 MHz. This signal plus a reference signal (which was also down-converted to 60 MHz) was detected by a phase comparator circuit that provided both a $\sin\theta$ and a $\cos\theta$ output. A discriminator circuit stabilized the 60-MHz i.f. frequency. Such a circuit provided a feedback voltage to a voltage-controlled oscillator in the receiver. This eliminated any drift in the 60-MHz i.f. frequency.

A detailed description of the interferometer system will be given in a separate report.

Magnetic (Momentum/Charge) Analyzer Development. The plasma target attained through use of laser irradiation of a pellet tends to be dominated by the details of the ion distribution function, since the ions largely determine the plasma decay time. With the 30-J laser test stand, a single-channel magnetic analyzer determined early²¹ that for a mixed-element target pellet such as polystyrene, $(CH)_n$, one has to consider all possible ion species: H^+ and singly through fully ionized carbon (C^+ through C^{6+}). With a single shot, we obtained only a single measure of each species distribution. But shots tended not to reproduce well in detail. This limited results to an averaged ion population for each species. Also, we took these single-channel measurements with an electron-multiplier structure-detector for amplification. Differences in secondary electron coefficient for the highly stripped heavy ions created uncertainties in determining absolute ion currents.

With this incentive, we constructed a new six-channel version of the magnetic analyzer that used Faraday cups for ion collection. The magnetic field for each channel of the analyzer was calibrated with H^+ and deuterium-ion (D^+) beams in the available 1- to 20-kV ion-beam test stand. It was also possible to bias the collector cup to suppress secondary emission on the collector surface. With six channels of mv/q (momentum/charge) and TOF information reasonably detailed, we obtained ion-species flux measurements for doubly through fully ionized nitrogen (N^{2+} through N^{7+}) for NH_3 pellets. These results illustrate a problem: the integrated H^+ flux was generally appreciably less than three times the integrated singly ionized nitrogen (N^+) through N^{7+} fluxes as expected. We postulated a possible cause for this discrepancy: an appreciable fraction of the

H^+ can charge exchange to H^0 (an ordinary hydrogen atom) in passing through the nitrogen-ion cloud from the pellet (H^+ velocities $>$ nitrogen ion velocities). As a test of this hypothesis, we biased a magnetically swept target to detect H^0 and measured a substantial flux of H^0 with times of flight similar to those of H^+ . Two problems arose with this test and with the Faraday cup detectors on the six-channel analyzer. These were the need for a high-gain amplifier with relatively fast time response for H^+ and the presence of a high background of laser-related electromagnetic noise earlier in time.

Plasma-Attenuation Detector. A 16-channel plasma attenuation detector was designed, then installed in the exit-beam line of the Baseball II-T facility. The resolution of the instrument was sufficient to provide spatial-density measurements at 1-cm increments in both the axial and radial directions. Each detector consisted of a secondary emission plate behind a series of three collimators positioned so the line defined by the collimators would converge to a point on the plane of the source extractor. We checked the collimation of the detector by observing the images of laser light passing through the collimators on planes located at both the source extractor and the plasma center.

We observed beam signals well above the noise level on all but one detector. Beam attenuations of $\sim 10\%$ were measured for particles that passed through the plasma center. The small attenuations observed made accurate measurements of spatial profiles difficult.

Ions from D-D Reactions as a Monitor of Plasma Parameters. We made an initial investigation into the feasibility of using the ions produced in D-D reactions to measure plasma parameters.²² Although the details of this diagnostic were only examined for the Baseball II-T experiment, for which it appears useful, it has possible applications to other magnetic-confinement experiments (e.g., 2XIB and the proposed LLL tandem mirror experiment).

Our technique measures the D-D reaction rate, from which either the fast-ion density or temperature can be estimated if the other is known. It may also be possible to determine the magnetic field in the high-beta plasma region using this diagnostic.

The ions exploited are those produced in these fusion reactions:

The large gyroradii of these ions aid in displacing them out of the plasma to regions where detectors can be placed. Spatial resolution of plasma parameters is practical because ion paths are calculable, especially for a constant magnetic field as found in Baseball II-T.

Collimated compact semiconductor detectors can readily record these energetic ions. These detectors can function in an environment that includes high magnetic field, good vacuum, and low temperature. They need not look directly at the plasma region, because the ion trajectories are curved.

Several observations can be made from a preliminary computer analysis of trajectories of ions from D-D reactions in the Baseball II-T magnetic field. Because of the curvature of the orbits, the detectors can be placed in out-of-the-way places. In observing the T^+ and H^+ ions especially, a detector need not be in any principal plane or along any principal axis; it can be tucked away near the coil structure. Axial spatial resolution to within a few cm, for a minimum observable density of about 3×10^{11} through 2×10^{12} particles/cm³ (depending on assumptions made), appears reasonable. For higher densities, better axial spatial resolution should be possible. Radial spatial resolution may be feasible, too. When the magnetic field near the center is depressed by the presence of a high-beta plasma, the trajectories of D-D ions leaving this region are altered somewhat. Orbit calculations show that this shift may be magnified enough out in the detector region to be observable, possibly with a single detector, but probably more effectively by observing both the T^+ and H^+ in coincidence (as suggested by R. F. Post).²¹

In initially checking equipment for this diagnostic on a beam test stand, we detected ions from D-D reactions produced at the face of a copper target in vacuum, which intercepted and was implanted by a D^+ beam.* A room-temperature surface-barrier detector with 25-mm² active surface area, located 20 cm from the copper target, was used to observe the ions. To protect the detector against unwanted radiation, we placed a 2- μ m-thick aluminum foil just in front of it. We observed D-D ions down to an incident D^+ energy of 11 keV at the target. With 340 mA of 15-keV D^+ , ~60/s each of the 1-MeV T^+ and 3-MeV H^+ were observed.

Thomson-Scattering System. Two 10-J ruby lasers with four-pulse capability were ordered: one unit

for upgrading the 2XIB system and the other for a new Baseball II-T Thomson scattering system. Our design goal was a system that could measure electron density and temperature along a chord through the plasma at four discrete time intervals. Studies of the state-of-the-art in image detectors indicated that the most satisfactory system would require the design and construction of a special detector. We made initial contact with possible vendors; further work will be done to refine the design so that a new generation of Thomson scattering systems will evolve.

Data-Collection System. The main diagnostic data-collecting system is based on a 16-channel, 4-MHz bandwidth video-disk recorder. Data signals are routed through a patch block to 16 paralleled differential amplifiers, then to the disk. Up to 33 ms of data can be recorded when the system is triggered. A dedicated oscilloscope or a computer "TV" monitor (at reduced bandwidth) conveniently previews the analog-data record. A computer data-disk interface allows complete control of the disk system from the computer console. This control is part of the modular expansion of the computerized data-handling system, an ongoing program.

A further step in the computer-control program is a dedicated A/D converter to digitize data-disk information for computer processing. Because of time constraints, we made use of an existing interface to Biomation 610-B's. The current version of the disk data-processing system uses four paralleled Biomations (optionally eight) with different front-panel settings. On command from the computer, the Biomations select a disk channel and digitize it in parallel; the four traces are displayed for the operator to examine. A correctly digitized trace is selected and stored in a digital file along with other relevant parameters resident in the computer. (Correctly digitized in this context means that the analog zero level is at least one bit and the maximum analog signal does not exceed the six-bit range of the digitizer). The data files are processed following the data collection run. The Biomations may also be used as an independent data-gathering system, a role envisioned for them when the dedicated digitizer is installed.

To measure the performance of the neutral-beam module, we installed a "paddle target" consisting of a 9 $\times$ 5 array of secondary-emission detectors. This target may be remotely inserted and removed from the beam. Signals from the 45 detectors are time-multiplexed by a fast scanner/digitizer into a 1024-word buffer. The buffer data represents the 45 data locations at 16 consecutive time intervals. The data buffer is interfaced to the computer, where it may be

*John M. Wyrick, Harris Teachers College, St. Louis, Missouri, a 1976 Summer Physics Institute participant, assisted in this experimentation.

stored in a file along with other relevant parameters for processing; or it may be graphed in a "three-dimensional" plot.

Data-Processing, On-Line Digital-Computer System. With the recent additions of a medium-speed line printer and a digital-magnetic-tape unit to our small-computer facility, the system now consists of the following:

- Digital minicomputer with 32-K core.
- Digital magnetic disks (two units).
- Digital magnetic tape (nine-track, 10-1/2 in. reel).
- Line printer.
- High-speed paper-tape reader and punch.
- Oscilloscope display terminal and keyboard, with hardcopy unit attached.
- A/D converter and multiplexer (16-channel).
- Graphic plotter.

Interfacings between the minicomputer and other equipment are available for the following:

- Analog disk (16 channels).
- Biomation 610-B transient recorders (eight channels).
- A second oscilloscope display.
- Multichannel pulse-height analyzer.
- Shot-number counter.
- CAMAC (computer-automated measurement and control) crate.
- Multichannel beam-profile analyzer.

Our computer-hardware arrangement and the programming procedures employed were extensively revised and expanded over the past year. In particular, we redid the computer bus-structured interface assembly, added new interfacings, and extensively used* the Digital Equipment Corporation (DEC) OS/8 software operating system.²⁴

We developed software to read the experimental data into the computer from temporary storage devices and put the data in long-term storage (on digital disk or tape). Much of our saved data were first recorded on the 16-channel analog disk. Currently, we transfer data from two analog-disk channels at a time to long-term storage from computer code. Additional programs retrieve the data from long-term storage. They display the data and analyze results in various ways, depending on the type of measurement and the information needed. Some analysis may be done between shots, whereas more thorough analysis can be completed later.

*The computer systems are expertly supported by W. Keith Mortensen, electronics engineer; Walter C. Ng, programmer; and Phillip A. Housel, electronics technician.

Present data-analysis programs include the following:

- Calculation of the energy distribution of particles reaching the TOF detectors after laser-pellet interaction.
- Calculation of the radial profile versus time of particles from the central plasma region reaching a set of gridded end-loss detectors.

Experimental Results

30-J Laser-Pellet Plasma-Target Production. We continued one- and two-sided laser irradiation of test pellets early in this period with the small Lumonics-601 30-J CO₂ laser. Reference 21 summarizes the geometry for this test stand and the results from one-sided irradiation of 100- μ m-diam (CH)_n pellets. Briefly, two-sided irradiation for this test stand was achieved by using one-half of a NaCl lens as a beam splitter-focusing element on one side; the other half-beam was focused back on the other side by a copper mirror. Alignment of the laser beams for coincident focal spots on opposite sides of a test Mylar target (or pellet) was a problem facilitated by replacing the rear mirror of the CO₂ laser. The replacement mirror included a 1-mm-diam central aperture to permit the introduction of a helium-neon (He-Ne) alignment laser beam into the unstable resonator (for single-mode low-divergence output) optics of the CO₂ laser system. This produced a continuous-wave (cw) He-Ne laser beam with the same hollow annular pattern as the CO₂ beam. This allowed cw focal tests and beam adjustments, but required correction for the differences in index of refraction of He-Ne and CO₂ wavelengths when refractive elements were involved. A period of iterative testing and systematic vignetting of the optical aperture with fibreglass was required to eliminate ghost multiple focal spots and multimode (poorly focused) output from the CO₂ laser. With these steps, we obtained satisfactory coincident single-mode output on Mylar film. With thin foils or pellets that burned through, however, the laser output was observed to go multimode after optical feedback of the two opposed beams had time to occur. This took place generally after the 50-ns gain switched pulse of interest.

Our principal purpose for the small-laser test stand was to develop CO₂-laser and NH₃-pellet techniques for application to Baseball II-T and for auxiliary diagnostic development. Diagnostics for stalk-mounted 100- μ m (CH)_n pellets and in-flight 100- μ m NH₃ (starting in December 1975) included an array of five TOF detectors, a magnetic analyzer for species analysis, and soft x-ray detectors. After only relatively brief operation, the test stand was

shut down to transfer to the higher energy 300-J CO₂ system. We observed much more nearly isotropic ion distributions for two-sided irradiation, with nearly complete accountability for the pellet mass. The ions and x-rays, however, were generally Δ lower energies (from the reduced specific laser-light intensities of the split beam and slightly larger focal spots). Thus, the absorbed laser efficiency was still $\gtrsim 25\%$. Significant details will be included in the Baseball II-T laser-pellet report being prepared.

Streaming-Plasma Measurements. In the 2XII-B experiment,³ we employed a warm streaming plasma from a deuterium-loaded titanium washer gun as both a target plasma and a source of low-energy ions. This was done to suppress the microinstability attributed to the mirror's loss cone.⁶ A similar stream was investigated in the Baseball II-T experiment as a target plasma for buildup of a hot plasma with high-energy neutral beams. The experimental results in the steady-state magnetic field of the Baseball facility were consistent with those observed in the 2XII-B experiment. The target plasma produced by the stream appeared suitable for both instability control and neutral-beam trapping.²

The experimental evidence indicated that the target plasma trapped $\sim 10\%$ of the hot neutral

beam. The resulting hot-ion density was estimated to be $\sim 2 \times 10^{12}$ ions/cm³ for a 22-Å neutral beam and a target density of 1.4×10^{13} particles/cm³. The plasma pulses from the titanium washer gun were 1 through 6 ms long.

For most of our operation, the gun tip was positioned at the north vacuum-chamber wall, 126 cm from the center of the magnetic well (the mirror was at ~ 48 cm). The ratio of the magnetic field at the mirror to that at the gun ($B_{\text{mir}}/B_{\text{gun}}$) was 10.8. We first located the gun on the magnetic axis, but later moved it 7.5 cm east to free the axis for alignment of the pellet system. It was still aimed at the center, and was positioned on a field line in the horizontal plane that passed only ~ 0.4 cm from the center. In general, the experimental results were not noticeably different for this off-axis position, except that the measurement profile was somewhat broader horizontally.

Figures 32 and 33 provide horizontal and vertical views of the Baseball II-T apparatus and magnetic field. They show the positions of diagnostics, such as the gridded end-loss detectors and the microwave apparatus, along with the streaming-plasma gun in its innermost position. These drawings, although somewhat schematic, are to scale.

The data from sets of end-loss detectors, labeled SELD and V-FELD in Figs. 32 and 33, indicate an

Fig. 32. Horizontal view (to scale) of Baseball II-T coil, magnetic field, vacuum-chamber wall, streaming-plasma gun, and diagnostics.

Fig. 33. Vertical view of Baseball II-T configuration (see Fig. 32).

integrated ion current to the south vacuum-chamber wall of as much as 22 A. To arrive at the south wall, the particles have to pass through both north and south mirror regions. This integrated positive current, comprised especially of ionized deuterium and titanium, is obtained by integrating over measured ion profiles. Figure 34 shows a horizontal profile at the south chamber wall, as measured by the six SELD collector plates. Projecting the ion profiles along magnetic-field lines from the detectors to the midplane indicates a stream size there of ~ 14 cm horizontally, perpendicular to the stream flow, and ≤ 7 cm vertically (for the gun centered on axis). This is a good match to the neutral beam. These projected streaming dimensions at the midplane are drastically different from those obtained by projecting, along field lines, the 5.1-cm plasma-gun diam from the north chamber wall to the midplane (~ 0.25 cm horizontally, ~ 26 cm vertically). This suggests motion of the streaming plasma across magnetic-field lines.

The ion current to the SELD detector plates, which are near the magnetic axis, was increased by two different parameter variations. We obtained a factor of ~ 4 increase when the streaming-plasma gun was moved in from a position where $B_{\text{mir}}/B_{\text{gun}} = 21.0$ to the standard position shown in Figs. 32 and 33, where $B_{\text{mir}}/B_{\text{gun}} = 10.8$. Also, when we increased the central magnetic field from 0.52 to 1.03

Fig. 34. Horizontal profile of streaming ions at south chamber wall, as measured by SELD. Gun was in off-axis position. Current magnitudes are corrected for losses on grids.

T, with the gun at its standard position, the integrated current to SELD increased by a factor of ~ 5 .

Retardation measurements of the streaming ions reaching SELD gave mean ion energies (if singly charged) of ~ 60 to 280 eV. In the more recent measurements, which needed higher biases to reduce the ion signal significantly, $\approx 20\%$ of the zero-bias signal level remained at $+500$ V retarding bias and $\approx 5\%$ at $+800$ V.

The 2-mm interferometer provided the experimental measurements of the target plasma line density, $n_e L$ (electron density $\times$ path length). Figure 35 shows the time-dependent behavior of the streaming plasma during a typical pulse. Note how the target density peaks between 1 and 2 ms, then decays to less than half its peak values by the time the beam is turned off (5.4 ms). The microwave density measurements are also consistent with $n_e L$, which would be calculated from the observed attenuation of the neutral beam ($\sim 10\%$).

Figure 36 shows the time-dependent $n_e L$ with both the stream and beam. The discontinuity at 4 ms corresponds to the time the beam is turned off. Although Figs. 35 and 36 are obviously from different shots, the reproducibility of the streaming plasma is excellent. Therefore, the difference be-

tween Figs. 35 and 36 corresponds to the $n_e L$ for the hot ions only. We plotted this difference in Fig. 37. Note that the product of $n_e L$ has a peak value of $\sim 3.5 \times 10^{13}$ particles/cm².

The measured value of $n_e L$ for the hot ions is in good agreement with values calculated from the buildup equation. We assume that charge exchange of the neutral beam with target ions is the dominant trapping process and that the characteristic ion loss time is 0.5 ms. Again, we estimate the decay time from the decay of the interferometer signal. Since this time is short compared to beam-on time, equilibrium has been obtained. Therefore,

$$n_H^+ = \frac{IL}{V} \left(\frac{\sigma_c^A \times v_r}{v_0} \right) n_T^+ \tau_{\text{loss}} \quad (15)$$

Substituting $I = 22$ A, $L = 10$ cm, $v = 2500$ cm/s, $(\sigma_c^A \times v_r/v_0) = 7.5 \times 10^{16}$ cm², $\tau_{\text{loss}} = 0.5$ ms, and $n_T^+ = 1.7 \times 10^{13}$ particles/cm³, we obtain

$$n_H^+ = 3.5 \times 10^{12} \text{ ions/cm}^3, \quad (16)$$

which is in reasonable agreement with the direct microwave measurements for a plasma diameter of 10 to 15 cm. This calculated hot-ion density would

Fig. 35. Line density for a streaming plasma.

Fig. 36. Line density for a streaming plasma plus beam.

be increased somewhat if we included the added trapping rate due to the hot-ion density.

In the density regime in which all neutral gas incident on the plasma is ionized, charge-exchange flux is independent of plasma density. In this "burnout" condition, charge-exchange flux is a measure of neutral-gas density incident on the plasma and not hot-ion density. This statement assumes that the charge-exchange flux is dominated by charge exchange with thermal gas instead of resonance charge exchange with the beam. Domination with thermal gas is consistent with experimental observations. Analysis of the charge-exchange flux measured with a solid-state detector operating in the current mode gives a charge-exchange flux at the detector of $\sim 1.1 \times 10^{14}$ particles/cm²·s. From geometrical considerations, we estimate this corresponds to a total charge-exchange flux rate of 1.2×10^{19} particles/s. Since the fraction of neutral flux incident on the plasma, which contributes to charge exchange, is $\sigma_{cx}/(\sigma_{cx} + \sigma_i^{eff})$, we obtain

$$\frac{n_0 v}{4} S \left(\frac{\sigma_{cx}}{\sigma_{cx} + \sigma_i^{eff}} \right) = 1.2 \times 10^{19} \text{ particles/s.} \quad (17)$$

Substituting and solving for the neutral gas density gives

$$n_0 \approx 1.7 \times 10^{11} \text{ particles/cm}^3, \quad (18)$$

where we have used $S = 5 \times 10^3 \text{ cm}^2$, $v = 7.9 \times 10^4 \text{ cm}^2$, $\sigma_{cx} = 7.2 \times 10^{-16} \text{ cm}^2$ and $\sigma_i^{eff} = 2.7 \times 10^{-16} \text{ cm}^2$.

300-J Laser Irradiation Results. Irradiation of NH₃ pellets in the magnet chamber began in late August 1976. Because of a concern for damage to optical components, we operated the Lumonix-622

laser at 80 through 85 kV rather than at the maximum value of 100 kV. This meant that the total laser energy was 200 J rather than the designed value of 300 J. The beam was apertured so that the output was 20-cm outside diam. Because of unstable resonator optics, the beam was hollow with a 5-cm-diam central hole. We measured the focused spot size to be 350- μm diam. Thus, the maximum laser intensity on the pellet was $4 \times 10^{12} \text{ W/cm}^2$. Figure 38 shows the temporal behavior of the pulse.

Figures 39 and 40 portray the diagnostics used to study the laser-pellet-produced plasma. Basically, freely expanding plasmas are studied using the TOF detectors and the six-channel momentum analyzer. Note that although only eight TOF detectors are shown, all of the end-loss detectors (SELD, V-FELD, and H-FELD) can also be used in the TOF mode. When the magnetic field is on, the plasma is diagnosed predominately by end-loss detectors, the microwave interferometer, and the fast-atom detector. We also have two monochromators that monitor visible radiation.

Much of the data taken are still being analyzed and will be presented in a report being prepared. Data presented here should be considered preliminary.

Freely Expanding Plasmas. As pointed out in Ref. 21, analysis of the TOF data required an assumption of the average mass and charge for the species. We assumed an average mass of 4.25 amu and an average charge of 2. This assumed that the nitrogen was ionized to the helium-like level, N⁵⁺. Since it was unlikely the average nitrogen charge was any higher than this, we felt this would give a lower limit to the total number of ions and, hence, the total energy.

Figure 41 shows the TOF results from the best shot analyzed to date. Unfortunately, some of the TOF detectors were malfunctioning at the time these data were taken. The data, however, indicate that both the charge collected ($dN/d\Omega$) and the total energy ($dE_{TOT}/d\Omega$) are roughly azimuthally symmetric about the laser axis. The total charge collected is somewhat smaller along the laser axis. The average energy, however, of these particles is large, so the total energy collected is nearly isotropic. Then, if the average $dE_{TOT}/d\Omega$ is 4 J/sr (i.e., the minimum signal measured), the total ion energy measured is $4\pi \times 4 \approx 50 \text{ J}$. We feel, however, that the assumption of an average mass overestimates this energy. This occurs if the velocity of the protons is higher than that of the nitrogen. Calculations using a model that assumes all species are freely expanding Maxwellian distributions indicate that the analysis procedure used here can be off by as much

Fig. 37. Line density for the hot-ion plasma.

as a factor of two, depending on the temperature assumed for each species. Thus, the total kinetic energy in the ions is between 25 J and 50 J; i.e., ~10 to 20% of the incident laser energy is coupled to charged particle energy. This is consistent with previous results.²¹

If we assume that the three-dimensional polar plot of $dN/d\Omega$ (as shown in Fig. 40) is an ellipsoid of revolution with a radius of 1.5×10^{16} /steradian and length of 3×10^{16} /steradian, the total number of particles is then 2.3×10^{17} . In contrast to the total energy, this number depends only on the average charge assumed. As pointed out earlier, we obtain a lower limit by assuming $\bar{Z} = 2$. Note that a 75- μ m-radius NH_3 pellet contains 2×10^{17} atoms. Thus, the pellet is completely ionized by the laser. These results contrast quite markedly with the

Fig. 38. Temporal behavior of 10.6- μ m output from 300-J CO_2 laser.

Fig. 39. Diagnostics mounted on vacuum chamber for laser-pellet target production.

Fig. 40. Diagnostics mounted on magnet for laser-pellet target production.

results of one-sided irradiation reported earlier.²¹ In those experiments, the charge collected was strongly peaked along the laser axis, and only ~40% of the pellet was ionized. We felt this difference was due to the elimination of pellet rocketing by the use of two laser beams. This is consistent with results reported by Sato.¹⁵

The momentum analyzer was used to obtain the energy spectrum of individual ion species. We set up the detector to look at six different momenta; i.e., we measured the current density of each species at six different energies on each shot. Shot-to-shot variation prevented any finer grained measurement. The momentum analyzer became operational around mid-October. Unfortunately, the quality of the hits had deteriorated by that time. Consequently, we did not get momentum analyzer data corresponding to the best hits shown in Fig. 40.

Figure 42 shows the energy spectra for N^{7+} and N^{6+} for a typical shot. Note the dip in the energy distribution. This is characteristic of all data analyzed to date and is not understood. The magnitude of the dip decreases for lower charge states of nitrogen, and it is not always present for the N^{3+} and N^{4+} . The total energy distribution, $\sum_{\text{species}} (dN/dE)_{\text{species}}$, is a monotonic function of energy. This distribution also appears in Fig. 41.

Figure 43 provides the total number of ions collected for each nitrogen ionization state, $\int (dN/dE) dE$. The ionization potentials are 98 eV for N^{4+} and 552 eV for N^{7+} . Thus, we would expect far fewer N^{6+} and N^{7+} to be produced than all the lower ionization states. The exponential nature of Fig. 42 is, therefore, somewhat surprising and not understood at this time. It should be pointed out that the number of protons collected is only ~10%

- Polar plot of $dN/d\Omega - 10^{16}$ particles/steradian
 ✕ $dE_{\text{total}}/d\Omega - \text{J/steradian}$

Fig. 41. Angular distribution of measured ion intensity and energy arising from 300-J CO_2 -laser irradiation of frozen NH_3 pellets. Upper scale is for $dE_{\text{total}}/d\Omega$ plot; lower scale is for $dN/d\Omega$ plot.

of the total ions observed rather than the 75% expected for NH_3 . We made some measurements that indicated a significant number of high-energy neutral hydrogen atoms present on these shots. Again, it should be emphasized that the TOF data taken at that time indicated an asymmetric ion distribution. Furthermore, these data indicated the pellet was only partially ionized. Thus, we felt this abnormally large neutral hydrogen signal was not typical of a "good" hit.

Expansion into a Magnetic Field One of the main questions that arises concerning the formation of target plasmas by laser irradiation of a pellet in a magnetic field deals with the size of the resulting plasma. To investigate this question, we collected data in two time regimes. On the short time scale ($t \gtrsim 5 \mu\text{s}$), we took framing photos of the expanding fireball. These data appear in Fig. 44 for three different shots. The exposure time for each frame was $0.5 \mu\text{s}$; the framing time was $1 \mu\text{s}$. The framing camera looked along field lines in the horizontal fan toward the center of the coil at an angle of $\sim 40^\circ$ from the magnetic axis. This first $0.5\text{-}\mu\text{s}$ exposure in each case indicated a fireball relatively free of structure. Assuming spherical symmetry and using a mean radius measured in these photos, we

Fig. 42. Energy distribution of N^{7+} , N^{6+} , and total ions measured in laser-irradiation experiments.

Fig. 43. Measured nitrogen charge-state distribution for 390-J laser irradiation of NH_3 pellets.

calculated that the volume of the fireball at 0.75 T (7.5 kG) was roughly 0.2 the volume at 0.5 T (5 kG). This was a factor of about two less than one would expect for a spherically expanding $\beta = 1$ plasma (see Appendix A-3 of Ref. 20). This may simply indicate the shot-to-shot variation in the energy coupled to the pellet.

A far more interesting feature of these data was the appearance of a flute-like structure by the second frame (1 μs). This structure persisted until the intensity of the visible radiation was too weak to record. The orientation of the flute seemed to repeat from shot to shot, but varied with the field. We felt that the equilibrium size of the plasma was determined more by this phenomenon than by a simple expansion to $\beta = 1$.

We determined the size of the plasma later in time by end-loss measurements on the SELD detector (Fig. 39). Figure 45 shows a typical set of radial distributions at 10- μs time intervals from 30 through 70 μs . We found that the plasma end-loss profile reached a "full width at half-maximum" (FWHM) of around 20-cm diam within the first few microseconds. The profile then remained nearly unchanged as the plasma decayed.

The decay of the laser-produced plasma appears in Fig. 46. The decay rate measured by the 2-mm microwave interferometer was consistent with that calculated in the multispecies Fokker-Planck code. The end-loss current, however, as measured on the

Fig. 44. Framing-camera photos of initial expansion of laser-created plasma in Baseball II-T magnetic field. We took the photos in (a) and (b) at 0.5 T (5 kG) and in (c) at 0.75 T (7.5 kG). Time increased downward in all cases.

SELD detector, decayed more rapidly (15 μs) than expected from the observed density decay. The integral of the end-loss signal indicated that $\sim 1.5 \times 10^{17}$ ($Z = 2$) ions were collected. Thus, $\sim 65\%$ of the particles in the pellet were collected. Since we took

Fig. 45. Radial profiles of decaying target plasma created by laser irradiation of NH_3 pellets. The magnetic field was 0.5 T. We measured radial profile "a" 30 μs after the laser fired. Profiles "b" through "e" were measured at 10- μs intervals.

these data when the other diagnostics indicated incomplete ionization of the pellet, we felt that the SELD detectors saw all the created ions.

Analysis of the signal from the fast-atom detector indicated that it also decayed almost exponentially with a 15- μs decay constant. Furthermore, assuming the neutral particles were emitted with spherical symmetry and the secondary emission coefficient was 0.1, we concluded that $\sim 8 \times 10^{16}$ fast neutrals were emitted from the plasma. If these particles originated from charge-exchange reactions between the laser-heated ions and a cold background gas, an equal number of cold ions was produced. Such ions were pushed out along field lines by the plasma potential. Consequently, an equal number of ions would have been collected coming out the fan. Thus, charge-exchange losses were included in the

SELD measurements. The discrepancy between the observed ion losses and the measured density decay has not yet been resolved.

Summary and Conclusions. Perhaps the most obvious conclusion to be reached was that the data analysis was not yet complete. There were many unanswered questions concerning the properties of the laser-produced plasma. We had, however, clearly shown that the techniques used for delivering a pellet to the laser focus would work. Many improvements remained to produce a technique that would yield reproducible results. We found, however, no major technical difficulties.

The experimental results indicate that irradiation of the pellet from two sides produced nearly isotropic plasma. It appeared that energy coupling

Fig. 46. Decay of laser-initiated plasma density (measured by 2-mm microwave interferometer) and measured end-loss current.

to ions was ~ 10 to 20% efficient. This is consistent with other experiments using short-pulse lasers. Thus, we conclude that the use of inexpensive, commercially available CO_2 lasers is satisfactory for these studies.

Theory and Code Development

LASNEX. We applied a two-dimensional version of the LASNEX code to a calculation to predict our results in free expansion with two-sided CO_2 laser irradiation of an NH_3 pellet. To match achievable parameters after mirror and window losses, we derated the 300-J, $10.6\text{-}\mu\text{m}$ laser pulse to 225 J on a 20-ns linear rise (and fall), 50-ns FWHM pulse. The focal spot assumed was a $400\text{-}\mu\text{m}$ -diam Gaussian

shape with the beams 180° opposed incident on a $150\text{-}\mu\text{m}$ -diam NH_3 pellet with an initial density of 0.8 gm/cm^3 . A problem with a code calculation such as this is the time-consuming need for a relatively fine mesh (particularly in radius). This insures that the local ion sound-speed transit times are $\lesssim$ the time increments, so as not to inject an artificial computer-averaged conductivity into the physics of the ablative burn. At any time, only the relatively thin energy-absorbing region needs this detail. Unfortunately, in the course of ablative burnthrough, this surface slowly moves from the outside to the center. This requires a fine-meshed problem throughout or variable zoning. Table 1 contains the results of this calculation.

Fig. 47. Total integrated ion flux vs angle. This was taken from a LASNEX two-sided, two-dimensional calculation for 112.5-J CO_2 -laser beams incident on opposite sides of a $150\text{-}\mu\text{m}$ NH_3 pellet. The angular distribution shown is only for $T = 50\text{ ns}$ just after burnthrough (this ignores possible minor changes due to underdense absorption on the longer duration laser pulse).

Table 1. LASNEX-predicted results.

Property	Value
Burnthrough time	~50 ns
Total energy absorbed	~100 J (~44%)
Total ion kinetic energy	64 J (~28%); ~8 J radiated away; remainder in electron energy
Average $\bar{Z}$	2.27 or $\underline{H}^+$ and $\underline{N}^{6+}$
Average T_e	~110 eV (locally to ~500 eV)
Total $\underline{N}$ (atoms)	~ 2×10^{17}
Average e_i	~2 keV/atom with average mass 4.25

The actual case with $B \neq 0$ was not attempted on LASNEX because of the uncertainties from instability effects on diffusion. Figure 47 shows the predicted integrated angular distribution for the ions.

Estimation of the Adiabatic Energy Limit vs Beta; Other Adiabaticity Orbit Calculations. Several estimates of the adiabatic energy limit versus beta were made. We based some estimates on analytic expressions; for others, we calculated particle orbits, inspected magnetic-moment jumps, and then derived adiabatic limits. The results were sensitive to the assumed variation of the combined vacuum-plus-plasma magnetic field. The calculated adiabatic energy limit fell rapidly with beta, even for a gradual magnetic-field variation. If we assumed a

sharp depression in the axial profile of the combined magnetic field for a finite-beta plasma, the adiabatic limit could be markedly reduced. Reference 26 summarizes the various estimates of the adiabatic energy limit versus beta and the calculation methods used to obtain them.

Orbit calculations concerning adiabaticity, of the type discussed in last year's annual report, progressed and expanded. Comparisons of these numerical results with the predictions of analytic expressions recently developed continued to be encouraging. Recent reports summarized some of the results^{27,28} of this continuing work.

Radially Dependent Fokker-Planck Code. The development of a radially dependent Fokker-Planck code, discussed in the previous annual report,¹ progressed to where it could be used to study plasma production by neutral injection in existing and proposed mirror experiments.

The Radial Fokker-Planck code (RFP) solves the time-dependent Fokker-Planck equation for an arbitrary number of charged species as a function of radius. The code also solves time-dependent rate equations for three neutral-gas species, taking into account gas sources such as diffuse and direct streaming of gas from beam sources, outgassing from the walls of the vacuum chamber, and wall reflux of neutral atoms following bombardment by various ion and neutral species. The three neutral gas species are thermal hydrogen molecules, thermal hydrogen atoms, and Franck-Condon atoms.

As an example, Figs. 48 through 52 show some of the output data for a two-species run that simulated

Fig. 48. Plasma-density decay.

Fig. 49. Proton-energy decay.

Fig. 50. Change in thermal molecular density.

the injection of 10 A of 35-keV neutral atoms through a target plasma of the same energy. For this run, the mesh had 25 grid points and the velocity mesh had 100 grid points. Figures 47 and 48 show the average ion energy and plasma density as a function of radius. Each curve corresponds to a different time during the run. We assumed the initial density

distribution to have a parabolic dependence with radius while the initial energy was constant. The discontinuity at 3-cm radius corresponded to the edge of the beam. The lower energy within the beam resulted from a greater rate for depositing electrons.

For this run, the plasma loss rate exceeded the trapping rate, and the plasma decayed. At the edge

Fig. 51. Change in energetic atom (Franck-Condon) density.

Fig. 52. Change in thermal atomic density.

of the plasma, charge-exchange losses eroded the plasma, and the plasma radius decreased with time. Figures 49, 50, and 51 show the plasma gas densities as a function of radius for thermal hydrogen molecules, Franck-Condon atoms, and thermal atoms, respectively. The movement of thermal gas into the plasma during the decay is evident in Figs.

49 and 51. Franck-Condon neutral atoms penetrated further into the plasma because of their greater velocity.

For a two-species run with 100 velocity points and 25 radial points, the present code took ~2 min per 100 time steps on the CDC-7600 computer. The RFP code is being modified to allow the option of

assuming the electrons have a Maxwellian velocity distribution. This modification should decrease the computer time when this option is chosen.

Mirror Experimental Facility

As of today, theory and experiment indicate that an experiment the size of 2XIIIB cannot do more than carry us to the threshold of the reactor regime. Longer confinement times will require yet higher plasma temperatures and larger plasmas. To this end, we have proposed²⁹ that the mirror experimental facility (MX) be constructed during FY 78 through 81 for \$81.7 million.*

Parameters and Goals

Figure 53 conceptualizes the MFTF. This experiment brings together the main elements of our present concept of a mirror reactor: a superconducting magnet and neutral-beam injection. Startup would be accomplished by injecting pulsed beams into a transient cold plasma provided by an array of

streaming guns. This method of starting up the machine was demonstrated in 2XIIIB. After startup, the plasma would be sustained by injecting high-energy neutral beams to achieve steady-state conditions for 0.5 s up to several seconds.

Table 2 lists the main MFTF parameters. With these machine parameters, we expect to obtain the plasma parameters listed in Table 3, which are the initial goals of the MFTF experiment and which correspond to $\beta = 0.5$ at the central field of 2.0 T. (β is the ratio of plasma pressure to the pressure of the confining magnetic field.)

In arriving at the machine parameters listed in Table 2, we considered a number of competing objectives. Since the overall MFTF objective is to provide the physics and technology bridge between present experiments and experimental reactors, such as the fusion engineering research facility (FERF), that could be in operation in the 1980's, we would like to require that

- MFTF be a technological prototype of FERF or other experimental reactors.
- ◆ The schedule and technical feasibility be consistent with completion as soon as possible (around 1981) so that FERF can become operational between 1986 and 1988.

*Shortly after the close of the report period, the MX was renamed the Mirror Fusion Test Facility (MFTF). For consistency, the latter designation will be used throughout the rest of this report.

Fig. 53. LLL's Building 431 as it will be configured for the MFTF machine.

Table 2. MFTF parameters.

Magnet	Sustaining beam	Startup beams
Central magnetic field strength, $B_{\text{central}} = 2.0 \text{ T}$	Electric field strength, $E = 80 \text{ keV}$	$E = 20 \text{ keV}$
Length between mirrors, $L_{\text{mirror-to-mirror}} = 3.4 \text{ m}$	Current, $I = 750 \text{ A}$	$I = 1000 \text{ A}$
Mirror ratio, $R_m = 2$	Power drain = 220 MW (10% duty cycle)	Pulsed (10 ms)

Table 3. Initial goals of MFTF experiment.

Plasma parameter	Value
Density, n	$10^{14} \text{ particles/cm}^3$
Ion energy, T_i	50 keV
Product of density and confinement time, $n\tau$	$10^{12} \text{ particles/cm}^3 \cdot \text{s}$

● The $n\tau$ and β in MFTF be as large as possible to provide a convincing demonstration that mirror physics is well in hand.

● The physical dimensions L/ρ_i and R_p/ρ_i (where L is plasma length, ρ_i is ion "Larmor" radius, and R_p is plasma radius) be large enough to test the theoretical scaling laws for all kinds of known instabilities.

The MFTF design meets all these objectives simultaneously with little need for compromise.

First, consider the magnet. To meet the schedule, we have chosen a conventional niobium-titanium (Nb-Ti) superconductor requiring a minimum development effort. This limits the field at the conductor to 7.5 T. To accommodate the mirror ratio of $R_m = 2$ and to provide adequate beam access, B_{central} would then be 2.0 T.

We chose the length, L , between mirrors to provide (1) adiabatic confinement of the high-energy tail of the ion distribution (several times T_i) and (2) an adequate test of scaling laws for the convective loss-cone mode. Both would depend on L/ρ_i and hence on the product BL and on β . The present design, which provides satisfactory adiabatic con-

finement at $T_i = 50 \text{ keV}$ and $\beta = 0.5$, would permit upgrading to $T_i = 100 \text{ keV}$ or more.

The principal constraint on the neutral-beam injection system is cost, most of which is in the sustaining beams. To realize the increase in $n\tau$ expected from higher values of T_i , we must fill a larger volume corresponding to a larger R_p/ρ_i . This would require more beam power, P_{HV} , at a correspondingly higher cost. In the MFTF design, we have settled on a beam power such that (1) $n\tau$ and β would be approximately the minimum values required for FERF; (2) $n\tau$ would be a significant, order-of-magnitude improvement beyond 2XIB; (3) the primary power drain of 220 MW would be an acceptable load for the local utility; and (4) the cost of the sustaining beam system would be about equal to all other facility costs combined.

Finally, we considered to what extent the MFTF design is flexible enough to take advantage of developing ideas to reduce end losses and enhance Q , the ratio of fusion power released to heating power input to the plasma. Perhaps the most promising avenue is suggested by the very high values of β (≥ 1) achieved in the 2XIB experiment; the plasma may create for itself a very high mirror ratio or even a field-reversed configuration. Being simply a different operating mode of the same machine, this approach would preserve the desirable engineering features of the main-line mirror concept and would have improved plasma confinement. Since the 2XIB machine would be essentially unaltered, advanced experiments along these lines could be carried out in MFTF to follow up any promising results yet to be obtained in the existing experiments. In fact, MFTF (also FERF) appears to be an ideal size for a self-contained reactor module based on the field-reversal concept.³⁰ The beam system would also be well matched to experiments at higher β , if indeed higher β yields higher $n\tau$. The greater beam power needed to fill a

given volume to a higher value of β tends to be compensated by the improved confinement. Reference 30 summarizes the present status of these and other possible ways to improve mirror confinement.

We conclude that the MFTF design meets the overall objective of providing the physics and technology bridge between the present mirror experiments and FERF or other experimental reactors. A larger step would require a new building, more development, and a prolonged construction period; a smaller step now would be more conservative than the physics dictates and would likely call for an extra intervening step before FERF could be undertaken.

Technological Objectives

One of the MFTF objectives is to develop technology that will provide a transition from present small mirror experiments to large steady-state devices such as the mirror FERF/fusion test reactor (FTR). Specific areas of concern that will be explored and developed in MFTF include

- Interaction of energetic particles and radiation with vacuum chamber walls at energies, intensities, and time intervals that exceed those in present experiments.

- Control and reliable operation of both pulsed and continuous neutral beams necessary to start and sustain an appreciable volume of plasma at reactor energies.

- Development of reliable high-current, high-energy, pulsed and steady-state neutral beams.

- Disposal with little (preferably no) backstreaming of the intense flux of plasma particles that emerge through the mirrors and of the intense flux of energetic ions emerging from the neutralizer.

- Steady-state, high-speed, high-capacity pumping techniques to handle the large throughput of gas in the neutral beams.

- Development of reliable, large-scale, complex, superconducting magnets.

Magnet System

Magnet size is characterized by the product of the magnetic field and the distance between magnetic field maxima, BL. The MFTF magnet, of 3.4-m mean diam operated at 2.0-T central field strength, provides a BL product for MFTF five times that of 2XIIB. As in Baseball and 2XIIB, $R_{m1} = 2$.

Of the common magnet winding patterns that provide minimum-B stable quadrupole fields, only the Yin-Yang provides access where perpendicular injection at large radii is possible. Access would be maximized in the MFTF magnet through the use of windings displaced toward each other so the center

of the major lobe of each winding is colinear with the center of the minor lobes of the other winding. This geometry would then allow each winding to act as a C-clamp for the other, thus minimizing required structural members.

To minimize superconductor development, the magnet will be constructed of fully stabilized Nb-Ti.

We initially considered both water-cooled and superconducting magnets. Preliminary cost estimates were about the same for either system. We chose the superconductor system for its relevance to reactor technology and its ability to provide a dc field.

Table 4 lists the MFTF magnet parameters.

Injection System

The MFTF injection system includes 100 2XIIB-type plasma generators to form a large-diameter plasma column for buildup, twenty-four 20-keV neutral-beam devices to inject a 1000-A startup current into the plasma stream for 10 ms, and twenty-four 80-keV sustaining neutral-beam devices to inject 750 A into the plasma. Figure 53 shows these neutral-beam injectors mounted on four-appendage vacuum chambers. The superconducting Yin-Yang magnet, with its axis oriented vertically, is housed in a vacuum chamber 12 m high and 9 m wide. Plasma generators are mounted on the top

Table 4. MFTF magnet parameters.

Parameter	Value
Target of field	Minimum-B mirror
Magnet type	Displaced Yin-Yang pair
Major radius (mean)	2.5 m
Minor radius (mean)	0.78 m
Axial half-displacement	0.78 m
Coil section	0.28 x 0.84 m
Mirror-to-mirror length	3.4 m
Vacuum-center field	2.0 T
Mirror ratio	2.09
Overall current density	3400 A/cm ²
Number of turns (each coil)	1180
Ampere turns (each coil)	8.03 MA
Total mass of coils with structure	195 x 10 ³ kg
Total stored energy	~500 MJ
Maximum allowable plasma radius	120 cm

dome. To protect the generators from plasma lost through the magnetic mirror, the intensity of the upper mirror is slightly greater than that of the lower mirror.

The 20-keV startup modules are basic replicas of the LBL-designed units now in operation on 2XII-B.

The dimensions of the 80-keV modules, also based on the LBL design, depend on the current density that can be accelerated to 80 keV. We expect the current density to be from 0.25 through 0.5 A/cm².

Specifications for the MFTF neutral-injector module appear in Table 5.

Vacuum System

The minimum vacuum requirement for continuous operation of a beam-sustained, magnetic-mirror-contained plasma is set by the balance (in the plasma surface layer) of charge-exchange losses by trapping of energetic neutral-beam particles through ion and electron impact ionization. Charge-exchange losses arise from the ambient neutral density external to the plasma and from molecular streaming of thermal neutrals from the neutralizing cells in the energetic beam lines. Gas diffusion through the magnet openings into the plasma chamber from the magnet chamber and from the beam tanks as well as reflux of particles from the containment chamber walls contribute to the ambient neutral density. The analysis leads to the following conclusions:

- Containment chamber walls during startup must act as pumps.
- The injected neutral-beam fraction that penetrates the plasma and ions lost through the

magnetic mirrors must be prevented from returning to the plasma as low-energy neutrals.

- Gas diffusion from the neutral-beam tanks into the plasma chamber must be restricted to values comparable to direct streaming from neutralizer cells.

The first requirement is met by forming active pumping surfaces on the containment chamber walls through deposition of titanium prior to each containment run.

Disposal of the unneutralized fraction of the accelerated ion beams, of the untrapped fraction of the ion beams, and of the plasma lost through the mirrors is complicated by the considerable energy content of these beams. This energy is collected by allowing these beams to fall on water-cooled panels in the beam tanks and in the end sections of the large vacuum vessel.

Facility

The MFTF machine and its support facilities will be located in and around LLL's Building 431, which formerly housed the Astron experiment. The building is 49 × 73 × 31 m (160 × 240 × 100 ft) tall and contains an enclosure of 21-m (7-ft) thick concrete blocks surrounding an area 20 × 32 × 23 m (67 × 106 × 74 ft) high. The floor of this enclosure is 6.5 m (21 ft) below ground level. A high bay 'hat runs the length of the building and contains the enclosure is served by an existing 60-ton-capacity bridge crane. Along both sides of the bay, mezzanines at two levels also run the full length of the building. The mezzanines and the ground floor

Table 5. Neutral-injector module specifications.

Parameter	Startup module	Sustaining module
Operating number	24	24
Spares	1	1
Total number	25	25
Maximum neutral-beam energy	20 keV	80 keV
Average neutral-beam energy	~16 keV	56 keV
Extracted ion current	80 A	80 A
Pulse length	10 ms	up to 0.5 s
Deuterium gas inlet	30 Torr-l/s	30 Torr-l/s
Beam divergence	±2° width × 0.5° height	2° width × ±0.5° height
Neutral-beam current at plasma	50 A of atoms	32 A of atoms

space beneath them provide about 4200 m² (44,000 ft²) of floor space.

Outside the building, a number of miscellaneous transformers, power supplies, and one small structure near the southeast corner will be removed. Large concrete slabs will be placed for the various components of the 80-kV injector power supplies that can be located outdoors. In addition, some site work will be required for expansion of the gaseous-helium storage facility east of the building.

The shielded enclosure was originally in the form of a rectangle, but we have since reduced it to an "L" shape and shortened the original roof beams. To restore the enclosure to the rectangular shape needed to provide the space required by MFTF would involve taking down and re-erecting about one-third of the existing wall blocks on their original foundation (which is still usable). In addition, several walls and much equipment on several levels will have to be removed from the area now ex-

cluded from the enclosure by the present location of the block wall.

The roof trusses over the present enclosure will have to be discarded; new ones will be cast with the same 1-m (3-ft) net concrete thickness as the original ones. Where the originals were of ordinary reinforced concrete, the new ones will be prestressed to provide a smaller total thickness.

A portion of the enclosure floor at the center will be broken and removed, and a foundation will be placed for the MFTF machine. This foundation will be of reinforced concrete construction with sufficient mass and strength to resist the static and seismic loadings imposed by the mass of the machine. A new 30-ton bridge crane will be installed inside the enclosure to permit parts handling when the concrete roof is in place.

The largest load on the primary power system will come from the power supplies for the sustaining neutral beam (220-MW peak, 10% duty cycle). The

Fig. 54. Tandem mirror geometry. Note the ambipolar barriers at each end.

required primary power will be drawn from the commercial power network (Pacific Gas and Electric Co.). Fortunately, the MFTF will be near (~ 1.5 km) a feeder from the center of the utility grid, thus providing us with stiff power service.

Tandem Mirror Experiment

During the latter part of this period, we began planning for a facility to test the new tandem mirror approach to Q-enhancement.^{31,32} The proposed tandem mirror experiment (TMX) would use two 2XIIB-type mirror cells connected by a long, cylindrical solenoidal magnet. By virtue of their positive ambipolar potentials, the mirror plasmas in the cells at either end of the solenoid would act as electrostatic plugs to better confine the central plasma

in the long solenoid. Figure 54 sketches the geometry and magnetic fields.

In a tandem mirror reactor, most of the fusion power would be produced by thermal burning in the solenoid, which might actually ignite. Although input power would be required to sustain the plasma in the end cells, the overall Q could be high if the plasma volume in the solenoid greatly exceeded that in the end cells.

The TMX experiment was not designed as a major step up the ladder of increasing "nr." Instead, it was designed to test the physics of the tandem mirror concept.

A proposal³³ for January 1977 submittal is now being prepared. If the project is authorized in February 1977, it could be completed by October 1978 at an estimated cost of \$11 million.

SECTION 2. SUPPORTING RESEARCH

Introduction and Summary

Supporting research activities (also called development and technology activities) provide the technical basis for future mirror-confinement experiments. The two major programs with applications to near-term mirror devices are neutral beams and superconducting magnets. Also included are conceptual design studies of various types of power reactors. The rotating target neutron source (RTNS) at LLL is used to study radiation damage caused by 14-MeV neutrons; such damage will severely limit the operating life of parts of any fusion reactor.

Other programs based on long-range requirements include tritium and high-vacuum technologies.

Superconducting Magnets

The industrial development of high-current, high-field (10 kA at 12 T), high-current-density (10^4 A·cm⁻²) Nb₃Sn conductors is the main program goal. It has already been demonstrated that practical conductors meeting these requirements can be produced in short lengths. Now, the major program goals are to develop economical fabrication methods for producing long lengths and to characterize the resulting conductors by laboratory tests. The more usual bronze process using Nb rods has been used to prepare triple-extruded conductor from a 8-in.-diam billet.

Because very small resistivities might cause significant heat generation in large coils, we greatly increased the sensitivity of residual resistivity measurements of both short samples and small coils. We concluded that lengths of conductor much longer than required for short-sample testing must be tested to eliminate current-transfer effects in the high-current conductors of ultimate interest; for this reason, and also to test small coils at fields of 12 T, we have initiated construction of a high-field test facility.

The 6.5 mm $\times$ 6.5 mm conductor for the MFTF coil was designed and production amounts have been ordered; stabilizing copper will be added and a large test coil has been designed.

Direct Energy Conversion

A method for recovering the energy of the ions that emerge from neutral-beam sources along with the neutral particles was developed and successfully tested at 15 keV using a MATS-III ion source. Space-charge of the ions caused them to "expand" and deposit their charge on properly designed electrodes with about $70 \pm 2\%$ efficiency. Because this technique appears to be applicable to high-power beams, a system was designed and fabricated for test on the 1/4-scale TFR beam at LBL (120 keV, ~ 15 A).

The periodic-focus (20-stage) and the Venetian-blind (1- and 2-stage) plasma direct converters were

experimentally shown to work as predicted at scaled-down voltage and power density. Conceptual designs of three-stage, reactor-scale Venetian-blind direct converters gave 64% efficiency; a single-stage design gave 48% efficiency but at a lower cost.

Reactor Studies

A power reactor based on the "standard" mirror configuration was designed and found to be very costly because of the large fraction of circulating power. To be economically more attractive, the ratio of fusion power to injected power (Q) should be higher (i.e., Q should be at least 2 to 3 instead of 1). Therefore, we studied several techniques for improving confinement; two appeared to be very promising: the tandem mirror reactor (TMR) and the field-reversed mirror (FRM). Preliminary reactor designs were started for both. The TMR is based on three mirrors in tandem; the ambipolar potential of the end mirrors electrostatically confines the reacting plasma in a large central solenoidal cell. The FRM uses neutral beams to maintain a strong steady-state internal current in a plasma so as to produce a pattern of closed field lines. An FRM reactor can be produced in small modular units.

We began work on an improved fusion-fission hybrid reactor design that is based on optimized parameters and more practical component designs. The design has a unique, reinforced-concrete, coil-support structure and modular blanket; the blanket and power-conversion systems utilize existing gas-cooled reactor technology and were designed by the General Atomic Company as participants in the study. In addition to electrical power, the hybrid studied can produce Pu for about \$50/g.

For comparison with the fusion-fission breeder, we made a preliminary study of a high-energy accelerator for producing neutrons. With the accelerator, the cost of Pu would be about two times that of the fusion-fission breeder, but the technology would be more conventional.

A detailed calculation of the plasma behavior in a mirror FERF showed that the peak neutron flux at the wall would be about 10^{14} neutrons·cm⁻²·s⁻¹, which is double that previously predicted.

Two other preliminary reactor designs were briefly studied: an electrostatically plugged cusp, which might have $Q \approx 5$, and a linear Z-pinch without external coils or solid walls.

During the year, we also prepared updated reviews of the safety and environmental aspects of both fusion and hybrid reactors.

Neutral Beams

The neutral-beam development program continued in three areas: experimental work, facility

construction, and conceptual design. Program highlights were as follows:

- A 120-kV, long-pulse source with 1/4 the area of a TFTR injector was designed and built; testing of this source began in the 80- to 150-kV, 20-A, 0.5-s test facility in August. This facility has several unique features, including a 172,000-*f* expansion volume to limit pressure rise during a 0.5-s pulse and a very complete beam diagnostic system with a computer and a graphic display of data.

- We completed a conceptual design of the complete TFTR injector system and began the detailed design of a prototype.

- The full-size, 120-kV, 0.5-s TFTR injector will be tested first for 30-ms operation. When facilities have been completed, a 0.5-s test will be conducted at the HVTS.

- The design and construction of the 200-kV, 25-A dc/65-A, 5-s HVTS facility continued. Completion is expected in late FY 1977. A model of the cryopump was successfully tested at 150,000 *l*/s.

- Negative-ion sources are required above ~150 kV for efficient injectors. We have produced a 200-mA D⁻ beam using double charge exchange in Cs. A 100-kV negative-ion accelerator was designed and completed.

RTNS-II

Construction of the rotating target neutron source-II (RTNS-II) was scheduled to begin in FY 1977. A parallel R&D program was started to build a prototype accelerator and to develop the target system.

Neutron Irradiation Studies

Twenty-four experimental runs (of about 1-week duration each) were conducted at the RTNS-I 14-MeV neutron source. Many different experimenters and institutions were involved. The main LLL experiments were investigations of mechanical properties using post-irradiation testing of miniature tensile specimens, e.g., Nb and V at ambient temperatures and Nb at elevated temperature (~700°C).

The neutron spectrum produced by bombarding a "thick" Be target with 30-MeV deuterons was measured using the cyclotron at the University of California, Davis. Spectra measured close to the source contain a much larger component of low-energy neutrons than those measured at a distance using low-angle time-of-flight methods.

Other neutron irradiation studies included the following:

- A technique for simulating intense, high-energy neutron damage was demonstrated by alloying metals with small amounts of ²³⁵U and

diating the alloy in a thermal reactor; Nb - 1.1 at.% ^{235}U was used.

- The production rate of He in carbon bombarded by 14-MeV neutrons was measured. Helium diffusion at high temperatures was studied in graphite, silicon carbide, and boron carbide (candidates for the first walls and liners of tokamak reactors).

- A facility was constructed to irradiate superconductors using 14-MeV neutrons and to measure the H-I properties of the conductors at magnetic fields up to 12 T. A unique feature of the apparatus is that the superconducting specimen can be irradiated and tested while the liquid-helium environment is maintained; initial tests were successfully conducted.

- Initial damage rates, as measured by electrical resistivity of Nb, U, and Mo, at 4.2 K, were compared using three different neutron sources (14-MeV, D-Be, fast-fission); the effects appear to scale with damage energy.

The mechanical effects of He in metals were studied using a tritium decay technique to inject ^3He into Nb and Nb-1% Zr specimens. Also, a computer model was studied which simulates high-energy collision cascades in a crystal lattice. Such many-body calculations can be compared to simpler collision models and to experimental results.

Tritium Technology

The successful development of fusion-generated power is dependent upon major advances in tritium technology. Tritium-related studies during the report period included the following:

- The chemical "gettering" of tritium from inert gases was examined as a method for reducing concentrations in a room atmosphere and for removing tritium from blanket coolants. Large-scale systems using Ce powder were studied. Initial measurements used D_2 in argon; measurements with T_2 are planned.

- We studied a variety of available pumps that are suitable for future tritium operations.

- An experimental study was made of the tritiated methane given off by stainless steel after its exposure to tritium gas; the effects of various cleaning methods were studied.

- We identified problems of mirror fusion reactors relating to tritium containment and removal and designed means for reducing emissions to the environment to below 1 Ci/day. Safety, operation costs, and capital costs were considered.

- In an attempt to correlate performance on the RTNS with measurements on coupons, we studied the operation of titanium tritide targets used at the

RTNS-I. We also began an experimental study of alternate target materials such as erbium tritide.

Vacuum Development

Apparatus was designed and fabricated for making basic measurements of cryopump performance.

Superconducting Magnet Development

During the report period, our work has been directed towards two main goals:

- Development of multifilamentary Nb₃Sn superconductors for large fusion devices, and
- Development of a conductor for the MFTF.

Multifilamentary Nb₃Sn Superconductors

The Nb₃Sn development work is a continuation of the program initiated in FY 1974³ to develop for large fusion systems a superconductor with a nominal rating of 10 kA at 12 T, with a current density of $10^4 \text{ A} \cdot \text{cm}^{-2}$. Fabrication development has continued at both Supercon and AIRCO using the niobium-tube and rod/bronze techniques, respectively.

Methods for measuring the properties of these conductors have been refined to increase their sensitivity. Previous tests had shown the conductors to be capable of carrying high currents before going "normal"; however, measurement techniques were not sensitive enough to detect the onset of resistance. This onset must be known because the limiting current in a large coil may be determined by resistive losses rather than by the "quench" current. Using the new methods, we have measured resistivities of $10^{-11} \Omega \cdot \text{cm}$, compared to about $10^{-10} \Omega \cdot \text{cm}$ at the quench current; data on both types of conductor are given in Ref. 34. Our results show that a current density of 10^4 A/cm (excluding the space occupied by Cu) can be achieved in the conductors at this level of detection. Higher resolution cannot be obtained from measurements on short samples because the signals are swamped by the voltage required to drive current across the bronze matrix from the outermost filaments to the inner ones as the conductor enters the high-field test region. At the ends of the short sample where the magnetic field is low, the current can be carried in the outer filaments only; however, in the high-field region, where voltages along the sample are being measured, all the filaments must carry current. The size of our 12-T test magnet is such that the voltage appearing across the center 1-in. length of the sample is partially the result of current flowing through the bronze matrix to meet the two conditions.

Improvement in the power supplies for the 27-cm-bore Nb₃Sn coil and for the Nb-Ti backing coil

have enabled higher resolution to be obtained on the Nb₃Sn coil than was reported in FY 1975.³⁵ By measuring across two turns in the high-field region, we can detect a resistivity of less than 10^{-12} $\Omega \cdot \text{cm}$ instead of 3×10^{-12} $\Omega \cdot \text{cm}$ indicated by short-sample measurements at the same current and field of 2000 A and 8.5 T. This result also indicated that any degradation by this nominal 1000-A conductor, due to strain induced by bending or magnetic forces is very small and well below the level that would be troublesome in future coils.

Scaling up the small AIRCO experimental billets to 8-in. diameter has accentuated difficulties with the barriers; means of overcoming these difficulties are now being pursued. Also, room-temperature tests on our recently commissioned tensile tester have revealed that conductors processed identically may have widely varying mechanical properties. Other workers in the field have obtained similar results. The popular explanation is that there is a critical ratio of Nb₃Sn (and perhaps Nb) to the cross-sectional area of the matrix which, if exceeded, causes the whole conductor to fracture as the Nb₃Sn filaments break at a strain of about 1%. We are exploring this hypothesis to ensure that future conductors behave overall as ductile materials.

We must continue to test and prove these new conductors in production lengths by building and operating full-scale coils. Therefore, we are building a new set of 1-m-bore Nb-Ti backing coils, complete with cryogenics, in which to test larger conductors and coils. The fabrication of the cryostat for this facility, known as the High-Field Test Facility (HFTF),³⁶ should be completed by the end of December 1976, and fabrication of the coils will begin during FY 1977.

MFTF Conductor

The conductor development for MFTF is now well underway. We have ordered 10-in.-diam sample billets from the four major superconductor manufacturers in the U.S.A. to be processed to the final size (6.5 mm square). Following evaluation of the conductors at LLL, stabilizing Cu will be added to 6000 ft of superconductor, which will then be wound into a test coil. This coil will simulate as closely as possible the conditions expected on MFTF and will enable us to evaluate its stability performance. The coil will be tested in the new HFTF cryostat, and the first Nb-Ti backing coils will be used to boost the field at the conductor close to the maximum value of 7.5 T needed for MFTF. Contracts have been placed with Supercon and AIRCO for the development of alternative fabrication processes for adding the required stabilizing Cu

and cooling surfaces to the MFTF superconducting core.

We have continued to develop stress-analysis codes and more refined calculations of the stresses and displacement characteristics of the MFTF coil structure. This work has been supported by an independent analysis by the Boeing Aircraft Co. Results of both studies confirm that the proposed structural concept is sound and that the stresses and deflections are acceptable.

Direct Energy Conversion

Beam Direct Conversion

Beam direct conversion is being developed as a means of raising the efficiency of neutral-beam production. Without it, only 50% of the D⁺ ions are converted to neutrals at 100 keV (50 keV for H⁺ ions); at 160 keV (80 keV for H⁺ ions), the conversion is 30%.

We have developed a compact, in-line direct converter³⁷ that can handle high-power beams continuously. Some converter designs involve grids that intercept either neutrals or full-energy ions that are being slowed down and collected, e.g., the converter being developed at Fontenay-aux-Roses.^{38,39} Although intercepting grids may be useful for pulsed operations (0.5 s) as in the Joint European Torus (JET) or the Tokamak Fusion Test Reactor (TFTR), they would be unacceptable from a heat-removal standpoint for either long-pulse (>1 s) or steady-state operation. Our design therefore does not incorporate intercepting grids.

Proof-of-principle tests at 15 keV have been completed. In an experimental test of an in-line beam direct converter,⁴⁰ a steady-state, MATS-III ion source was masked to produce a 15-mm-thick, 60-mm-wide slab beam that consisted mostly of H⁺ ions. The ion energy was varied from 10 keV to 15 keV; the full-energy ion current varied from about 50 mA to 130 mA because the ion current from the source varies approximately as $W_0^{1/2}$. We expected and found the same efficiency at all beam energies.

The direct converter (Fig. 55) is constructed from molybdenum and is cooled by radiation only. When the voltages are varied, the temperatures of the various electrodes range up to about 1600°C. At the optimum setting, the collector is only dull red because most of the power is recovered electrically. We determined the efficiency by measuring the currents and voltages at all electrodes and by measuring the ion beam power with a calorimeter. The calorimeter can be seen in its retracted position in Fig. 55. By recording the total beam power

Fig. 55. Scaled direct converter tested at 2 kW of 15-keV H^+ . Efficiency is 70%.

transmitted through the direct converter with no applied voltages and also with voltages set to stop all ions, the neutral component of the beam could be subtracted out to give a measure of the total incident ion beam. The currents to the different electrodes were measured as the voltage at the collector electrode was varied from zero to above the source voltage. Maximum recovered power, and hence maximum efficiency, occurred at about 0.98 of source voltage. Measured efficiency was typically $\eta = 0.70 \pm 0.02$ for the total ion beam, including the ~20% of beam current in half-energy protons.

Figure 56 shows the measured currents to the positive collector and to both negative electrodes versus the voltage applied to the collector. The negative electrodes were both held at -3 kV, the source voltage was 12 kV, and the total ion-beam power was 1450 W (as measured with the calorimeter). At 11.8 kV, the collected power reached a maximum of 1050 W, and the drain on the negative power supply was 48 W. Therefore, the efficiency was

$$\eta = \frac{1050 - 48}{1450} = 0.69.$$

The 1450 W includes the half-energy ions whose effect can be seen at about 6 kV in Fig. 56. These results agree with predictions based on trajectory calculations made with the DART code.

We have prepared for the next step in scaling up our beam direct converters to fulfill the requirements of large neutral-beam injectors, e.g., TFTR.⁴¹ Such converters must operate at 120 kV with a total beam of about 60 A for each injector. By using beam direct converters, many megawatts of electrical power and several millions of dollars in the capital cost of power supplies can be saved.⁴¹

After completing computations and experiments at voltages up to 15 kV and at beam powers up to 2 kW, we designed and fabricated a converter for the 120-kV beam (a 1/4-scale TFTR beam) being developed at LBL. This converter will operate with a total beam of 15 A and will serve as a prototype for the full-size, 60-A system planned for next year.

Fig. 56. Data taken from the device in Fig. 55 using 2 kW of 12 keV H^+ . The effect of half-energy ions can be seen.

The charged component of the beam emerging from the neutralizer will consist of about 7 A of D^+ ions or 11 A of H^+ ions and will also contain smaller components derived from molecular ions. The converter will collect 800 kW of charged beam power, which will be dissipated in a variable-load resistor. (Future systems will recycle the recovered power back to the ion source.) By operating at a pressure not greater than 3×10^{-5} Torr, the system will minimize losses due to ionization and to charge exchange of the background gas. The equipment and diagnostics have been designed and fabricated and are now being assembled in preparation for experiments in FY 1977.

A review of beam direct conversion is given in Ref. 37.

Plasma Direct Conversion

During the report period, we completed the first phase in the development of plasma direct conversion for mirror reactors: proof-of-principles.³⁷ The periodic-focus (20-stage) and the Venetian-blind (one- and two-stage) plasma direct converters have

been proven to work as predicted. Since work in this phase began in 1969, experiments have included the effects of ion energy spread, where we considered energy selection, ion density sufficient to have space-charge effects on energy selection and efficiency, electrons requiring removal before ion deceleration, secondary electrons, and expansion to convert random motion to directed motion. We developed DART,⁴² a simulation code which accurately predicts the results of the experiments and which can be used to design plasma direct converters for reactor application. A final report describes the results of the measurements and of the computer simulation of the periodic-focus plasma direct converter.⁴³

The second phase of the development of plasma direct conversion for mirror reactors is operation at high power and high voltage (~ 100 keV). We have completed the designs for a modification to the present apparatus in which a 100-keV, 0.1-A beam will be added to test the Venetian-blind plasma direct converter.

In addition to the experimental direct conversion work, we have been preparing conceptual designs for reactor application. Two conceptual designs have been completed: a three-stage direct converter for the reference mirror reactor and a single-stage direct converter.

The three-stage, Venetian-blind direct converter for the reference mirror reactor design study⁴⁴ has a net efficiency of 64% for the particular ion energy distribution that is assumed. Because of the positive ambipolar potential in the confined plasma, the ions arrive at the direct converter with an average energy of about 170 keV; none have energies below 100 keV. The electrons arrive at the direct converter with a mean energy of about 15 keV. Because the grounded grid receives all of the electron power plus some intercepted ion power, it must remove more heat than the other grids. Hence, it is made of tubes that are cooled with He at 1000 K to allow thermal recovery of the electron power. The negative grid and the two intermediate collector stages are made of graphite and are radiatively cooled. The third collector stage is cooled by He at 1000 K.

The single-stage direct converter has the same energy distribution as the three-stage converter, but has a predicted efficiency of 48%. The grounded grid and the ion collector are again cooled with He at 1000 K. Because the power flux is too high to allow radiatively cooled grids, the negative grid is water-cooled and the heat is not recovered.

Our recent work on plasma direct converters (for both beams and leakage plasmas) is summarized in Ref. 37.

Advanced-Fueled Fusion Reactors Suitable for Direct Energy Conversion

The period 1/76 to 1/77 was the first year of a 2-year project sponsored by the Electric Power Research Institute, Inc. (EPRI) under contract no. RP645-2 and performed by LLL in conjunction with Brookhaven National Laboratory (BNL) and the University of Illinois. LLL has been concerned with the analysis of the efficiency, cost, power handling, and coupling of single-stage and multistage Venetian-blind direct converters to the designs for tokamak reactors fueled by catalyzed-D and D-³He that are being developed by BNL and the University of Illinois.

Initially, we assembled some key results from earlier studies of direct converters and neutral-beam injectors.⁴⁵ Since then, we have constructed and analyzed models with varying degrees of complexity. On the bases of the earlier models, we have developed efficiency and sizing data for direct converters attached to a low-beta, catalyzed-D tokamak.^{46,47} In Fig. 57, we show the reactor along with three single-stage converter designs that correspond to three different power densities.

As the escaping plasma passes radially from the diverter to the outer reach of the toroidal field coils, it is subject to the transverse toroidal field. Additional coils to cancel the effects of this transverse field are being studied. We are also studying design details related to the electrical insulators and alternate grid structures that can tolerate higher power fluxes.

Reactor Studies

"Standard" Mirror Reactor

In FY 1976, we designed a fusion power reactor based on the "standard" mirror configuration (Yin-Yang minimum-|B| coils) with classically predicted confinement.^{44,48,49} The reactor design is shown in Fig. 58; a power-flow diagram for the reference case is shown in Fig. 59.

The design is based on a steady-state, mirror-confined D-T plasma sustained by the continuous injection of D⁰ and T⁰. The Yin-Yang magnet is oriented vertically to permit lowering the bottom half of the magnet and the complete blanket by means of a float. Once lowered, the blanket segments can be removed by a crane.

The blanket is a spherical shell, segmented into shapes called lunes. The plasma is continuously sustained by negative-ion neutral-beam injectors. Venetian-blind direct converters are used for the direct energy conversion of plasma and leakage. The reactor is enclosed in a reinforced-concrete, dome-

shaped building that is sealed to prevent the escape of radionuclides (principally tritium) released inside the building. Not shown in Figs. 58 or 59 is the thermal conversion system, which consists of a two-phase, potassium, primary cooling system coupled to a potassium-topped steam cycle.

The reference design was optimized to minimize power cost. Even so, we found the cost of power from this reactor (289 mills/kWh) to be much higher than present-day power costs for two reasons:

- The ratio of fusion power output to injected beam power, Q , is only 1.1, and 77% of the gross electrical power must be recirculated to the injector power supplies; and
- The reactor components are large and complex.

Several possible modest improvements in Q (by a factor of 2 or 3) within the basic framework of the neutral-beam-sustained, Yin-Yang confinement concept would significantly reduce the cost of power and to some extent reduce the requirements for advanced technologies. However, the predicted cost of power is still considerably higher than present-day costs.

We conclude that, to achieve economic competitiveness with other energy options, mirror machine fusion reactors probably require both a considerably higher Q and major design simplifications. These requirements may necessitate a departure from the "standard" mirror configuration. A number of variations on mirror confinement hold the promise of high Q and design simplicity (see later discussions of the field-reversed mirror and the end-stoppered, or tandem, mirror).

Q-Enhancement Ideas

Realizing that the energy balance of a conventional D-T mirror reactor would be only marginally satisfactory, we conducted a survey of possible "Q-enhancement" schemes to increase the energy gain factor, Q , of future reactor designs. Some of these might represent relatively minor modifications in the standard mirror configuration, e.g., programming neutral injection to move the mirror points apart and back together in a cyclical fashion (Appendix B, Ref. 30) or applying rf fields either to move particles away from the loss cone⁵⁰ or to raise the plasma temperature (Section 3, Ref. 30). Other schemes might involve major physical changes in the conceptual mirror reactor design, e.g., linking several mirror cells in a mirror-torus hybrid⁵¹ or using long, linear, multiple-mirror or end-plugged solenoidal reactors.^{31,52,53}

Fig. 57. The low-beta, catalyzed-D tokamak reactor with a single-stage, direct converter accommodating three different power densities:
 (A) 150 W/cm^2 ($\eta_{dc} = 45\%$)
 (B) 100 W/cm^2 ($\eta_{dc} = 52\%$)
 (C) 50 W/cm^2 ($\eta_{dc} = 59\%$)

A report of the survey work was prepared midway through FY 1976.³⁰ Table 6 repeats a summary table from this report. Work since the publication of Ref. 30 has focused on two areas:

- Q-enhancement of the basic mirror design, where the new tandem mirror reactor (TMR) concept³² is being vigorously studied, and
- The field-reversed mirror reactor (FRM).

Our evaluation of the other items in Table 6 was, as reported in Ref. 30, that they represented areas

where other research groups were actively working and where any contributions we could make would arise naturally from work already in progress (such as the high-beta 2XIB results, which affect the possibility of ion bumpy torus reactors). The FRM offers the potential of a compact reactor of convenient unit power output, but many areas of physics pertaining to it remain to be explored. The Q-enhanced mirrors such as TMR, which operate in physics regimes that have been more thoroughly

Fig. 58. Mirror fusion reactor.

Fig. 59. Power-flow diagram for mirror fusion reactor (power in MW), where recirculating power fraction = power consumed/gross electrical = 0.76.

studied, lead to attractive, though considerably larger, reactor designs. The program that has evolved represents a balanced consideration of these two approaches.

Field-Reversed Mirror Reactor

The field-reversed mirror (FRM) is an axisymmetric, plasma-confinement configuration (see Fig.

that uses neutral-beam injection to maintain a steady state. In such a configuration, Q should be considerably enhanced by virtue of toroidal confinement. The plasma, by properly induced currents, creates and maintains a pattern of closed field lines. The plasma equilibrium is very similar to a field-reversed theta pinch⁵⁴ and has some similarities to the Astron device,⁵⁵ although the current in the FRM is carried by plasma particles rather than by a distinct high-energy group of ions or electrons. Recent experimental results in 2X11B⁵⁶ and encouraging experiments on field-reversed

theta pinches in the Soviet Union⁵⁴ have suggested that we may be able to achieve this plasma geometry using neutral-beam technology that is either available at present or under active development.

During the report period, we undertook a preliminary reactor design to see if the FRM had any possibility of making an economically attractive reactor.⁵⁷ From early theta-pinch experiments, we knew that the plasma would be unstable if it were wider than 10 to 20 gyroradii,⁵⁸ and we felt that such a small plasma might not lead to an economical reactor, regardless of its energy-multiplication (Q) or ignition characteristics. We found that, under reasonable assumptions about plasma and energy containment time, we could find sets of parameters that would lead to attractive capital costs and unit sizes; direct costs of under \$1000/kW(e) and unit sizes of 100 MW or less appear feasible. Because of the economics of putting several plasma cells in a single, large solenoid, multicell reactors appear most attractive. A sample set

Table 6. Summary and evaluation of mirror alternatives studies.

Category	Problems	Available theoretical tools	Applicable near-term experiments	Evaluation
Means to improve Q	Detailed balance of gains and losses	Mainly Fokker-Planck codes.	2XIIB, Baseball II-T (p limits).	Should continue theoretical study. Might increase Q by $\geq 50\%$ and decrease cost of mirror reactor proportionately.
Field reversal	MHD stability. Startup.	SUPERLAYER code revised for neutral injection. Stability analysis.	Cornell Astron; Kurtnullaev experiment. Possibly 2XIIB. High-intensity ion sources.	Should actively pursue; has greatest potential for small, cheap reactor, though still great uncertainty in physics. Needs development of intense ion sources.
Field optimization and simple mirror	MHD beta limit. Heat loss by "line tying."	Three-dimensional equilibrium code. Stability analysis.	2XC and certain aspects of 2XIIB.	Should build 2XC: could substantially reduce reactor cost and magnet development.
Mirror-torus hybrids	MHD beta limits. Field design.	Field design codes. Point model energy-balance code.	2XC (to model a single mirror cell). Elmo bumpy torus (EBT). TORMAC, MIRACLE.	Ion bumpy torus (IBT) may be promising if simple mirror cell can be made to work.
Long, linear machines	Large size because of heat leakage at the ends.	MARTENI code. Analytical models.	2XIIB in two-component mode. Multiple-mirror experiments (UCB, Novosibirsk).	The size still seems too large.

of parameters is shown in Table 7; Fig. 61 shows a parametric survey of costs. Basing our work on what appear from these studies to be the best parameters, we undertook a preliminary reactor engineering design. The result was a 12-cell reactor assembly, shown in Fig. 62, which would put out approximately 120 MWe. The energy-multiplication factor (Q) was roughly 5, which indicates that the recirculating-power fraction and general energy economics of this design will be favorable.

In order to proceed, the design work to date has required a number of assumptions about FRM plasma physics. These will receive continuing effort in FY 1977.

- One of the most critical assumptions is the assumed plasma loss at the ion diffusion rate [$\tau = (a^2/\rho_i^2) \tau_{ii}$, where a is the plasma radius, ρ_i is the ion gyroradius, and τ_{ii} is the collision time].

- Another assumption is our ability to create and maintain a steady-state configuration using neutral-beam injection.

- A third assumption is the stability of the FRM configuration, and the maximum value of a/ρ_i , which is stable.

Tandem Mirror Reactor

The concept of a tandem mirror reactor (often called the "end-stoppered" mirror) was developed independently by Dimov *et al.*,^{31,33} and by Fowler

Fig. 60. Field-reversed mirror reactor.

Fig. 61. Power cost and fusion power versus injection energy for optimum cell lengths. M is the blanket energy multiplication.

Table 7. Typical field-reversed mirror reactor design.

Parameter	Value
Plasma minor radius, a	0.031 m
Plasma major radius, R_p	0.062 m
Plasma length	0.19 m
a/ρ_i	5
Vacuum field	8.2 T
Ion energy	77 keV
Electron energy	29 keV
Peak density	3.6×10^{21} ions/m ³
Fusion Q	5.3
Fusion power	18.5 MW/cell
Plasma β	1.5
Blanket thickness	1 m
Blanket multiplication, M	1.7
Shield thickness	0.6 m
Superconducting solenoid radius	2.4 m
Wall radius	0.61 m
Cell length	1.1 m
Injected current	17 A/cell
Injected power	3.5 MW/cell
Mirror coil current	46 kA
Ioffe bar current	10 kA
Mirror coil cross section	13 cm ²
Ioffe bar cross section	14 cm ²
Resistive power	0.28 MW/cell
Neutron heating	0.38 MW/cell
P_{net}	10.2 MWe/cell
Total cost	\$745/kW(e)

and Logan.¹² In this design, two "standard" mirror cells are located at the ends of the third cell, which is a long solenoidal magnet. Under certain conditions, the plasma confined in the two mirror end cells can plug end losses from the relatively long solenoidal cell. The plugging action is due to the electrical ambipolar potential inherent in open-ended confinement. The conditions are:

- $n_{end} \gg n_{center}$ and
- $T_{i, end} \gg T_e \approx T_{i, center}$,

where n is ion density and T is temperature.

These conditions imply high plasma pressure ($P \propto n_{end} T_{i, end}$) in the end cells; in turn, that requires

Fig. 62. Multicell, field-reversed mirror reactor.

very high magnetic field strengths (~ 18 T) and high injection energies (~ 1 MeV). Fortunately, the volume of the end cells can be very small relative to the volume of the central cell.

We have addressed the questions of economics and feasibility. Given relatively stable confinement,

feasibility rests on two critical technological questions:

- Can a relatively small, "standard" mirror magnet be made at field strengths of about 18 T or more?

- Can D⁰ beams of several hundred MW and 1 MeV or more be made at reasonable efficiency (50 to 70%)?

The input power to a TMR is only that needed to sustain the end-plug plasma, whereas the output fusion power comes from the central cell, which can be lengthened as much as necessary to make the circulating power fraction small.

The cost of the TMR is

$$C \approx C_{\text{plug}} + \frac{C_{\text{center cell}}}{\text{unit length}} \ell$$

The electrical power output is

$$P_e = -P_{\text{injection plug}} + \frac{\eta P_{\text{fusion center cell}}}{\text{unit length}} \ell, \quad (19)$$

where η is the usual thermal conversion efficiency, and ℓ is the length of the central cell. From Eq. (19) we see that a favorable power balance can always be attained for a sufficiently long central cell. For cases of interest, we find that the cost of a central cell long enough to make the recirculating power small is much more than the cost of the plugs. Also, the cost per unit power C/P_e is less than \$1/W for 18-T magnetic field strengths and 1-MeV injection energies.

The preceding discussion is qualitative because the concept is quite new; however, the conclusion is in sharp contrast to the results for the standard mirror reactor, which relies heavily on advanced technology to achieve a high-cost [$\sim$ \$5/W] reactor with a marginal power balance ($Q \approx 1$). In contrast, given the advanced technology of the standard end plugs, the resulting TMR is low cost ($<$ \$1/W) and has a favorable power balance ($Q \approx 5$). The problems associated with ⁴He accumulation have thus far been ignored but will be studied in FY 77.

The TMR study begun at the end of FY 1976 will be extensively pursued during FY 1977.

Fusion-Fission Reactor

In FY 1975, we completed the conceptual design of a mirror fusion-fission (hybrid) reactor.⁵⁹ The purposes of this study were

- To determine a manner in which all necessary components could be integrated into the plant,
- To assess the technological problems, and
- To develop a cost estimate.

The design was based on a mirror-confined D-T plasma and a fast-fission blanket that produces both energy and fissile material. It was not optimized in either an engineering or economic sense, but rather was a reference point from which further study could proceed.

During the past year, we concentrated on optimizing the mirror hybrid for the production of fissile material and on refining the design of selected reactor components. Because the plasma performance parameters for a hybrid reactor are much less stringent than for a pure-fusion reactor, the hybrid is a reactor that could be a relatively near-term goal of the fusion program. We therefore restricted our design to components based on existing technology where possible and on minimum extrapolation of technology otherwise. Results of this year's work were presented at a series of technical meetings.⁶⁰⁻⁶⁷ (For convenience, we have issued a single report⁶⁸ containing Refs. 62 through 67.)

Optimization Studies. Point-design cost estimates⁵⁹ suggest that incorporating both fusion and fission components in the hybrid reactor would make the capital cost of the hybrid (\$/kWe) greater than that of a fission reactor. However, the impressive fissile breeding performance of the hybrid, compared to that of a fast-breeder reactor of comparable thermal rating, indicates that the most promising avenue for commercialization of this reactor concept is as a breeder that produces fissile fuel for thermal fission reactors.⁶²

Optimization studies during the past year used the technique of parametric system analysis of the plant economics,⁶³ where optimization was defined as a determination of the reactor parameters that minimize the cost of producing fissile fuel. We developed a system model of the mirror hybrid that included a reactor description, fuel management, and the economics of the hybrid plus the fission reactors that use the hybrid-produced fissile fuel. The results of these optimization studies were used to establish the reactor parameters for a new hybrid point design to be completed in FY 1977.

Blanket Neutronics Studies. Plant economics are highly sensitive to the neutronics performance of the blanket. We therefore performed neutronic analyses of various forms of blanket fuel to determine those that yield the highest breeding ratios. Fuels studied to date are uranium carbide, uranium - 7 wt% molybdenum, and thorium metal.⁶⁴ In FY 1977, we shall extend this list to include uranium silicide. We also completed a comparison between the reaction rates obtained from our neutronics model for 14-MeV neutrons in uranium and those obtained experimentally.⁶⁶

Component Design. We developed a design for a superconducting Yin-Yang magnet that includes a post-tensioned concrete restraining structure and in which the magnet is mated with a blanket shaped like a spherical annulus. The magnet-blanket design

incorporates features that offer solutions to the difficult problems of magnet separation and blanket removal.

In consultation with the LLL staff, General Atomic Co. (GA) has completed a study of the feasibility of adapting existing gas-cooled reactor technology to the mirror hybrid reactor.⁶⁷ GA concluded the following:

- A blanket and power-conversion system using He coolant and components developed for He-cooled fission reactors is an attractive design option for the mirror hybrid reactor.

- According to a preliminary safety analysis, there appear to be no inherent features in the hybrid concept that could compromise the safety aspects of the reactor.

Electronuclear Breeding

As a corollary to our fusion-fission hybrid work, we have taken a brief look at accelerator-produced neutrons for the conversion of fertile to fissile fuel.⁶⁹ This was done to establish a basis for comparing the mirror hybrid with electronuclear breeding.

Electronuclear breeding is based on the generation of neutrons with high-energy ions and the subsequent capture of these neutrons by a fertile material. This concept is not new: the MTA program at LLL (1949-1954) examined this concept both experimentally and theoretically. We have built upon the MTA results by applying more recent calculations of the nuclear cascade processes and a reasonable extrapolation of present accelerator technology. As an example, we have considered a system in which an Alvarez Linac produces 0.375 A of 500-MeV deuterons; a lithium primary target converts the deuterons to high-energy neutrons by stripping and other nuclear processes, and a secondary target of uranium and/or thorium multiplies the high-energy neutrons by spallation cascades, nuclear excitation, and fission events. The resulting neutrons are then captured in the secondary target to produce fissile material(s).

A preliminary economic analysis predicts that this system would produce ²³⁹Pu for \$92/g, compared to \$55/g for a mirror hybrid if similar economic ground rules are assumed. At a ²³⁹Pu cost of \$92/g, the electronuclear breeder would compete with isotopic enrichment of ²³⁵U when uranium ore (U₃O₈) costs ~\$175/lb. The cost of electric power from a light-water reactor (LWR) fueled with \$92/g ²³⁹Pu is predicted to be 27 mills/kWh(e), of which ~25% is the cost of fuel produced by the electronuclear breeder.

150-keV D⁰-T⁰ Injector

Neutral beams have been successfully used for plasma heating in both tokamak and mirror MFE experiments. Therefore, it is likely that vast injectors operating continuously (or nearly so) will be required for future FERF and EPR machines. Irrespective of the type of reactor, the very size of the injector handling the equivalent of thousands of amperes of D⁰ (and T⁰) at hundreds of thousands of electron volts makes operating efficiency and capital cost a major factor in the system design. Recent estimates have the neutral-beam equipment accounting for 10 to 20% of the total reactor cost.

With this in mind, we have assessed the technical requirements of several types of very large neutral-beam injectors for the reference mirror reactor, including those using positive- and negative-ion sources.⁷⁰ Our study included

- An evaluation of photodetachment in place of electron stripping by metal vapor,

- Calculations showing the comparative power efficiencies as a function of beam energy.

Because of the relative ease of electron stripping, negative-ion systems offer the best results at higher beam energies, but recovery of the power in the unneutralized fraction of the beam is important for good efficiency. A major problem of injector design will be providing high-voltage insulation in the presence of intense neutron and gamma radiation.

Figure 63 shows a layout of an injection system designed to inject 1800 A of D⁰ and T⁰ atoms into a mirror reactor at 150 keV. Four such systems are required for the reference mirror reactor design.

Fusion Engineering Research Facility (FERF)

The recent successful stabilization by streaming warm plasma of the drift-cyclotron loss cone mode in 2XIIB, coupled with the theoretical explanation of the stabilization process, has prompted us to recompute the parameters for a mirror fusion engineering research facility (FERF).⁷¹

While maintaining the physical design of the previous study,⁷² we find that the fusion power is increased from 3.38 to 7.95 MW, with a corresponding increase in peak neutron flux at the wall from 0.531×10^{14} to 1.2×10^{14} cm⁻²·s⁻¹.

Environmental Studies

Fusion. In a comprehensive review of environmental aspects of fusion, we examined fuel supplies, materials requirements, routine emissions, accident pathways and consequences, radioactive waste characteristics, and safeguards considerations.

Fig. 63. D^0-T^0 injector: 1800 A of 150-keV D^0 plus T^0 ; overall efficiency = 80%.

stressing the importance of innovative approaches to reactor design in exploiting favorable environmental characteristics of the fusion process.⁷³ This was part of an updated review of safety and environmental characteristics of magnetic-confinement fusion reactors, in which we emphasized the importance of learning how to use low-activation structural materials such as vanadium-titanium to achieve the potential environmental advantages of fusion.⁷⁴

We adapted the Nuclear Regulatory Commission's consequence model⁷⁵ to investigate the consequences of large, hypothetical, accidental releases of tritium oxide (HTO) from fusion reactors. The release of 10^4 Ci of HTO [40% of the inventory of a nominal 1-GW(e) tokamak reactor] was shown to be capable of delivering, under adverse meteorological conditions, a dose producing early fatalities among half of those exposed over an area of 0.1 km^2 . Under the same meteorological conditions for the worst hypothetical fission-product release (designated PWR-1) studied in Ref. 75, the equivalent exposure area would be 10 km^2 . An investigation of the hazard of tritium versus plutonium as a radiological dispersal weapon showed that plutonium is two to five orders of magnitude more effective in contamination of air, but that the two are about equally effective in contamination of water.

Fusion-Fission Hybrids. In a review of hybrid safety characteristics, we related the safety aspect to other aspects of the rationale for hybrids and identified ingredients needed for a systematic safety assessment.⁷⁶ An investigation of once-per-year versus continuous tritium extraction in hybrid blankets demonstrated that the buildup of tritium in the once-per-year mode does not significantly increase the accident hazard, which is always dominated by fission-related isotopes in the blanket.

Electrostatically Plugged Cusp Fusion Reactor

The electrostatically plugged cusp is a configuration that has electrodes located at the extremely thin cusp regions. This configuration creates electrical potentials that confine both ions and electrons. Experiments are being carried out at Kharkov by Lavrentev *et al.*,⁷⁷ at Montreal by Stansfield *et al.*,⁷⁸ and at the University of Missouri by R. L. Hayward *et al.*⁷⁹

During the report period, we performed a design study to uncover the technical problems with the concept.⁸⁰ A Fokker-Planck^{81,82} computer code was used to study the loss rates. Subject to the assumptions made, the reactor looks very attractive. The Q value is 5, and because of the high β , economics may

be favorable. However, an economic analysis was not carried out.

The reactor would be steady state except for a periodic flush of impurities. The most critical assumptions are the holding of high voltages (300 kV) over small distances and the stability of the electron plasma in the extremely thin cusp sheath (~ 0.1 mm).

Gas-Embedded Z-Pinch Reactor

During the report period, we completed a preliminary conceptual design for a fusion reactor based on the magnetic confinement of a high-density plasma by a Z-pinch.⁸³ The magnetic configuration is a straight, self-constricting current channel in which the confining magnetic field is provided solely by the plasma current; no external magnets are required. Ohmic heating, compression, and alpha particles provide the plasma heating.

Because Q values in the desirable range of 5 to 10 apparently require refueling the plasma during the current discharge, we examined a reactor concept based on the gas-embedded Z-pinch, where the pinch is assumed to be refueled radially by photoionization of the gas blanket. The pinch electrodes are lithium jets attached to capacitors at either end of the spherical reactor vessel. There is no solid first wall or blanket structure. Rather, the blast energy and fusion neutrons are absorbed in a rotating vortex of liquid lithium inside the reactor vessel. The reactor is characterized by simplicity, small minimum size (~ 100 MW(e)), and the potential for minimal hazards from radioactivity.

Neutral-Beam Development and Technology

Introduction

The main elements of the neutral-beam development program for the report period were as follows:

- Experimental work on pulsed beams, efficient beam, and advanced development;
- Test-facility construction; and
- Completion of a conceptual design and start of a more detailed design for the TFTR beam line.

In the pulsed-beam program, a new, long-pulse plasma source was developed and tested, and a 120-kV accelerator structure was designed and constructed. By the end of the report period, we had begun testing the 102-kV, 0.5-s, 15-A injector system (one-fourth the area of a TFTR injector).

In the efficient-beam program, we produced a 1-keV, 200-mA, pulsed D⁺ beam that is suitable for acceleration to higher energies; we also designed and constructed a 100-kV accelerator structure for

this beam. Tests on this system will begin in FY 1977.

In this transition phase of developing higher-voltage injectors, the availability of test facilities (power supplies and vacuum chambers) continues to be a critical-path item; therefore, much of the development effort has been devoted to the construction of test facilities. Operation of the 80- to 150-kV, 20-A, 0.5-s test facility with the 120-kV, 1/4-scale TFTR module began in August. Design, site preparation, and construction of the 200-kV, 25-A, dc/120-kV, 65-A, 5-s HVTS facility continued on schedule (for operation in July 1977).

We completed the conceptual design of a neutral-beam injection system for TFTR and began a more detailed prototype beamline design. To ensure compatibility with TFTR and to maximize commonality with the ORNL design, we have worked closely with PPPL and ORNL.

Pulsed Beams

The development of a 120-kV, 0.5-s neutral-beam injector system is proceeding along the following lines:

- To develop a suitable, long-pulse plasma source.
- To design, with the aid of the WOLF code,⁸⁴ an accelerator-slot configuration for 120-kV beams.
- To construct and test a test system incorporating the above (one-fourth of the area that will be required for TFTR).
- To construct a full-size TFTR source and test this in two stages:
  - For ~ 30 -ms operation on the short-pulse, 120-kV test facility, and
  - For 0.5-s operation on the high-voltage test stand (HVTS) when it is completed.

A 10-A (equivalent), 15-cm-diam plasma source⁸⁵ was modified⁸⁶ to demonstrate the long-pulse operating capability (≥ 0.5 s) that is required by the TFTR as well as by other experiments now being planned. This source incorporates 56 dc-heated filaments, oriented so as to provide a ring-shaped magnetic field (~ 45 G) between the plasma volume and the side wall. Langmuir-probe measurements indicate that the current density of the deuterium ions in the central, 8-cm-diam region is uniform to $\pm 1\%$ for 1-s pulses at $J_0 = 0.25$ A/cm², and to $\pm 4\%$ for 0.5-s pulses at $J_0 = 0.5$ A/cm². A saturated ion-current density profile for this test source, obtained with Langmuir probes near the plane of the first accelerator grid, is shown in Fig. 64; the position of the filaments is also indicated.

A combination of this test source and a standard 10-A (equivalent) accelerator structure with uncooled molybdenum and tungsten rails was

0.1 s/div.

0.1 s/div.

Fig. 64. Profile of ion current density for the plasma generator. Also shown are oscilloscope traces of arc current (475 A), arc voltage (40 V), and saturated-ion current drawn by two probes placed 3 cm on either side of the axis.

operated successfully at 15 keV with 1.0-s, 7.5-A deuterium-beam pulses and at 20 keV with 0.75-s, 15-A beam pulses. The measured long-pulse performance characteristics are shown in Table 8 for two

accelerating voltages. The upper limits to the angular divergences are greater than those previously reported¹⁵ for short-pulse operation because of earlier limitations on calorimetry.

Table 8. Typical operation of a long-pulse 20-kV, neutral-beam source for two accelerating voltages.

Item	Performance characteristic	
Ion-current density	0.25 A/cm ²	0.5 A/cm ²
Ion-current density variation	±1%	±1%
Pulse length	1.0 s	0.75 s
Gas flow (D ₂)	4 T·l/s	4 T·l/s
Beam energy	15 keV	20 keV
Power supply drain		15 A
Beam divergence parallel to slots (±1/e)		≤0.6°
Beam divergence perpendicular to slots (±1/e)		≤2.6°
Ion species	67% D ⁺ , 29% D ₂ ⁺ , 4% D ₃ ⁺	72% D ⁺ , 25% D ₂ ⁺ , 3% D ₃ ⁺

A cross section of a single slot of the 120-kV ion accelerator is shown in Fig. 65. The design is a conventional, accel-decel system with the addition of a gradient grid that provides the capability of electrostatic focusing; we hope this addition will reduce the problem of electrical breakdown. The scale size was set by our desire to limit the potential gradient in the second gap to 100 kV/cm; this scale size, together with the applied voltages, sets the current density at 0.31 A/cm² for an optimally focused, pure-D⁺ beam or at about 0.28 A/cm² for a beam with a realistic ionic composition (including some D₂⁺ and some D₃⁺). The transparency of the first set of grids is 60%.

With the WOLF code, we optimized the design for minimum beam divergence by varying the shape of the first (or beam-forming) electrode, the current density, and the potential of the second electrode. The shapes of the second and third (negative) electrodes were chosen to minimize energy deposition in the structure by the secondary particles (ions and electrons) that are created either by collisions of the beam ions with the background gas or by secondary

emission from surfaces. If the background gas density in the accelerator were known, we could calculate the power deposited in the electrodes. Calculations based on a reasonable assumption of the gas density indicate that the maximum heat rise in any electrode after the 0.5-s beam pulse will be less than 500°C and that the electrodes need not be cooled during the pulse.

We have also used WOLF to calculate the effect that perturbation of the most critical electrical and mechanical parameters has on the beam divergence. Our calculations show that the power supplies will be adequately regulated and that, even with allowance for expected mechanical misalignments, the beam divergence perpendicular to the slots should not exceed 1 degree.

The 15-A, 120-kV, 0.5-s module, incorporating the plasma generator and accelerator designs described above, is shown in Fig. 66. The accelerator consists of an outer, vacuum-wall insulator that is sectioned to distribute the potential gradients; to keep these insulators reasonably short, the outside of this insulator is pressurized with two

Fig. 65. Calculated beam trajectories and equipotentials for a 120-keV accelerator, where ion current density = 0.31 A/cm² (D⁺); transparency = 0.6; and beam divergence = ($\sqrt{2} \theta_{\text{rms}}$) = 0.53°.

atmospheres (absolute) of SF_6 . The plasma generator and grid assembly are mounted on an inner, plug-in structure. The tubular insulators to which grid assemblies are mounted also carry cooling water to the plates that support the final three grids; cooling for the first (beam-forming) grid is obtained from the plasma-source body. The 10-cm-long grid rails, arranged in a 10-cm-wide array, are end-cooled. The solid-molybdenum rails are brazed to a fixed support on one end, forming a comb-shaped structure, and are allowed to expand in the long direction to prevent buckling when heated. The heat is conducted and radiated away in the 1-min interval between pulses.

The neutralizer to which this structure is attached is constructed of iron to shield the beam from stray magnetic fields. It has an internal cross section of 15 cm $\times$ 30 cm and is 2 m long. D_2 gas emerging from the plasma generator through the grids will produce a line density of $\sim 10^{16}$ molecules/cm² ($\sim 0.5 \text{ Pa} \cdot \text{m}$) in this section.

Efficient Beams

We are continuing to work on the negative-ion program, our purpose being to obtain intense negative-deuterium beams, to accelerate them to 10 to 200 keV, and to strip the attached electron to yield a neutral beam produced at high power efficiency. A negative-ion beam, 200 mA of D^- , has been produced using double charge exchange in Cs, and an accelerator has been designed and constructed.* At the end of the report period, the accelerator and power supply were being tested.

The production and propagation of the negative-ion beam have been studied both experimentally and theoretically. Results are summarized below.

*In addition to the double charge-exchange approach, we are making a preliminary study of an alternative in which a D^- beam is produced directly by surface conversion of a gas jet formed from a $\vec{j} \times \vec{B}$ accelerated arc plasma.

Fig. 66. Cross section through the 120-keV, 15-A, 0.5-s injector module.

Production of 1-keV D^- Beams. We investigated D^- beam production efficiencies using an LBL 10-A (equivalent) source and a Cs-vapor cell.⁸⁷ The source utilizes a three-grid, accel-decel extractor design to produce 10 A of 1-keV deuterium ions. Some neutralization of the accelerated D^+ ions occurs near the center grid; ~ 1 A (equivalent) of high-energy neutrals (~ 10 keV) is formed. Recent results show this high-energy component to be concentrated along the beam axis. For measurement purposes, we tilted the beam source slightly to exclude the 10-keV species. We measured the negative-ion-beam production efficiency at 1 keV to be $J_e/J \leq 0.18$. The aperture size of the Cs-vapor cell limits the total negative-ion beam current to ~ 200 mA.

With the aid of an axially and vertically movable set of three Faraday cups, we have studied negative-ion-beam profiles. This study was used in the final design of the system for accelerating 1-keV negative ions to 100 keV.

Measurements of 1-keV D^- Beam Propagation. Without space-charge neutralization, an ion beam (initially parallel) doubles in radius in a distance $L(\text{cm}) = 0.16 V^{3/4} J^{-1/2}$ (where units are keV and $A \cdot \text{cm}^{-1}$). In practice, this distance is frequently so short that neutralization is mandatory. Because positive ions are required for a negative beam, a problem in plasma transport arises. This problem has been investigated at LLL both experimentally and computationally.⁸⁸ A 1-keV D^- beam with L only 3.5 cm was propagated over 100 cm using D^+ or Cs^+ neutralization. Measured profiles (within and outside the beam) of floating potentials n_i and n_e were compared with results from a computer model. The measured electron density was less than the beam density over the beam wall section, thus minimizing the problem of eliminating electrons from the beam before acceleration. As predicted, the profiles are quite different from those obtained with a D^+ beam. With D^- , the plasma potential sometimes appears to have a small negative gradient, which causes a slight contraction of the D^- beam.

Plasma in the Negative-Ion Beam. The plasma associated with the negative-ion beam has several important effects: space-charge neutralization is required to prevent beam blowup, but the background plasma also can strip the beam through collisions, charge exchange with the beam (e.g., $D^- + Cs^+ \rightarrow D + Cs$), and deliver electrons to the accelerator. Measurements and calculations have been made to understand these effects.⁸⁸

Figure 67 shows an example of one-dimensional, fluid-model calculations of the spatial distribution

accompanying a negative-ion beam. Quasi-neutrality requires that the ion and electron densities n_i and n_e be related to the beam density n_b by $n_i = n_e + n_b$. In the example, $n_b = 2 \times 10^9 \exp(-x^2)$, and ionization by the beam is quite weak. In accordance with the Bohm condition, at large x the fluid velocity is taken to approach the speed of sound, $c_s = (T_e/M_i)^{1/2}$. The space-charge potential $\phi = T_e/N_e$ changes very slowly throughout the ionization region, thus yielding a low transport rate to balance production.

Two-dimensional calculations are being done. Of particular importance is the variation of n_e along the beam. In regions of low gas pressure, and thus low ionization rates, ambipolar transport should cause n_e to approach zero at large distances from the Cs cell. This effect should limit the flow of electrons into the accelerator.

Plasma effects in the Cs cell may be serious because of the high density ($\sim 10^{14} \text{ cm}^{-3}$) of Cs. Atomic and plasma processes have been analyzed.^{89,90} For $T_e \lesssim 0.5$ eV, ionization is slow enough that the plasma density can be limited by transport; for $T_e > 0.5$ eV, "burnout" of the Cs is predicted. Measurements indicate $T_e < 0.5$ eV. The most serious effect is predicted to be $D^- + Cs^+ \rightarrow D + Cs$; this could be important at high beam densities. Measurements will be required to verify this result.

Fig. 67. Example of one-dimensional, fluid-model calculations of the spatial distribution accompanying a negative-ion beam. Here, n_i = plasma ion density, n_e = electron density, and v/c = ion speed divided by sound speed. The ionization rate is low.

Angular Scattering in Charge-Exchange Cell. The Boltzman equation has been solved for the angular distribution of charge-exchanging beams.^{91,92} Figure 68 gives the total numbers of neutral atoms and negative ions at angles less than θ for three Cs line densities. The total negative-ion production approaches equilibrium for Cs line densities $N^+ \approx 2 \times 10^{15} \text{ cm}^{-2}$. The calculations indicate that angular scattering is negligible at these densities but important for $N^+ > 10^{16} \text{ cm}^{-2}$.

100-keV Negative-Ion Accelerator. We have designed and constructed a structure to accelerate the negative-ion beam to 100 keV. Figure 69 shows output from the WOLF code. The code indicates that by using the first three electrodes for focusing, a wide range of beam densities can be accelerated with good optics. The structure to house the electrodes, shown in Fig. 70, was constructed to permit the use of new electrodes when desired. To prevent external breakdowns, the entire structure is surrounded by SF_6 .

We have also constructed a power supply that yields 1 A, 100 kV for 100 ms and prepared the beam line. By the end of the report period, the system was almost complete.

D^- Production by Surface Conversion of a D^0 Jet. The double-charge-exchange method of D^- production currently being used at LLL has the immediate advantage of being operable. However, in simple form it has certain long-term disadvantages, e.g., in gas efficiency. Although these disadvantages may be

alleviated by the research and development program, we are also exploring an alternative method of D^- production using surface conversion of a D^0 jet.⁹³ This scheme not only may eliminate the problems listed above, but also scales readily to TMX or reactor sizes.

We have proposed a small, inexpensive, prototype system with an initial design goal of 5 A of D^- at 20 keV. This prototype could be tested on any of the existing 10-A (equivalent) test stands and could be upgraded later for testing at 200 keV on the LLL HVTS.

Advanced Development

Although most of the neutral-beam development resources are allocated to meet near-term goals and milestones, there has been an occasional opportunity to pursue advanced-development topics. High-quality ion-beam optics require a noise-free plasma source. To obtain such operation, only very weak magnetic fields can be used for electron containment. This means that the required arc power consists of high arc currents and low arc voltages. For such source geometries, the cathode becomes the most important design consideration, particularly when very long arc pulses are required. Considerable thought has been given to the cathode structures that would be needed for continuous operation, e.g., modifications of our present designs and alternate structures such as the "hollow-cathode" and rare-earth designs. A number of these designs are being constructed for tests that should

Fig. 68. Total number of neutral atoms and negative ions p ; angles less than θ : (a) $N^+ = 1.0 \times 10^{15} \text{ cm}^{-2}$, (b) $N^+ = 8 \times 10^{14} \text{ cm}^{-2}$, and (c) $N^+ = 4.1 \times 10^{16} \text{ cm}^{-2}$. The fraction of negative ions is also shown; $F^+ = 0.1$ has been assumed. The dots indicate measurements as discussed in Ref. 91.

Fig. 69. Output from the WOLF code showing a D^- beam accelerated from 1 keV to 100 keV.

also disclose the part played by the various cathodes in generating a plasma that contains a high percentage of atomic ions.

Test Facilities

Pulsed-Beam Facility. The vacuum system for testing pulsed beams (Fig. 71) was completed during this fiscal period. Because gas to the system is on for only 0.5-s pulses at intervals of 1 min or more, it is convenient to use a large-volume vacuum chamber to handle the peak gas load by volume expansion. The chamber has a total volume of 172,000 litres, and the vessel pressure does not exceed about 2.5×10^{-5} Torr (3.3×10^{-3} Pa) at the end of a 0.5-s pulse. Two well-baffled, 0.9-m-diam diffusion pumps return the system to its base pressure in the interval between shots. The measured pumping speed of the two baffled pumps (for D_2) is 65,000 l/s. The pumping fluid is a polyphenyl ether that has a very low vapor pressure [5×10^{-10} Torr (6.7×10^{-3} Pa)] at room temperature, is resistant to oxidation, and does not break down to form insulating layers on surfaces struck by the beam.

To minimize oil contamination during routine source operation, the system also incorporates two 8000-l/s (D_2) titanium sublimation pumps. A 75-kW array of lamps suspended at the center of the sphere allows a mild bakeout of the chamber. This array can maintain the walls 50°C above ambient

and is effective in shortening the pump-down time. The base pressure of the system is $\sim 5 \times 10^{-6}$ Pa.

This vacuum system is equipped with two beam lines, one of which is to be used to test the 120-kV, 15-A, 0.5-s source described earlier. The power supply, described in detail in Ref. 94, is a shunt-regulated transformer/rectifier system. Strings of silicon-controlled rectifiers (SCR's) are used for switching to the source and for fault protection. The voltage to the gradient grid is regulated by a string of zener diodes. The power supply was installed during this fiscal period; testing and troubleshooting will proceed in conjunction with source testing.

We have developed a flexible, beam-diagnostic system for the pulsed-beam test facility based on a MODCOMP II computer. In this development, we were fortunately able to use software already developed at LBL for the Bevalac control system. The beam-diagnostic system is based on a "thermal inertia" calorimeter that is instrumented with an array of thermistors. We measure the temperature distribution before the shot and again after the shot and also read the beam voltage every 2 ms. From this information, we calculate and display on graphics terminals the beam energy, the total beam-on time, the current to the calorimeter, selected ΔT contours on the calorimeter, beam divergences based on these contours, the coordinates of the center of the beam on the calorimeter, and other pertinent information. All display and timing parameters can be easily changed from the same terminals.

Fig. 70. Structural design electrodes for the 100-kV negative-ion accelerator.

Fig. 71. Pulsed-beam test facility.

In conjunction with Draper Laboratories (Cambridge, MA), we are developing a control system for this beamline. Draper Laboratories has purchased a MODCOMP IV computer with additional peripherals and is writing a control program based on the same software used for the diagnostic system. When this development is completed, we shall be able to operate the beamline in several modes ranging from manual control to full, closed-loop computer control; we shall also be able to "break in" a source to its design voltage under computer control.

We are also developing the capability to record and store all data required to reconstruct a shot. We use digital telemetry of data from the high-voltage deck; this telemetry has been designed and made so that the data stream can be fed directly into the computer's memory for later storage on magnetic tape.

High-Voltage Test Stand (HVTS). Design and construction of the HVTS has proceeded during the past year. Modification of the test-stand pit is nearly complete, with only some interior electrical

and mechanical work remaining. The high-voltage (200-keV) power supply is well along; a switch tube designed for TFTR will be delivered in June 1977 for testing and use. The filament power supply is nearly complete, and the arc power supply is nearly designed.

The first HVTS cryopump module (shown partially assembled in Fig. 72) was tested in October 1975 and found to have nearly twice the design pumping speed. The D_2 speed of $\sim 150,000 \text{ l}\cdot\text{s}^{-1}$ remained constant even at very high throughput ($\leq 2 \times 10^{-3} \text{ Torr}\cdot\text{l}\cdot\text{s}^{-1}\cdot\text{cm}^2$). This speed results from an area effectiveness of the pump of $\sim 9 \text{ l}\cdot\text{s}^{-1}\cdot\text{cm}^2$, which is approximately the maximum theoretical value for a sticking coefficient of unity. The maintenance of speed at high throughput confirms the utility of this type of pump for neutral-beam work.

The test results from the cryopump module were applied to the design of the HVTS main cryopump, which will now have a D_2 pumping speed of $500,000 \text{ l}\cdot\text{s}^{-1}$ in a smaller physical envelope than originally conceived. This pump, most components of which are in hand, incorporates cryogen storage reservoirs

to enable it to be isolated at high voltage when necessary. Total HVTS pumping speed, to be supplied by the main cryopump and three cryopump modules, will eventually be $950,000 \text{ l}\cdot\text{s}^{-1}$. Initial operation, now scheduled for the testing of TFTR sources, will be with an installed speed of $\sim 600,000 \text{ l}\cdot\text{s}^{-1}$.

TFTR Neutral-Beam Injection System

The basic conceptual design of the injection system for the TFTR was completed in August 1975.⁹⁸ In June 1976, a detailed mechanical design of this system was begun. Several engineering workshops, attended by engineers from LLL, LBL, ORNL, and PPL, were held to ensure compatibility of the design with TFTR and to maximize commonality with the ORNL design. As this work has progressed, the system has changed considerably in form but not in function from that described in Ref. 95. The injector system, shown in Fig. 73, incorporates some $3.5 \times 10^6 \text{ l}\cdot\text{s}^{-1}$ of

Fig. 72. Cryopump module for the high-voltage test stand.

Fig. 73. Conceptual LBL/LLL design for a neutral-beam injection system for the tokamak fusion test reactor.

cryopumping per beam line, which pumps the chamber down to $\sim 10^{-6}$ Torr in the last of three differentially pumped stages against a gas load of ~ 100 Torr $\text{l}\cdot\text{s}^{-1}$. Certain parts of the system, such as the calorimeter, the bending magnet, and the remotely maintainable source-terminal assembly, are the subjects of R&D efforts being carried out concurrently with the design process.

RTNS-II

Design, contracting, and construction activities on the Rotating Target Neutron Source - II (RTNS-II) project began in FY 1976. This project is a federal budget line item intended to provide two 14-MeV neutron sources, each producing 4×10^{11} neutrons/s for DMFE investigation of fusion reactor materials. During FY 1976, the building and sources passed through Title I and Title II design; the first major procurement contract was let in June and construction began in October. Construction costs to date indicate that the project will be completed on schedule within the approved \$500 thousand cost.

During FY 1976, we have concentrated the parallel R&D effort upon the production of prototype accelerator and target components, with emphasis on the examination of those systems judged to be high-risk items. The complete high-voltage terminal assembly—ion source, species-separation magnet, pumping system, and all control and power electronics—has been assembled for test. A 5000-rpm target assembly has been prepared for installation on RTNS-I, and a prototype tritium scrubber has been built for evaluation. These systems and a complete accelerator will be operated in FY 1977 to provide experience necessary before the mid-FY 1978 turn-on date for RTNS-II.

Neutron Irradiation Studies

RTNS-I Irradiations and Dosimetry

During the report period, we performed 24 irradiations, involving a total of more than 350 samples. The irradiations supported research on the effects of 14.8-MeV neutrons by 29 individuals representing 11 institutions. Although most of the experiments were carried out at room temperature, three were at elevated temperatures (up to 700°C) and four were at cryogenic temperatures. For runs of 50 h or more at room temperature, neutron fluxes near 1×10^{12} neutrons/cm²·s were typical. Irradiated materials included the following elements, alloys, and compounds:

- Elements: C, Al, Ti, V, Cr, Fe, Ni, Cu, Zr, Nb, Mo, Sn, Ta, W, Au.
- Alloys: NbTi, stainless steel, α -brass, Al(Cu).
- Compounds: Nb₃Sn, V₃Ga, Al₂O₃, MgO, various glasses, SiC, BuC, YAG, SrCl₂.

The experiments were designed to study the effects of 14.8-MeV neutrons on mechanical properties, on critical parameters of superconductors, on defect production, on radiation-enhanced diffusion, on microstructural features, on helium generation, and on the production of long-lived isotopes. Experimental techniques included tensile testing, TEM, ESR, optical absorption, dilatometry, electrical resistivity, mass spectrometry, and gamma spectroscopy. The $^{93}\text{Nb}(n, 2n)^{92m}\text{Nb}$ reaction was used to determine 14.8-MeV neutron fluences.

For each irradiation, the experimenters were given a report detailing the experimental conditions and irradiation history as well as individual sample dosimetry.

Characterization of a 30-MeV D-Be Neutron Source

The neutron spectrum produced by bombarding a thick Be target with 30-MeV deuterons is of interest in studying the effect of neutrons on materials to be used in future fusion reactors. We used the cyclotron at the University of California at Davis for the measurement; the spectrum was inferred from the activation of two sets of detector foils placed at 0° to the deuteron beam, one immediately behind the Be target block and one 40 mm to the rear. The initial irradiation lasted 72 m at an average deuteron current of 20 μA . Details are given in Ref. 96; the water-cooled Be target is described in Ref. 97.

The foil activation data were analyzed using the SPECTRUM code at LLL⁹⁸ and the SAND-II code at ANL.⁹⁹ At neutron energies above 7 MeV, the agreement was good; below 7 MeV, the results differed by more than a factor of two. Because the low-energy neutrons were primarily determined by the $^{54}\text{Fe}(n,p)^{54}\text{Mn}$ reaction, differing theoretical corrections for ^{54}Mn production by high-energy neutrons through $^{54}\text{Fe}(n,n'p)^{54}\text{Mn}$, $^{56}\text{Fe}(n,n'd)^{54}\text{Mn}$, and $^{56}\text{Fe}(n,t)^{54}\text{Mn}$ accounted for the difference.

To avoid this uncertainty, foils of nearly pure ^{54}Fe and ^{56}Fe have since been irradiated to determine the correction experimentally. The previous spectra were adjusted to take the new experimental data into account. The results (Fig. 74) are now in reasonable agreement over the entire energy range.

The spectra shown in Fig. 74 exhibit much larger numbers of low-energy neutrons than expected

Fig. 74. Neutron yield from a 30-MeV D-Be source operating at 20 μ A. The multiple-foil activation technique was used to determine yields at two positions: 3.6 mm and 43.6 mm. Note that the yield from the rear foil packet is multiplied by a factor of 10.

Table 9. Neutron flux ($E > 1$ MeV) and damage energy cross sections for 30-MeV D-Be neutrons.

Source	Position (mm)	Flux (neutrons/cm ² ·s)	Damage energy cross section for Cu (barn·keV)
30-MeV D-Be ^a	3.6	5.0×10^{12}	210
30-MeV D-Be ^a	43.6	1.9×10^{11}	225
KTNS-I	4.0	1.0×10^{12}	285

^aAt 25- μ A beam current.

from low-angle, time-of-flight measurements. It appears from the present data as well as from larger-angle, time-of-flight data that this difference can be attributed to the fact that foils placed at distances comparable to the size of the beam spot intercept neutrons emitted at large angles to the direction of the deuteron beam. These neutrons generally have lower energies than the forward-directed component because they arise from compound-nucleus interactions rather than from stripping.

Uncertainties in the near-source spectra are still substantial due to the small number of reactions for which accurate cross-section data in the 20- to 30-MeV range are available. Further work utilizing a variety of techniques is required. Cross-section data at these energies will also be necessary in candidate

fusion materials in order to interpret the results of experiments.

In a recent irradiation, the beam current averaged 25 μ A over several days. Since this is more typical of the cyclotron operation, the neutron yields of Fig. 74 should be increased by 25%. In Table 9, the total neutron flux ($E > 1$ MeV) for a 25- μ A beam is given for both positions. For comparison, a typical flux for long irradiations at the RTNS-1 is also given, as well as estimates of damage energy cross sections for Cu based on the work of Doran and Graves⁹⁹ and Parkin and Goland.¹⁰⁰

Bulk Radiation Damage Effects of High-Energy Neutrons

High-purity V tensile specimens were irradiated at ambient-temperature ($\sim 25^\circ\text{C}$) by 14-MeV neutrons at fluences up to 2.5×10^{17} neutrons/cm² to determine the increase in yield strength with neutron fluence. Results are shown in Fig. 75, along with previous results on Nb irradiated by 14-MeV neutrons.¹⁰¹ As can be seen in Fig. 75, the V data, although obtained at a somewhat higher neutron fluence than those for the Nb, are in close agreement with the Nb results.

Elevated temperature ($\sim 700^\circ\text{C}$), 14-MeV-neutron irradiations of Nb tensile specimens were carried out on the RTNS to fluences up to $\sim 1 \times 10^{17}$ neutrons/cm². Tensile tests on these specimens showed no measurable increase in yield strength. Annealing of the radiation damage at this higher temperature causes an increase in the neutron fluence threshold for measurable changes in mechanical properties. It is not clear whether the threshold at 700°C is within the fluence range that can be practically obtained ($\sim 10^{18}$ neutrons/cm²) with the neutron flux of the present RTNS.

We examined the feasibility of using fission-fragment damage to simulate the effects of radiation by high-fluence, bulk mechanical property fusion

Fig. 75. Radiation strengthening of MRC vanadium by 14-MeV neutrons at $\sim 25^\circ\text{C}$, curve (a), compared with (b) RTNS fission neutrons at 25°C (MRC Nb), (c) LPTR fission-reactor neutrons at 65°C , $E > 0.5$ eV (store-grade Nb), and (d) LPTR fission-reactor neutrons, $E > 0.5$ eV (MRC Nb).

neutrons and concluded that internal fission-fragment bombardment offers many advantages for simulating high-fluence, fusion-neutron radiation effects in Nb.

In this technique, tensile specimens of an Nb-1.1 at.% ^{235}U , solid-solution alloy were fabricated and irradiated with thermal neutrons to produce ^{235}U fissions. When a ^{235}U nucleus undergoes thermal neutron fission, it produces two fission fragments (ternary fission occurs less than one time in 10^4 events). The fission fragments have a range of masses and energies, but can be roughly divided into two groups. The heavier fragments have an atomic mass of 139 and an average energy of 70 MeV; the lighter fragments have an average mass of 95 and an average energy of 150 MeV. When released in solid metals, fission fragments have ranges on the order of a few micrometres. At the beginnings of their paths, the fragments lose energy primarily to electrons. At the ends of their paths (when the energy is below about 1 MeV in Nb), collisions with nuclei of atoms in the solid become the dominant process, and atomic displacements result.

We used LSS¹⁰² theory to calculate the amount of energy per fission that goes into producing atom displacements (damage energy) and obtained a damage energy of 6.84 MeV per fission. We also calculated the primary knock-on (PKA) spectrum in Nb for fission fragments; this is compared in Fig. 76 with spectra taken from Ref. 103 for fusion-reactor and fission-reactor neutrons in Nb. Note that the fission fragments give a closer simulation of the PKA spectrum of the fusion-reactor neutrons than do the fission-reactor neutrons, at least in the energy range shown.

Also note that fission fragments can produce recoils of energies up to about 100 MeV; these are not shown in Fig. 76. However, the significance of these higher-energy recoils can be estimated from Fig. 77, which shows the fraction of displacement damage produced by recoils of less than a given energy for the three types of irradiation. For the fission fragments, about 1% of the displacement damage is produced by recoils of energies greater than 10 MeV, whereas about 84% is produced by PKA's of energies less than 1 MeV. This is a consequence of the fact that the higher-energy PKA's lose energy primarily to electrons, as mentioned above. Thus, although a few recoils of much higher energy are present with fission fragments, their contribution to the displacement damage is small.

An important aspect of fission-fragment damage is that for each fission, it introduces two impurity atoms into the material. About 25% of the fissions

Fig. 76. Primary recoil spectrum in Nb for (a) fusion reactor neutron spectrum,¹⁰³ (b) unmoderated fission-neutron spectrum,¹⁰³ and (c) fission fragments.

produce gas atoms, principally Xe and Kr. Fortuitously, the number of gas atoms introduced per atomic displacement using fission fragments is comparable to the number of He atoms produced by (n,α) reactions in Nb during irradiation in the neutron spectrum of the fusion reactor. The fission-fragment technique produces one gas atom per 27.4 MeV of damage. A pure-DT fusion neutron spectrum produces one He atom per 28.6 MeV of damage energy, if we assume a He production cross section of 10 mbarns. The exact value for a fusion reactor will depend on the blanket design. Note, however, that although Xe and Kr are noble gases with the same chemical behavior as He, because of size differences they may not interact in the same way with other lattice defects.

Fig. 77. Fraction of atomic displacements produced by recoils of less than a given energy for (a) fusion-reactor neutron spectrum,¹⁰³ (b) unmoderated fission-neutron spectrum,¹⁰³ and (c) fission fragments.

To examine the effects of fission-fragment damage on mechanical properties, six polycrystalline tensile specimens of Nb-1.1 at.% ^{235}U were fabricated and tested. One of the specimens was tested at $\sim 25^\circ\text{C}$ in the unirradiated condition; it exhibited a stress-strain behavior similar to that of Nb-1Zr. The other five specimens were irradiated to different thermal neutron fluences in the graphite west thermal column of the Livermore pool type reactor (LPTR) at a temperature that did not exceed 80°C . We determined the doses in terms of the number of fissions per gram of specimen to an overall uncertainty of $\pm 10\%$ by gamma ray counting the specimens themselves, correcting for decay and self-absorption, and applying a fission yield of 6.5% to the ^{95}Zr observed.

The five irradiated specimens were tested in tension at 25°C ; the results are shown in Figs. 78 and 79. Figure 78 shows the increase in 0.2% offset yield stress versus delivered damage energy. Also shown in Fig. 78 are previously reported data¹⁰¹ for pure Nb irradiated with DT fusion and fission-reactor neutrons. It can be seen in Fig. 77 that the functional dependence of the increase in yield stress with displacement damage produced by the fission fragments is similar to that for the fusion- and

fission-reactor neutrons over the range of damage states where data exist. It is also apparent in Fig. 78 that the increase in yield strength is not a unique function of damage energy for the three types of irradiations. This could be due to uncertainties in the calculations of damage energy, differences in specimen material, or differences in quantities and distributions of resultant damage.

Figure 79 shows the substantial reduction in ductility that occurred for fission-fragment damage, as well as the simultaneous increase in ultimate tensile strength. Data of this type are not available for fusion neutrons because the doses achieved thus far are too small; however, an empirical correlation with the fission-fragment results indicates the behavior to be expected.

Helium in Metals

Helium is produced in materials subjected to 14-MeV neutrons as a result of (n,α) and similar nuclear reactions. The overall objectives of this project are thus

- To accurately measure the amount of He introduced in metals by (n,α) reactions induced by 14-MeV neutrons,

Fig. 78. Comparison between radiation strengthening of Nb by (a) fission-reactor neutrons at 65°C (stores-grade Nb), (b) fission-reactor neutrons at 65°C (MRC Nb), (c) fusion neutrons at 21°C (MRC Nb), and (d) fission fragments at -80°C (Nb-1.1%U). Curves (a), (b), and (c) are taken from Ref. 101.

Fig. 79. Effect of fission fragments on ductility and ultimate tensile strength.

- To determine the rate of diffusion of He in materials of interest,
- To study the nucleation of voids in irradiated and nonirradiated specimens, and
- To evaluate the effect of He concentration and distribution on mechanical properties.

We have been using our equipment for heating and melting a sample in vacuum and then analyzing the He liberated by means of a mass spectrometer (Ref. 1, p. 69). Because the equipment can measure $<10^{10}$ atoms of He, we can typically determine concentrations of parts per billion in 10-mg specimens. This equipment has an important and unique feature: specimens can be heated in a controlled way and the temperature monitored so that the rate of release of the He can be observed and mechanisms of migration in the solid deduced. Such measurements coupled with electron-microscope examination of specimens show whether the He condenses into bubbles within the solid or escapes by atomic migration to surfaces.

In some conceptual designs of fusion reactors, graphite or other carbon-containing material is proposed as a curtain to protect the metallic first wall and to reduce high-Z impurity buildup in the plasma. The amount of He produced is directly related to the total of (n, α) cross sections; although the cross sections of the various α -producing reactions have been calculated, there is disagreement as to their correct values. To our knowledge, before our study the total cross section for He generation in carbon had never been verified by directly measuring the amount of He generated within a solid sample.

We measured the cross section for the generation of He in neutron-irradiated carbon and found it to be 654 mbarn at 14.4 MeV and 744 mbarn at 14.9

MeV. At 14.1 MeV (the fusion reaction energy), the cross section for the (n, α) reaction is 75 mbarn and for various $(n, n' \alpha)$ reactions is 180 mbarn; the total He production cross section is therefore $75 + 3 \times 180 = 615$ mbarn. By using these data together with other published values, we can estimate the He production cross section in SiC to be 660 mbarn per molecule and in B_4C to be 1200 mbarn per molecule.¹⁰⁴

The diffusion coefficients of He have been measured in dense, polycrystalline graphite and in pyrographite¹⁰⁵ and found to be $D = 7.2 \times 10^{-7} \text{ m}^2 \cdot \text{s}^{-1} \exp(-80 \text{ kJ/RT})$ (see Fig. 80). We found that diffusion is primarily in the basal plane direction of the graphite crystals. In polycrystalline graphite, the path length is a factor of $\sim\sqrt{2}$ longer than the measured distance because of the random orientation mismatch between successive grains. Isochronal anneals (measured He release as a specimen is steadily heated) were run; maximum release rates were found at 200°C in polycrystalline graphite, at 1000°C in pyrographite, at 1350°C in boron carbide, and at 1350°C and 2400°C (two peaks) in silicon carbide (see Fig. 81). We conclude that in these candidates for certain materials in fusion reactors, the He releases can probably occur without bubble formation in graphites, may occur in boron carbide, but will probably cause bubble formation in silicon carbide.

The high fluxes of very energetic neutrons generated by fusion reactors will cause serious radiation damage to the materials used in these reactors. Neutrons having energies near 14 MeV not

Fig. 80. Diffusion coefficient versus $1/T$. Closed triangles represent polycrystalline dense graphite; open triangles represent pyrographite.

Fig. 81. Helium release on heating specimens at 10°C/minute: (a) solid line is ZTA polycrystalline graphite, dashed line is pyrographite; (b) boron carbide polycrystalline, and (c) SiC single-crystal platelet. Note that multiple peaks in SiC are suggestive of internal trapping of He bubbles.¹⁰⁵

only cause a larger number of displaced atoms per PKA than do thermal neutrons, but also produce greater quantities of He via (n,α) reactions per equivalent fluence than thermal neutrons.

Helium produced uniformly in the microstructure during irradiation at elevated temperature can migrate to favorable nucleation sites at crystallographic defects and form He gas bubbles in the matrix. Upon reaching a critical bubble size in the material, the He is nearly immobile. Helium-gas bubbles trapped in the microstructure can severely alter the mechanical properties and often lead to embrittlement of the material as He is accumulated.

To separate the effect of He on mechanical properties from displacement-damage effects, we are using the tritium-decay reaction $^3\text{H} \rightarrow ^3\text{He} + \beta$ to test Nb and Nb-1Zr creep and tensile specimens into which various concentrations of ^3He have been introduced. To prepare our test specimens, a predetermined amount of tritium gas is reacted with the Nb or Nb-1Zr materials at temperatures near 400°C. The tritium dissolves and equilibrates with these materials under these conditions so that about 7 atomic ppm ^3He is formed per day within the microstructure. When the desired concentration of ^3He has been incorporated into the microstructure, the more mobile, dissolved tritium is removed by high-vacuum pumping near 500°C. Polycrystalline Nb and Nb-1Zr specimens have been doped with from 25 to 500 atomic ppm of ^3He .

We are using these specimens to study creep rupture and ductile-brittle behavior as a function of ^3He content. Preliminary results show that the mechanical properties of Nb-1Zr alloy specimens are altered to a greater degree than those of the pure-Nb specimens by a ^3He concentration of 25 atomic ppm. Though there is some strengthening and reduction of ductility in the Nb-1Zr alloy, tensile tests show that this alloy retains some ductility at temperatures from ambient to 800°C.

Neutron Irradiation Effects on Superconductors

In designing the magnet shielding for the fusion engineering research facility (FERF) and for magnetic fusion reactors now in the planning stages, we must know the effects of radiation on candidate superconductors as a function of neutron fluence. We know from the work of Parkin and Schweitzer¹⁰⁶ that a catastrophic reduction in the critical current of Nb₃Sn occurs at a fluence of 2 to 3×10^{15} neutrons/cm² of fission reactor neutrons at an irradiation temperature of 60°C and with an applied field of 4 T. The corresponding fluence at which such a reduction might occur under MFE operating conditions (i.e., at fields up to 12 T, with operation at 4.2 K, and with neutrons having energies up to 14 MeV) is not known from either measurements or theory. However, we can infer from present knowledge that these conditions are likely to be more severe in every case. The goals of this project are to simulate as closely as possible the MFE environment and to measure the effects of this environment on candidate superconductors.

The work in progress has the following three objectives:

- To determine the effects of neutron irradiation (from about 4 to 14 MeV) on the critical

current on Nb₃Sn, Nb-Ti, and other superconductors at 4.2 K and in the presence of magnetic fields up to 12 T.

- To correlate the electrical properties of these materials with both initial microstructure and radiation-induced changes in microstructure.

- To measure the recovery of the radiation-induced changes in critical current during annealing up to room temperature.

During the report period, the following tasks were completed: sample procurement and characterization, equipment construction, and equipment check-out at the RTNS. Since both Nb₃Sn and Nb-Ti superconductors are candidates for use in magnetic fusion reactors, samples of both materials will be irradiated in this program. Nb₃Sn samples were obtained from BNL and from AIRCO. The BNL samples are identical to those being studied by investigators at BNL and ANL in fission-reactor irradiation experiments; consequently, our results on 14-MeV neutron damage can be compared to fission-neutron damage. The AIRCO material represents state-of-the-art commercial fabrication of Nb₃Sn superconductors for use in magnetic fusion coils. Samples of Nb-Ti manufactured by AIRCO were obtained; at BNL, identical samples are being irradiated with 30-GeV protons and fission-reactor neutrons.

To simulate fusion-reactor operating conditions as closely as possible, a mobile cryostat was constructed so that the samples could be irradiated at 4.2 K in magnetic fields up to 12 T without warming the samples. The apparatus constructed for our low-temperature radiation damage studies of superconductors was assembled at the RTNS. In a check-out run, a sample of AIRCO 121-filament Nb-Ti was cooled to 4.2 K and irradiated for 4 h at a source flux of 4×10^{12} neutrons/cm²·s. The sample was positioned approximately 7 mm from the source, and subsequent analysis of the dosimetry wires indicated a flux at the sample of 1.5×10^{11} neutrons/cm²·s. The sample positioning fixture has been improved so that on subsequent runs the sample can be placed approximately 5 mm from the source; this change should enable us to achieve a flux of greater than 2×10^{11} neutrons/cm²·s at the sample.

After the irradiation, the mobile cryostat containing the sample was inserted in the bore of the superconducting solenoid and the Nb-Ti critical current was measured as a function of field. As would be expected for a fluence of only 2×10^{15} neutrons/cm², the critical current values were the same as the unirradiated values. Additional heating due to the neutron beam was only 0.25 K, and the temperature

of the sample during irradiation and measurement was maintained at 4.5 ± 0.1 K.

This initial experiment demonstrated that our approach is sound and that the equipment functions properly at the RTNS. Irradiations to fluences equivalent to a 10-year operating period in a fusion reactor will be performed on both Nb-Ti and Nb₃Sn during FY 1977.

Computer Modeling of Cascade Development

A fully dynamic study of 2.5-keV collision cascades in W has been completed (for preliminary results, see Ref. 107). Sixteen cascades with random, primary-knock-on (PKA) directions were initiated in a crystal containing ~4000 atoms ($13 \times 13 \times 13$ BCC cells) with periodic boundary conditions. Because this work was primarily undertaken to study the influence of transient thermal effects on final defect configurations, damping was applied to the boundary layer to simulate the cooling of the cascade region by the surrounding lattice. The damping constant was chosen to match cooling rates observed for small crystals imbedded in a larger matrix. The W-W potential is the same as that used in previous studies of displacement thresholds¹⁰⁸ and defect diffusion¹⁰⁹ in W.

The development of a collision cascade can be divided into two regimes: a displacement spike followed at somewhat longer times by a thermal spike. In the present study, the displacement spike ends in approximately 1×10^{-13} s. At this time, displacements have ceased, and all cascade atoms have energies less than a few eV. After 1×10^{-12} s, unstable Frenkel pairs have collapsed, but local thermal equilibrium is not established until $\sim 2 \times 10^{-12}$ s. Cooling is completed by 1×10^{-11} s.

The dynamic, many-body calculations can be compared to the binary collision model by noting the defect configuration at the end of the displacement spike. Unstable pairs can then be manually eliminated using an appropriate static recombination volume (as is done in binary calculations). Such a comparison is made in Table 10, where the results for 2.5-keV collision cascades in W are compared to the binary calculations of Beeler and Bisco.¹¹⁰ The effect of choosing different values for the recombination volume is shown. The 52-site recombination region is the correct one for the present potential.¹⁰⁸ The larger cascade size and the number of stable Frenkel pairs in the binary calculation are the direct results of longer replacement sequences. Whether this reflects the somewhat softer potential of Beeler and Bisco or the handling of replacement sequences in the binary calculation remains to be seen.

Table 10. Comparison between 2.5-keV collision cascades in W.

	Binary collision model ^a	Dynamic many-body model
Cascade volume	670	540
Initial displacement	23	25
After recombination:		
30 sites	14.5	10
52 sites	12	9
90 sites	8	7.5
Final displacements	—	3.3

^aRef. 110.

Only 37% of the stable pair created survive (the end of the thermal spike). The observed defect transport is more than an order of magnitude greater than that expected from the known¹⁰⁹ equilibrium transport coefficients. This survival rate in the thermal spike appears consistent with recent experimental work.¹¹¹

Initial Damage Rate Studies at 4.2 K

Initial damage rates, as revealed by changes in electrical resistivity at 4.2 K, have been measured in Nb, U, and Mo containing 300 ppm of Zr. Three neutron sources were used: the LLL RTNS-I 14-MeV source; the University of California, Davis, 30-MeV D-Be source; and the LLL LPTR fast-fission plate.

The studies were part of an interlaboratory project¹¹² to measure damage rates in these alloys in a wide variety of irradiation damage sources. While final dosimetry results and damage energy calculations have not yet been completed, preliminary estimates indicate that the results for these three neutron spectra scale with the damage energy.

Tritium Technology

Tritium Containment and Processing

Because the processing of tritium results in tritium-contaminated waste gases, we are investigating the use of metal getters for scavenging tritium from inert gases. We are also investigating the use of cryotrapping and selecting the most suitable pumps for tritium processing.

Chemical Getters. The removal of tritium from inert gases has two important MFE applications, i.e., scavenging tritium from a room atmosphere

contaminated by a spill and the routine removal of tritium from the blanket coolant gases.

The conventional process for tritium recovery includes catalytic oxidation of tritium to water followed by adsorption on a molecular sieve and conversion of tritium from T₂ gas to the more hazardous T₂O form. Using a chemical getter to react directly with tritium makes the tritium recovery simpler and less expensive and avoids the production of T₂O.

Mathematical models were used to assess the ability of a chemical getter (cerium metal) to scavenge tritium from an inert gas.¹¹³ Factors considered in this choice were dissociation pressure of the hydrided solid, reactivity of the metal, capacity for reacting with tritium, cost, and availability.

Both fixed and fluidized beds were considered possible for this application. We assumed that diffusion from the bulk gas to the getter surface would be the controlling step in the gettering process. Mathematical models were constructed for both types of bed, allowing comparisons with each other and with a traditional tritium-recovery system that was designed elsewhere.⁵⁹ The model for the fixed bed was based on a mass balance; that of Kato and Wen¹¹⁴ was chosen for the fluidized bed. A system using each type of bed was designed to handle a flow of 10 m³/s of argon that initially contained 3.8 ppm tritium (10 Ci/m³), to perform a 10-fold reduction in tritium concentration, and to continue purifying effectively to levels at least as low as 0.2 ppb (500 μ Ci/m³).

Our calculations indicate that a 3.5-m-diam fixed-bed reactor containing 650 kg of Ce powder (100- μ m-diam particles) should provide adequate purification at the rated flow. Alternately, two parallel, 5.0-m-diam, fluidized-bed reactors, each containing 1000 kg of cerium powder, would be required for purification at the rated flow.

The fixed-bed reactor required less Ce and a smaller reactor vessel, and should be simpler to construct and operate than a fluidized-bed reactor. However, the fluidized-bed reactor has a lower pressure drop, a continuously replenishable bed, and more flexible operation than a fixed-bed reactor. Moreover, the capital cost of a gettering system, estimated to be between \$115,000 and \$166,000/m³·s⁻¹, is competitive with that of the conventional catalytic-oxidation molecular-sieve system (\$330,000/m³·s⁻¹) now used. The gettering concept, therefore, warrants further investigation.

To assess the feasibility of using Ce metal as a chemical getter for the removal of low-level tritium mixed with inert gases, we performed preliminary experiments with mixtures of D₂ and Ar flowing

through a Ce-metal trap. The trap contained Ce metal dispersed in three segmented layers to reduce the possibility of channel formation. Several experiments were performed with mixtures of 0.5 - 1 vol% D_2 in Ar and flow rates of 17 to 133 cm^3 STP/s. The trap efficiency was expressed as the ratio of the D_2 concentration at the trap inlet to that at the trap outlet. Results of preliminary experiments show that the efficiency of Ce metal for gettering D_2 is higher at 200°C than at room temperature. The trap can be poisoned to reduce its gettering ability, but it can easily be reactivated by heating it in vacuum at 400°C. Since these results were encouraging, the experimental apparatus is being modified to test the trap with mixtures of T_2 and Ar.

Pumps. MFE reactors will require pumping operations with tritium involving pressures ranging from submillipascals to megapascals. To form a basis for selecting pumps in various future tritium applications, we collected and reviewed available data on pumps suitable for tritium. A variety of pumps operate at portions of this range; these can be staged to cover the entire pressure range.¹¹⁵

Certain features are necessary for pumps used for tritium service; that is, they must not have either moving shaft seals or organic fluids. At least 10 types of pumps are suitable; various types can be adapted to meet any size and pressure requirements. Suitable pumps include liquid-helium cryopumps, mercury-vapor diffusion and ejector pumps, wobble pumps, diaphragm compressors, and smaller pumps such as Toepler and Sprengel pumps. Special attention must be paid to construction features, quality of materials used, and methods of fabrication.

Cryotrapping. Molecular-sieve beds are often used to maintain low partial pressures of tritiated water in MFE applications. These molecular-sieve beds can be regenerated to operate at lower partial pressures ($\geq 10^{-9}$ atm) by using an auxiliary molecular-sieve bed to regenerate the primary bed. The auxiliary bed can be regenerated in a conventional manner.¹¹⁶

Tritiated Methane in Stainless Steel Vessels

Tritiated methane, which could be a deleterious impurity in the D-T fuel cycle of a mirror fusion reactor, is produced when stainless-steel tubing is exposed to tritium. We have completed a set of experiments designed to determine the effect of the cleaning received by the stainless-steel tubing on subsequent methane production.¹¹⁷

Steel tubing was first cleaned in different combinations of degreasing, rinsing, machining, and baking. The tubing was then exposed to tritium gas at either 100°C or at 22 to 25°C. A gas

chromatograph was used to analyse the tritium gas for methane. The results showed that methane formation is very dependent on the cleaning method:

- Specimens that were machined showed only 2 to 6 STP cm^3 of methane produced per m^2 of exposed steel after a 60-day exposure.

- Unmachined but degreased, rinsed specimens produced 7.5 to 30.0 STP cm^3 of methane per m^2 exposed steel after approximately a 60-day exposure.

When one set of specimens was exposed to new tritium, there was a lower rate of methane formation than in the original run. These results indicate that a pickling, or conditioning, step helps reduce the rate of tritiated methane.

Tritium Control in Mirror Fusion Reactors

During the report period, we identified tritium containment and removal problems associated with the blanket and power systems for a mirror fusion reactor and designed means of reducing emissions to the environment to below 1 Ci/day.^{118,121} In the design process, we started with this emission goal of 1 Ci/day and worked inward to the blanket; at each decision point, we considered worker safety, operational labor costs, and capital cost tradeoffs.

The conceptual design used tertiary containment:

- Secondary containment was provided by isolating the blanket from the coolant, and

- Tertiary containment was provided by hermetically sealing the reactor hall and circulating the air through a continuous catalytic oxidizer-molecular sieve adsorber cleanup system.

The cleanup system maintained a $40\text{-}\mu\text{Ci}/m^3$ tritium level ($5\text{-}\mu\text{Ci}/m^3$ HTO) against a 180-Ci/day leakage from reactor components, energy recovery systems, and process piping. A computer model developed for this catalytic, oxidation-adsorption process was used for the design and performance evaluation.

The blanket contained submodules with $Li_2Be_2O_3$ -Be for tritium breeding and submodules with Be for energy production. The method for secondary containment is illustrated in Fig. 82. Tritium production was handled by confining these breeding materials to a container and scavenging this container with a He gas stream that was doped with Li vapor. The container consisted of molybdenum-alloy (TZM) tubes and tube sheets; the breeding material was packed and sintered in the shell surrounding the tubes. Potassium-vapor (also Li-doped) coolant passed through these tubes to recover the heat at 950°C. Tritium leakage from the scavenging He into the potassium vapor within the blanket submodule was reduced to 3600 Ci/day. After an intermediate TZM exchanger, loss into the

Fig. 8Z. Flow diagram for a conceptual fusion reactor, showing tritium levels in the tritium breeding loop, the potassium vapor cooling loop, and the reactor containment vessel.

stream via a Haynes-25 alloy boiler (potassium boiling) was reduced to 0.7 Ci/day. A moving getter bed was used to recover the tritium from the LiT and Li₂T scavengers in both the He flow that scavenged the blanket and in the potassium-vapor coolant.

We also examined the effect upon the leakage of replacing the TZM alloy container with niobium; the increased leakage was not acceptable.

Tritide Target Development for the RTNS

Our efforts to upgrade the neutron output and lifetimes of the targets used on the LLL RTNS are continuing in the same areas described last year.¹

- Analysis of titanium tritide targets currently used on the RTNS, and
- Development of alternate target materials.

Titanium Tritide Targets. During the report period, we established procedures for receiving both the production data from ORNL for each target and the performance logs taken during the RTNS operation. Operational data include neutron strength, beam current, tritium release, target position, total neutron fluence, and elapsed time. We are also attempting to measure beam characteristics. Chemical information derived from coupons (i.e., tritium and titanium content and metallography) is also now available for each new and used target.

Each target data set is being computer-analyzed by a number of numerical modeling techniques, principally by single-step, multiple-regression analysis. This allows us to determine which variables are important to the neutron strength produced by a target, the mathematical form of that variable (e.g., logarithmic or sinusoidal), and the correlation between variables (e.g., the radial position of the beam on the target and the beam current can also be deduced). As we gain more knowledge from this effort, we expect changes in the data we use and in our collection techniques. The modeling effort should provide guidance in improving target design and RTNS operation. We anticipate significant progress in this area by early 1977.

Alternate Target Materials. Small, high-quality targets of titanium, erbium, yttrium, and scandium tritides have been received and will be tested in a pulsed mode on the RTNS. These experiments should provide comparisons between the neutron production from different target materials and may lead to estimates of target lifetimes.

We plan to compare results from two standard-size (9-in.-diam) erbium tritide targets with those from two titanium tritide targets. The erbium tritide targets will be more highly characterized than production targets and will allow us to compare the production targets with one other binary tritide without interfering with the normal operation of the RTNS.

Vacuum Development

We have begun to develop the vacuum technology and components deemed necessary for the current and projected MFE program. Initially, effort will be focused on developing very high-capacity pumping methods that are compatible with magnetic fusion systems using neutral-beam injection. During the report period, we progressed as follows:

- A 1.2-m-diam, 1.5-m-long vacuum chamber with an LN-cooled liner was fabricated and installed on its test stand. Forelines, a 10-in. mercury diffusion pump with an LN trap, and a valve were assembled. All of the components were vacuum-checked as a system.

- A 4.2 K cryocondensation pump with a 1.125-m² surface area was designed and is being fabricated. The pump is a small-scale mockup of the LHe cryopump planned for the MFTF experiment. Associated with this pump is a small, cryogenic, scavenging pump designed to test a degassing method that precludes the normally excessive pressure rise.

SECTION 3. RESEARCH

Theory and Computations

Introduction and Summary

The report period has witnessed a rapid maturation of our ability to describe theoretically the behavior of ion-cyclotron noise in the 2X11B experiment and the influence of that noise on the confined plasma. The notion developed last year of saturating the drift-cyclotron loss-cone (DCLC) mode by partially filling the loss cone has been incorporated into a quasi-linear code that describes ion diffusion in velocity space under the action of the fluctuations. The resulting plasma behavior is in quantitative agreement with experimental results both in the presence and absence of the stabilizing

stream. The notions that have proven successful in describing saturation of the DCLC mode are also applicable to a number of other loss-cone-driven modes.

The success in controlling instability has led to much higher values of β in 2X11B, and this achievement has prompted much theoretical analysis of the properties of high- β equilibria and stability, including those of a field-reversal state. The numerical aspects of this work are summarized below. One interesting realization was that the condition for onset of the mirror mode, because it represented a loss of equilibrium due to the development of nonanalytic magnetic profiles, also signaled loss of particle adiabaticity. Thus, with increasing β , breakdown of

single-particle confinement should precede onset of the mirror mode. Theory of the high- β Alfvén ion-cyclotron (AIC) mode has emphasized the effects of finite axial and radial scale lengths on the condition for marginal stability. In contrast to the situation of a year ago, the agreement between analytic theory and computer simulation has improved and shows (subject to the uncertainty of the anisotropy to assign) that finite geometry accounts for the apparent lack of occurrence of the AIC mode in 2X-11B.

During the report period, we made excellent progress in the development of a number of computer codes that are applicable to magnetic-mirror problems. The emphasis remains in three main areas: three-dimensional, finite- β , guiding-center equilibria; field reversal; and Fokker-Planck codes.

The three-dimensional, guiding-center equilibrium codes have been applied to many pressure profiles in designs for 2X11B, FERF, and reactor coils. The magnetic well in the present FERF design is too weak to confine a high- β plasma without some reversal of field-line curvature before the mirror-mode limit is reached. The 2X11B coils seem adequate for most profiles examined, and some of the more expensive reactor coils need much less than the design curvature. The highest β achievable in a given coil set also depends strongly on the pressure profiles and injection angles. We can now obtain a realistic calculation of the optimum coil and injector configurations by coupling the coil design, plasma equilibrium, and Fokker-Planck codes.

The two-dimensional SUPERLAYER code is being used to study the possibility of using the current of injected neutral-ion beams for field reversal. The code, which now includes electron drag and charge exchange off the neutral beam, predicts that reversal is possible in the 2X11B experiment if the beams are focused off-axis. In addition, the code shows that these steady states are stable to both tearing modes and the AIC mode. A linearized version of the code shows that the AIC mode is stable for a sufficiently short plasma.

The Fokker-Planck codes have developed along two fronts this year. One area of development provides a more complete description of the behavior of 2X11B: Nonclassical particle transport in velocity space due to quasi-linear diffusion has been included in the two-dimensional code; and work has also progressed on coupling an axial flow code to the quasi-linear code to describe the plasma stream. The second area of development has been the improvement of the Fokker-Planck codes to treat classical processes more realistically. We have

incorporated the average over the axial bounce motion of the ions in a spatially varying magnetic field and ambipolar potential. Further, we have included a self-consistent modification of the magnetic field by a high- β plasma. Results from this code *vis a vis* πr are in reasonably good agreement with previous calculations of classical ion confinement based on the magnetic-square-well model. Consequently, our basic version of the Fokker-Planck code HYBRID II has continued to be used almost daily in connection with our reactor optimization studies and for evaluating Q-enhancement ideas; however, to obtain more detailed information such as pressure profile, the more sophisticated version of the Fokker-Planck equation must be used.

Quasi-Linear Codes for Ion Transport in Mirrors

We have developed two computer codes that solve for the evolution of the ion distribution function F in a mirror machine subject to loss-cone modes. One code solves for the distribution function in one velocity dimension ($v_{\parallel}$);¹² the second is a modified HYBRID II code¹³ that solves for F in two velocity dimensions (v, θ). Both codes include classical collision processes as well as self-consistent turbulent diffusion due to microinstabilities as described by quasi-linear theory. The two-dimensional code is more general in that it includes the effect of ion-ion pitch angle scattering and allows for a spread of the distribution function in $v_{\parallel}$, the velocity along the magnetic field. However, the one-dimensional code is about 10 times faster and, owing both to the dominance of electron drag over pitch angle scattering and the narrow angle distribution function in 2X11B, similar results are obtained from both codes.

The major accomplishment of the codes has been to reproduce the observed temporal behavior of 2X11B. Most important is the requirement that a stabilizing stream of code plasma be injected to suppress the turbulence level of the DCLC instability.⁴ This suppression of turbulence allows one to increase the density and temperature of the plasma with neutral-beam injection. A detailed comparison between the experimental measurements and the calculated results is shown in Fig. 83. Although the results of the two-dimensional code are not shown in Fig. 83, they coincide with the results of the one-dimensional code. All parameters are the same for the two codes except that the stabilizing stream is 50% larger for the two-dimensional code. For another run, we obtained a close comparison between the one-dimensional code results and measurements taken by the charge-exchange

analyzer that samples the ion distribution function at numerous energy channels. This comparison clearly showed the heating of the ions to higher energies by the wave turbulence. In obtaining these comparisons, we modeled various processes such as variation of stream strength with time and variation of charge exchange with energy and also the effect of the reservoir of stream plasma on the electron temperature.

Determining the electron temperature is especially important since electron drag is the dominant transport process when the wave turbulence is suppressed. Because the electron temperature in 2XII B is now believed somewhat lower (~90 eV) than initially thought, we had to modify our electron-energy equation. The new term in this equation allows us to obtain the experimentally measured electron temperature by describing a thermal flux of electron energy away from the hot center of the machine to the cooler stream region outside the mirror. The relatively large density of stream plasma supplies the conduction path for this heat loss.

To have a more complete description of the wave turbulence, we are also including more detailed effects in the quasi-linear; for example:

- Dupree-Weinstock perturbed orbit diffusion in calculating the growth rate and evaluating the diffusion coefficient [one-dimensional (1-D) and two-dimensional (2-D)].

- A term in the growth rate describing the effects of the radial density gradient (1-D and 2-D).

- Solving for the precise wave number at each harmonic from the real dispersion relation (1-D).

- Velocity-dependent, transit-loss term (2-D).

- Enhancement of mirror ratio and angle of neutral-beam injection with increasing plasma β (2-D).

- Bounce average of the turbulent diffusion operator (2-D).

Of the above effects, the inclusion of the radial density gradient appears to be quite significant. However, because the current two codes do not consider the radial spatial dimension, a self-consistent flattening of the density gradient can not occur. We are therefore developing a third code that solves for the ion distribution in one velocity dimension (v_1) and in the radial spatial dimension. The form of the new equation is

$$\frac{\partial F}{\partial t} = \left(\frac{2n\omega_{ci}\partial}{\partial v_1^2} + \frac{\ell}{\omega_{ci}} \frac{1}{r} \frac{\partial}{\partial r} \right) D(v_1^2, r)$$

Fig. 83. Comparison between 2XII B experimental results and the one- and two-dimensional codes for ion temperature T_i , density n , and electron temperature T_e for 300 A.

$$\times \left(\frac{2n\omega_{ci}\partial}{\partial v_1^2} + \frac{\ell}{\omega_{ci}} \frac{1}{r} \frac{\partial}{\partial r} \right) F + \nu_D \frac{\partial}{\partial v_1^2} (v_1^2 F) - \nu_1 F + Q(v_1^2, r).$$

The first term on the right is due to quasi-linear wave diffusion in velocity and in radius, where ℓ and n are the azimuthal and harmonic mode numbers, respectively. The last three terms are electron drag, finite transit loss in the unconfined region of phase space, and an external source term due to neutral-beam and stream injection.

This radially dependent code should help answer questions concerning the effect of radial density gradient and the radial localization of the instability. This is an especially important question for larger-radii mirror machine, where the instability may only reside on the outer edge of the plasma. To have a good understanding of the wavelength and frequency range of the instabilities expected for larger-radii mirror machines such as the MFTF, we have also performed an extensive study of the linear dispersion relation for a parameter range.

Lastly, we have developed a quasi-linear model for the electromagnetic AIC instability⁹ and implemented it in the modified two-dimensional HYBRID II code. Preliminary results indicate that this instability prevents a buildup of the density by neutral-beam injection. Because these results contradict 2XIIIB experimental results, we shall conduct a more thorough study of the quasi-linear stabilization.

Stability Boundaries for the Drift-Cyclotron Loss-Cone and Negative-Energy Modes

The stability boundary for the DCLC mode and the negative-energy wave for various warm-plasma fractions and hole sizes have been determined. Prior calculations determined this boundary by setting the local dispersion relation evaluated at the mid-plane equal to zero: $L(\omega, k, s, \text{parameters}) = 0$. The appropriate normal-mode analysis¹²³ shows that the pertinent dispersion relation (where L is the plasma length) is

$$\int_0^L ds k_1^2 L(\omega, k_1, s, \text{parameters}) = 0.$$

In addition to this refinement, we have included the influence of the quasi-linear turbulent-diffusion coefficient on the particle orbits (orbit diffusion) in the dispersion relation through the addition

$$\omega - n\omega_{ci} \rightarrow \omega - n\omega_c + ik^2 D \left(\frac{\omega}{k} \right)$$

for the ions and similarly for the electrons so that

$$L = \frac{\omega_{pe}^2}{\omega_c^2} + 1 + \frac{\omega_{pi}^2}{\omega_c^2} \left[-\frac{\omega_{ci}}{k_1 R_p} \frac{1 + \beta_1/2}{\omega + ik_1^2 D_e} + \sum \frac{F_n(k_1 a_i) \omega}{\omega - n\omega_{ci} + ik_1^2 D} \right].$$

The results of these surveys are depicted in Figs. 84 and 85. In Fig. 83, we show the fraction of warm plasma required to stabilize a 2XIIIB- or MFTF-size plasma as a function of radius for $\beta_1 = 0.1$ and $\beta_1 = 0.5$ for a range of $(v_{hi}/v_h)^2$. Note that v_{hi} is the average perpendicular velocity of the confined plasma and that v_h (the hole velocity) is the mean velocity of the missing part of the loss-cone distribution. From the graph, we see that there is a reduction in required warm-plasma fraction of about a

factor of 6 in going from 2XIIIB to the high- β operation in MFTF. From the predicted electron temperature, also plotted on Fig. 84, there is a 10-fold increase in $n\tau_e$. Figure 85 shows the relation between stable radius and inverse density for a mean ion energy of 50 keV for no warm plasma and for fractions of stabilizing warm plasma equal to 10^{-4} and 10^{-2} . For a level of 10^{-4} , the electron-temperature model shown in Fig. 84 gives $T_e = 3.7$ keV; whereas for 10^{-2} , $T_e = 0.7$ keV, as compared to the classical value of 5 keV.

The marked reduction in the size of the stable radius at high density is due to two cooperative effects: the stabilizing influence of beta described elsewhere¹²⁴ and the fact that orbit diffusion reduces the magnitude of the perpendicular wave number, which makes the beta term that much more effective.

In Fig. 85, we also show the maximum axial magnetic scale length consistent with stability to the flute-like, negative-energy wave.

Alfvén Ion-Cyclotron Mode

During the past year, we have investigated the operating limits on beta and pressure anisotropy set by the AIC mode.^{9,125} These limits become more stringent as the device size increases. The results agree well with those of the particle simulation code SUPERLAYER, thereby lending credence to the many and varied approximations used.

Figure 86 displays regions of AIC stability¹²⁶ for 2X and MFTF; the boundaries actually mark the onset of absolute instability.^{127,128} In the short 2X plasma, convective growth is negligible. In the MFTF plasma, about 10 e-foldings occur; the displayed boundary therefore need be raised only slightly to take account of convective growth.

Ion velocity distributions in Fig. 86 are approximated by bi-Maxwellians. Much analytic and computational work has been done on collisional distributions,¹²⁹ drag-dominated distributions,¹³⁰ and numerically specified distributions.¹³¹ The constraints implied by Fig. 86 are not greatly affected thereby.¹³⁰

The curve labeled "infinite plasma" marks the onset of absolute instability in an infinite plasma. The effect of finite width is modeled by a finite perpendicular wave vector; perpendicular gradients are ignored. The effect of finite length¹²⁸ is treated in the WKB approximation; the parallel variation of plasma parameters is taken to be parabolic. The effect of finite beta on the magnetic field within the plasma is taken to satisfy the long, thin approximation.

The plan of work outlined above may be carried out not only for real or proposed devices but also

Fig. 84. Minimum plasma radius and predicted electron temperature versus the fraction of a warm plasma.

for "plasmas" occurring in particle simulation codes. The linearized, one-dimensional version of SUPERLAYER^{132,133} is convenient for this purpose. The corresponding "plasma" has infinite width and very short length, creates no magnetic well, and supports only linearly polarized Alfvén waves. Corresponding adjustments to the AIC stability code yield boundaries of stable operation agreeing to within 20% with the particle-code observations.

The two-dimensional, unlinearized SUPERLAYER code,^{132,133} describing plasma buildup and field depression, was studied briefly with a view to including electron currents. A proof was discovered jointly by B. L. Cohen and D. C. Watson that electron currents obeying Ohm's law would permit field reversal, provided the density increased with radius in the region of incipient reversal.

Effects of Fanning and Electron Temperature Upon the High-Frequency Convective-Loss-Cone Mode

The axial length of a mirror machine is limited by the Rosenbluth-Post (R-P) convective mode.^{134,135} This mode amplifies while propagating almost parallel to B with $\omega \approx \omega_{pi}$, $\lambda_{pe}^{-1} > k \gg \rho_i^{-1}$, and $k \approx k \sqrt{m_e/m_i}$. The velocity-space scattering resulting from these fluctuations has been obtained by Baldwin-Callen (B-C),¹³⁶ and the form of their result when bounce-averaged is shown in Eq. (20):

$$\left. \frac{\partial f}{\partial t} \right|_{B-C} \approx \frac{1}{v_{\perp}} \frac{\partial}{\partial v_{\perp}} v_{\perp} D_{B-C} \frac{\partial f}{\partial v_{\perp}}. \quad (20)$$

Fig. 85. Stable radius and maximum axial scale for stable negative-energy wave as a function of $(\omega_{ci}/\omega_{pi})^2$ for various fractions of warm plasma.

The basic scattering time scales as the electron drag time, t_{drag} , modified by the degree of wave amplification:

$$D_{B-C} = \frac{\bar{v}^2}{t_{drag}} \frac{\hat{D}(v_{\perp})}{(1 + \omega_{pe}^2/\omega_{pe}^2)^2} e^A. \quad (21)$$

Fig. 86. Convective-absolute boundaries for 2X, MFTF, and infinite plasma for finite-width and finite-length effects, a bi-Maxwellian ion velocity distribution, and the following parametric values:

2X: $R_p = 2.7a_i$, vacuum; $L_0 = 15a_i$, vacuum
MFTF: $R_p = 15a_i$, vacuum; $L_0 = 50a_i$, vacuum.

where

$$A \equiv 2 \int_{-L/2}^{L/2} ds \operatorname{Im} k_{\perp} \\ = \alpha \left[\frac{\omega_{pe}/\omega_{ce}}{(1 + \omega_{pe}^2/\omega_{ce}^2)^{1/2}} \frac{L_M}{\rho_i} \right]_{\text{midplane}}$$

The velocity dependence of the scattering is incorporated into the function $\hat{D}(v_{\perp})$, which has a maximum $<0(1)$ in the region of the positive slope of the ion distribution, is linear at small $v_{\perp}$, and decreases as $v_{\perp}^{-1}$ for large $v_{\perp}$. The number of wave-energy e-foldings A is conveniently expressed by a dimensionless quantity $\alpha \equiv \max \operatorname{neg} [yF(y)]$ in the notation of R-P, which is a very sensitive function of the ion distribution, particularly at low energy where there exists the population inversion driving the mode. Electron temperature and the axial dependence of plasma parameters taken together reduce the values of α from the R-P values by about 1/4, giving for collisional distribution $\alpha \approx 0.08$, although this is increased for analytic models having an ambipolar cutoff. For scattering by these fluctuations not to exceed classical electron drag, A must be $\gtrsim 5$, placing a limit on L_M/ρ_i of about 65, where L_M is the local magnetic scale length, and ρ_i is the midplane Larmor radius in the actual magnetic field.

The experimental evidence for this mode is limited; although it is suspected of dominating the low-energy ("quiescent") runs in 2XII, the mode identification was never complete. However, to the extent that the identification was valid, at $L_M/\rho_i = 60$ it conformed to the above-mentioned length limit and provides a basis for confidence in this scaling. As in 2XII, a concomitant requirement is that the local (β -enhanced) value of $\omega_{pe}^2/\omega_{ce}^2$ exceed unity, preferably by at least 3 or 4. Again, 2XII densities in this range decayed with n_7 values close to the classical value for $T_i/T_e \approx 30$. Under stream-stabilized operation of 2XIIb, the mechanism of partially filling the loss cone, which is seen as stabilizing the drift-cone mode, also reduces the amplification of the convective mode to the point that it would not be expected to dominate plasma loss. Under nonstabilized operation, of course, plasma loss is dominated by the ion-cyclotron noise.

At 50 keV and 1.2-T central field, the proposed MFTF has an L_M/ρ_i value only 10% larger than that of 2XII; therefore, with respect to the R-P convective mode its behavior should be similar. Such

experiments, which stabilize the drift-cone mode by increased plasma radius rather than by complete filling of the loss cone, permit investigation of the less-virulent convective mode. Present reactor designs exceed the estimated limiting length ratio by a factor of 3 for the large, 900-MW-output size and by 50% for the shorter 100-MW case.

Three-Dimensional Plasma Equilibria

The McGUS equilibrium code has been applied to many different plasma profiles in several coil designs including 2XIIb, FERF, and reactor coils.^{133,137,138} The effects of the quadrupole field of such coils on shaping the plasma is quite strong; nevertheless, particle drift surfaces remain omnigenous up to the highest β 's, thereby validating the connection between fluid and particle models. This important property of omnigenity can be destroyed by some coil sets that use trim coils to adjust the mirror points (Fig. 87). The peak plasma current induced by the coil geometry lies on a closed curve like a baseball seam (Fig. 88), a simple consequence of the symmetries. The long, thin approximation to the plasma pressure balance is

$$\frac{8\pi p_{\perp}(0)}{B_{\text{max}}^2} = \frac{\beta_{\perp}}{R_{vac}^2} = \left(\frac{1}{R_{vac}^2} - \frac{1}{R^2} \right) \left[1 + 0(kr_p) \right],$$

where R_{vac} and R are the vacuum and finite- β mirror ratios, and kr_p is the product of plasma radius r_p and field curvature k at the plasma surface. This relation is quite well satisfied unless the plasma is very short $0(r_p)$ in length or the field curvature is large. Typical results are given in Fig. 89. In fields with adequate curvature, the β limit is determined by the mirror-mode criterion on the axial variation $p_{\perp}$ of the perpendicular pressure

$$\frac{\partial}{\partial B} (\hat{p}_{\perp}(B) + B^2/8\pi) = 0.$$

This is strongly affected by the pressure profile, as shown in Fig. 90 for typical pressures of the form

$$\hat{p}_{\perp} = c(B_{\text{max}} - B)^{n+3/2}/B^n, \quad \hat{p}_{\parallel} = -B^2 \frac{\partial}{\partial B} (\hat{p}_{\perp}/B).$$

In weakly curved fields, such as the FERF coil design, the magnetic well is shallow (Fig. 91) and field-line curvature in the plasma reverses (Fig. 92) at much lower β . The plasma is then susceptible to ballooning modes, and it will require an MHD stability code to evaluate the true β limit in these cases. The pressure profiles are determined by the neutral-injection process, and the reactor design process clearly involves a careful calculation of coil

Fig. 87. Drift surfaces in the center plane of a trimmed set of reactor coils. The dotted lines are $J = \oint v_{\parallel} d\ell = 0$ surfaces. The solid lines are contours of the average drift surface, $\bar{T} = \oint p_{\parallel} d\ell / B$, at low β . The two sets are close (omnigenous) only near the axis.

Fig. 88. Plasma field lines encircle plasma current in 2XHB. Because of the quadrupole fields, the peak current lies on a curve like a haseball seam.

design, injection, and high- β equilibrium calculations.

The McGUS code is now run on the MFE computer by a very sophisticated controller that provides backup and restart facilities, disc and tape

Fig. 89. Comparison of McGUS results with the long, thin approximation (dotted) for $p = (B_{\max}^2 - B^2)/4\pi$, $B < B_{\max}$ 2XHB plasma, 1.4 m long, radius 14 cm; B_0 , the external guide field increased to reduce mirror ratio to 1.6 and decrease fanning; short plasma pressure is zero at $B_{\max}/B_0 = 1.14$; and plasma bubble at well center, $B_{\max}/B_0 = 1.08$.

Fig. 90. McGUS results plotted to show relation between mirror-mode stability limits, I , $n = 0.5, 1, 2$ and the long, thin approximation curves, I, R . Nearby computed results are labelled MR (McGUS); R is the vacuum mirror ratio. Field curvature weakens at points X. A result of the bounce-average Fokker-Planck code, F , is shown for comparison. Curve I is for the idealized pressures (used in Fig. 88) for which there is no mirror limit.

error checking, and recovery from machine dead starts.

Nonadiabaticity in Mirror Machines

The theory of nonadiabaticity in mirror machines described in last year's annual report¹ has since

Fig. 91. B contours in a FERF magnet set with plasma $\beta_{\perp} \approx 10\%$. Labelled points show: (a) section of V in coils, (b) mirror point, (c) plasma fan dips a wedge in the vacuum field, (d) small, minimum-B well, (e) mirror point.

proceeded in several directions.²⁸ We have developed an expansion technique that allows formal application of the theory to magnetic field regions where $B(s)$ possesses closely spaced singularities in the complex s -plane. Here real s labels position along a field line. Consequently, for magnetic moment jumps for particles on field lines near the axis of a mirror machine we are now able to obtain analytic expressions that have the same high degree of accuracy as those previously obtained for field lines far from the axis; this has been verified by comparison with results obtained by Footc from the TJIBRO orbit code.¹³⁰

Fig. 92. Comparison of vacuum field lines (lower line of each pair) and field lines in high- β (25%) plasma in FERF field of Fig. 91. The vertical scale is magnified, and curvature is actually reversed in several places.

We have applied the theory to model fields derived from the long, thin, axisymmetric equilibrium approximation, with parameters representative of the proposed MFTF experiment and 2XIB. We have used the axial field variation to estimate the maximum energy at which particles are adiabatically confined. We have shown that increasing β lowers this energy limit appreciably, due to the decrease in the axial scale length of the magnetic field and the minimum field strength. The effect is particularly significant if the axial extent of the plasma is short compared to the vacuum axial scale length; for the shortest plasma considered in the MFTF model, the energy limit decreases by more than an order of magnitude (from 13 MeV to 210 keV) as β is varied from 0 to 0.5.

When the gyroradius at the energy limit computed as above is comparable to the radial scale length, as is the case for 2XIB, one must use orbit-averaged, rather than guiding-center, quantities in the nonadiabaticity calculation. Using a highly simplified model for the radial variation in 2XIB, we have demonstrated that finite-orbit effects raise the energy limit considerably (from 14 keV to over 32 keV in our model, but the numbers are sensitive to details of the model), and that (above this limit) confinement is only mildly degraded.

Nonadiabaticity and the Mirror Mode

In a long, thin mirror equilibrium, mirror-mode stability⁸ is governed by the parameter $h' = (1/2)dB^2/dB$, where B_0 and B are the vacuum and nonvacuum fields, $B_0^2 = B^2 + 8\pi P_{\perp}$. We have demonstrated¹⁴⁰ that, for equilibria in which the onset of mirror-mode instability limits β , the size of the nonexpandable dumps in the magnetic moment of a particle^{28,141} is governed by the location of the complex zeroes of h' . A related observation is that,

at the minimum of B on a field line, the parameter $L_{\parallel} = (2B)^{1/2}(d^2B/ds^2)^{-1/2}$, where s is arc length, vanishes with h' . As a consequence, the β limit imposed by adiabaticity requirements is always more severe than the condition for mirror-mode stability.

Field Reversal

Reversed-field mirror configurations have closed field lines containing some fraction of the plasma volume and should greatly improve particle containment and thus enhance Q . A two-dimensional, axisymmetric, equilibrium code has shown the existence of small-aspect-ratio (fat), reversed-field configurations. Our best working tool for analyzing the reversed-field mirror configuration is the SUPERLAYER code¹² developed for the LLL Astron program. Revised to simulate neutron injection, it is now being used to study buildup to field reversal in a mirror machine and to determine properties of the steady state. The code now includes electron drag and charge exchange on the neutral beam, but as yet no angular scattering. The main function of the code is to calculate the self-field generated by the ions and the ion orbits in this field as a function of time. In the past, the code predicted reasonably well both the failure to achieve field reversal by multiple injection of electrons in the Astron experiment and the success achieved at Cornell by injecting a single, high-current pulse.

For present purposes, the main defect of the code is the assumption of axisymmetry (no quadrupole component). We believe this to be of limited importance in determining the equilibrium configuration in the interior region where the closed-field pattern forms. However, imposing symmetry suppresses possible modes of instability that must then be examined either analytically or numerically with other, more complex codes (see below). Also, as of this writing all runs have concentrated on the present 2XIIIB parameters ($a/\rho_i \approx 2$); modifications to treat a/ρ_i up to 10 are in progress.

The code is limited in scope, allowing no electron currents or space-charge effects, but including five phase-space dimensions in the ion motion. Within these limitations, the code should be able to examine the r, z equilibrium, including all effects of the mirror-tearing mode and the AIC mode, a related electromagnetic mode with $k_{\perp} = 0$.¹⁴ One rather severe approximation is made: the relevant time scales τ , such as the drag time or filling time, are shortened considerably, typically by factors of order of 100. The product $L\tau$ is kept consistent with the experiment, and an attempt is made to keep τ long compared to an axial bounce period.

The initial work indicated that field reversal was easily obtainable and persisted in steady state after

initial transients if the beams were arranged to form a coherent ring current. This injection prescription is actually unrealistic, and this past year we have concentrated on simulating 2X with realistic injection. Currently, the code predicts that reversal is possible in the 2XIIIB experiment if the beams are focused off-axis; high $\beta_{\perp} > 1$ is obtainable regardless of the focusing. This condition, however, is accompanied by a slow but steady axial loss of particles (this did not occur with ring-like injection). This loss is persistent, but it is not yet known if it is caused by the physics (nonadiabatic containment?) or by numerical effects. Even if real, the loss rate is sufficiently slow that it may not prevent buildup in a system with realistic time constants. That is, the loss rate is of the same order as the actual real-time loss rate of hot particles due to electron drag ($\nu_{\text{loss}}/\omega_{ci} \approx 10^{-4}$ and $\nu_{\text{drag}}/\omega_{ci} \approx 10^{-4}$ for $n = 10^{14} \text{ cm}^{-3}$, $T_e = 100 \text{ eV}$).

For 2X-like parameters, we have obtained a strong reversed steady-state for $I \approx 600 \text{ A}$ with $\xi = \Delta B/B_{\text{vac}} \approx 2$. This case used uniform injection over a length L_{inj} of 20 m centered at the midplane and over a radius $r_0 = 5 \text{ cm}$; employed a drag coefficient appropriate to $T_e = 100 \text{ eV}$; and included charge exchange on the beam. Allowing higher T_e will lead either to higher ξ and β for the same current or to marginal ξ for lower currents.

A typical result is shown in Fig. 93. The mirror ratio R_{vac} over the occupied region is only 1.05; that is, the self-field alone confines the axial pressure. Shown in Fig. 93 are typical field lines in an $r-z$ cross section indicating a central core of closed field

Fig. 93. Field lines and half-peak-density contour (dashed closed line) in the $r-z$ plane for a field-reversed equilibrium. Because of geometry, the density of the field lines in this illustration does not indicate field strength. Closed field lines are shown as dotted curves.

lines. The figure shows that the high-density region, defined as the region enclosed by the contour of half-peak density, is contained nearly entirely within the closed lines. This still leaves a sizable fraction of the total number of particles—perhaps half—outside the closed-line region, because for equal densities the amount of net mass is greater at a larger radius in the open-line region. The plasma has expanded radially to a radius $r = a$, somewhat beyond the injection radius r_0 . Much of this contact with the open region is due to the large orbits, $\rho_i/r_0 \approx 1$, in this example. Smaller orbit systems may improve on this.

In the example of Fig. 91, the plasma has pinched in axially to a mean length (full-width half-maximum) of $L \approx L_{inj}/4 \approx r_0$. This is a typical result. Longer axial systems can exist if the injection region is extended. In one example, a steady state occurred for $L \approx 8r_0$. Even longer systems are subject to breakup due to tearing modes. In essence, the system appears to adjust itself to a finite-length equilibrium with conditions necessary for prevention of the mirror-tearing mode and the AIC mode.

We have not fully resolved how stability to the AIC mode is maintained. That is, the existence of high- β equilibria in many of the code results and in 2XIIIB is in conflict with theoretical predictions of limits on $\beta \approx 0.1$ to 0.2 that are due to the AIC mode. The code should allow both the mirror-tearing mode and the AIC mode. We have evidence that small axial scale lengths can add strong stabilizing effects. Figure 94 shows initial results from a linearized code that models instabilities about a given equilibrium. We find complete stability for a case with $T_\perp/T_\parallel = 10.0$, $L/a_i \approx 1.5$; whereas the infinite-medium result gives a growth rate $\gamma/\omega_{ci} \approx 0.08$. However, this stabilizing effect rapidly disappears as the plasma length is increased. Consistent with this result, most of the SUPERLAYER code runs to date have been restricted to systems with

Fig. 94. Effect of finite length on growth rate of Alfvén ion-cyclotron mode in simulation.

only a small number of gyroradii (a/ρ_i , $L/\rho_i < 2$), and a major question is how well these results stand up for larger L/ρ_i , a/ρ_i systems. Although precise limits on lengths have not yet been obtained, a major effort for extending the code work to large L/ρ_i , a/ρ_i systems is underway. In this regard, the one long example referred to above with $L \approx 8r_0$ occurred for a ring-like injection; moreover, this case resulted in generation of considerable axial temperature. That is:

$$\frac{\sum v_r^2 + v_\theta^2}{\sum v_z^2} = 2.6,$$

in some sense perhaps equivalent to a "temperature" ratio $T_\perp/T_\parallel = 1.3$, which is close to isotropy. Also, some reversed-field results have been obtained with $a/\rho_i = 4$. The latter result, while still not an ideal steady-state, may be most significant because it indicates that one need not take great care in programming the injection when passing from single-orbit to many-orbit size systems.

In progress are the following:

- Monte Carlo techniques to simulate classical Coulomb scattering and rf-induced velocity-space diffusion.
- Examination of instability modes involving θ perturbations. We are actively developing three-dimensional particle codes that will start from a given steady-state and examine the stability to $e^{im\theta}$ modes, specifically the sausage and kink modes, which along with the AIC mode are considered to be the greatest danger.

Computer Simulation of Field Reversal With Electron Physics

We have designed computer simulation algorithms for studying low-frequency phenomena in magnetized plasma, e.g., the buildup of plasma currents to a magnetic field-reversed configuration following neutral injection in mirror plasmas.¹⁴⁴ So far, we have constructed particle simulation codes with a one-dimensional slab geometry in both quasi-neutral electrostatic limit and quasi-neutral electromagnetic limit in the Darwin approximation. These codes dispense with the electron time scales (ω_{ce} and ω_{pe}) by modeling the electrons as a space-charge-neutralizing fluid that can have finite pressure, current, and resistivity. The ions are treated as particles. We have analytically constructed the general linear dispersion relation for arbitrary $f(v_\perp)$, including temporal and spatial grid corrections and describing small-amplitude waves

propagating across the magnetic field. These results have been used to check both linearized and fully nonlinear codes and to improve their performance by minimizing grid effects. Preliminary computer studies of injection have shown agreement with the analytic results of Berk and Pearlstein in demonstrating the relaxation of plasma return currents on time scales of the order of many Alfvén transit times. We have also successfully simulated the drift-cone, Dory-Guest-Harris, and Alfvén-ion-cyclotron microinstabilities.

Monte Carlo Simulation of Velocity Diffusion

DCLC Turbulence. We recently demonstrated that velocity diffusion of ions caused by DCLC turbulence is an important process affecting the containment time of mirror-confined plasmas. It is desirable, therefore, that this process be included in particle codes used to simulate such systems. In a code such as SUPERLAYER that ignores electrostatic forces, it is natural to simulate the diffusion in velocity space arising from electrostatic turbulence by means of a Monte Carlo scattering technique.

In such a scheme, the velocity of a particle is randomly incremented at regular time intervals in accordance with prescribed rules. The scattering prescription is given in terms of a probability density $P(\Delta v_{\perp}, \Delta t | v_{\perp}, t)$, where $\Delta v_{\perp}$ is the deviation caused by the random force in time Δt of the exact velocity from what it would be if only the non-stochastic force field were present.

A quasi-linear diffusion equation for P was obtained, and it was shown that in the proper coordinate system the diffusion tensor is diagonal, which greatly simplifies the statistical sampling on which the simulation technique is based. An approximate solution to this equation has been constructed from its three lowest-order moments. The solution takes into account the velocity dependence of the diffusion tensor and is valid for time steps short compared to typical time scales for turbulence growth, electron drag, charge exchange, and end loss. The accuracy of the approximate solution has been checked by comparing it to a finite-difference solution to the same equation, with which it agrees well.

The validity of the simulation scheme was checked by using it to propagate a particular initial distribution of individual particles 800 time steps forward in time. The resulting distribution was compared with that obtained by a finite difference solution to the equation governing the diffusive evolution of the same initial distribution. The two calculations were found to agree to within statistical uncertainty.

Implementation of the Monte Carlo scheme in SUPERLAYER is currently underway. Preliminary results are encouraging, in that achievement of plasma density buildup appears to be extremely sensitive to the level of turbulence present.

Coulomb Collisions. The basic scheme developed to simulate the velocity diffusion induced by DCLC turbulence can also be used to simulate the random scattering in velocity space caused by Coulomb collisions. Use of the technique, therefore, should make it possible to include collisional effects in particle codes such as SUPERLAYER.

The probability density governing the scattering process, $P(\Delta v, \Delta t | v, t)$, satisfies the standard Fokker-Planck equation, with the diffusion tensor and dynamic friction coefficients being given by the Rosenbluth potentials. A useful approximate solution of this equation valid for short times has been constructed and will be tested by comparison with the predictions of Fokker-Planck codes.

Confinement Studies With the Orbit-Averaged Fokker-Planck Code

During the report period, we have refined the Fokker-Planck model for computing the plasma ion distribution function to include several aspects of the spatial variation of the plasma along magnetic field lines. In addition to the basic orbit average of collision and source terms, the model now includes the following features:

- Maxwellian electrons with the temperature either fixed or a specified fraction of the mean ion energy
- An ambipolar potential profile determined by local quasi-neutrality, with the magnitude of the potential at the mirror throat being equal to some multiple of the electron temperature.
- A time- and space-dependent magnetic field profile that incorporates finite- β effects via the long, thin approximation:

$$B^2/8\pi + P_{\perp}(B, t) = B_v^2(z)/8\pi,$$

where $B_v(z)$ is an arbitrarily specified vacuum magnetic field profile.

- Inductive effects associated with conservation of magnetic moment, μ , and longitudinal invariant, J , in time-varying magnetic fields.

In Figs. 95 and 96, we compare steady-state results for the confinement parameter $n\tau$ and the mirror-mode β limit $\beta_{m, \beta 1}$ derived from the usual magnetic-square-well model¹³⁷ with results from the newly developed bounce-average model.¹³³ Although the confinement parameter is somewhat smaller than for the square-well model, it is also less sensitive to variation of the injection angle; thus,

Fig. 95. Particle confinement parameter versus source injection angle for magnetic square well and bounce-averaged parabolic models.

more flexibility in the design of a mirror system may be possible.

The time-dependent aspect of the bounce-average code has been utilized to investigate the "moving mirror" concept¹³³ as a means of Q enhancement. In this scheme, the neutral-beam source is programmed to inject ions further and further from the mid-plane as the plasma density builds up and approaches the mirror-mode β limit. During this phase, energy will be removed from the parallel motion of the confined ions as the β -dependent magnetic field profile expands, and particle confinement should be improved. Figs. 97(a) and (b) show the density and magnetic field profiles during the buildup for the parameters listed in the figure caption. When the mirror-mode β limit is reached, the beams are turned off and the plasma decays. The Q of the system is defined as the ratio of the total fusion energy produced during the cycle to the total energy injected during the buildup phase. Preliminary results indicate that Q for this system is smaller than for a comparable steady-state injection system. Apparently, the kinetic energy removed by the "moving mirrors" increases the Coulomb scattering rate, thus compensating for the expected gain due to the steepening of the pitch-angle distribution.

Electron Dynamics and Energy Loss in Mirror Wells

Reconsideration of electron dynamics leads to significant corrections in computing the classical equilibrium of mirror confinement systems. Earlier

Fig. 96. Mirror-mode beta limit versus source injection angle for magnetic square well and bounce-averaged parabolic models.

work¹⁴⁵ on the need to revise the Fokker-Planck model has been expanded,¹⁴⁶ and the effects upon energy loss in the electron channel due to secondary electron emission at the ends have been analyzed.^{146,147} New computations of Q and $n\tau$ are made from the Fokker-Planck codes modified to more realistically account for the electron dynamics.¹⁴⁶

Supplementary Heating of Mirror Reactors With Electrostatic Wave Turbulence

The modified HYBRID II code, which includes a turbulent diffusion term for the quasi-linear calculation, has been used to study the supplementary heating of mirror machine reactors by imposed electrostatic waves. It was assumed that the waves were coupled into the plasma at either the first or second harmonic of the ion-cyclotron frequency. We investigated whether one could reduce the neutral-beam injection energy and then heat the ions by electrostatic turbulence. When the energy supplied to the ions by the imposed turbulence was included in the calculation of the Q of the reactor, we found that comparable Q 's could be obtained using a combination of neutral-beam heating and turbulent heating. However, the use of turbulent heating never improved the Q above that obtained with neutral beams alone. One would expect the turbulent heating to be even less favorable if the problems of coupling the waves into the plasma were considered realistically.

Fig. 97. Results of investigation of the "moving mirror" means of Q enhancement, showing (a) density profiles and (b) magnetic field profiles for the following parameters:

Curve no.	t (ms)	β	R	Beam width (cm)
1	0	0.0829	2.088	20
2	20	0.1236	2.136	40
3	40	0.2886	2.371	60
4	56	0.5721	3.057	76

Electron Heating for Q Enhancement

We have investigated the possibility of Q enhancement by electron heating. The basic idea is to eliminate the electron drag on ions by increasing the electron temperature. Previous work by Haste and Lazar¹⁴⁸ indicated that a small Q enhancement was possible. The Q of the system is defined by

$$Q = \frac{\text{fusion power } (P_F)}{\text{neutral-beam power } (P_b) + \text{electron heating power } (P_{eh})}$$

and can be expressed in term of the energy confinement time, τ_E ,

$$Q = \frac{1}{4} (n\tau_E) \frac{E_F}{\bar{E}_i + \bar{E}_e}$$

where $E_F \approx 17.6$ MeV is the energy release per fusion event, $\bar{E}_i$ and $\bar{E}_e$ are the mean ion and electron energies, n is the density, and σv is the fusion reaction rate parameter.

The two-dimensional velocity-space Fokker-Planck code HYBRID II¹⁴⁹ has been used to find the energy confinement time for various combinations of neutral-beam and electron-heating power. Ambipolar potential effects are included. Results are summarized in Fig. 98, where we plot the energy confinement as a function of the mean ion energy for several neutral-beam injection energies (E_b) and electron heating powers (P_{eh}). We see that for a given ion energy $\bar{E}_i$, the largest $n\tau_E$ (hence largest Q) is obtained with no electron heating. For different mirror ratios and with alpha particle energy deposition included, the basic conclusion is the same: Q is not enhanced by electron heating.

Dynamical Evolution of the Mirror Mode

If the dynamical evolution of the mirror mode in the absence of collisions maintains μJ invariance, then the Fokker-Planck equation coupled with the equilibrium constraints contains all the necessary physics. As will be described, J invariance implies that the particle distribution function at $v_e = 0$ is only affected by Coulomb collision; since these are the particles that dominate in determining mirror-mode limitations, there is no self-limiting process. Consequently, for a given injection profile there is current beyond which buildup no longer occurs.

The equations followed numerically are the Fokker-Planck equation

Fig. 98. Energy confinement versus mean ion energy for several neutral-beam injection energies E_b and electron heating powers P_{eh} for $R_m = 10$, $\theta_i = 60^\circ$, and no alpha particles.

$$\left(\frac{\partial f}{\partial t} \right)_{\mu J} = C[f]$$

and the long, thin equilibrium equation

$$p_{\perp} + \frac{B^2}{2} = \frac{B_{vac}^2(s)}{2}.$$

Now, since the equilibrium is changing in time, and since the Fokker-Planck equation is solved in $\epsilon, \sin^2 \theta_0$ space, we must modify the standard bounce equations averaged to include time-dependent terms; viz,

$$\begin{aligned} \left(\frac{\partial F}{\partial t} \right)_{\mu J} &= \left(\frac{\partial f}{\partial t} \right)_{\epsilon, \sin^2 \theta_0} + \dot{\epsilon} \left(\frac{\partial f}{\partial \epsilon} \right)_{\sin^2 \theta_0} \\ &+ \sin^2 \theta_0 \frac{\partial f}{\partial \sin^2 \theta_0} \left[\frac{B_0}{B_0} = \frac{\dot{\epsilon}}{\epsilon} \right], \end{aligned} \quad (22)$$

where from

$$J = \oint ds [2(\epsilon - \mu B + |e|\phi)M]^{1/2}$$

$$0 = \frac{dJ}{dt} = \oint \frac{ds}{v_{\parallel}} \left(\frac{d\epsilon}{dt} = \mu \frac{\partial B}{\partial t} + |e| \frac{\partial \phi}{\partial t} \right) M,$$

where

$$\dot{\epsilon} \equiv \left(\frac{d\epsilon}{dt} \right)_{\mu J},$$

we obtain

$$\begin{aligned} \frac{1}{\epsilon} \frac{d\epsilon}{dt} &= \frac{1}{\tau_B} \oint \frac{ds}{v_{\parallel}} \left[\frac{\sin^2 \theta_0}{B_0} \frac{\partial B(s,t)}{\partial t} \right. \\ &\left. + |e| \frac{1}{\epsilon} \frac{\partial \phi(s,t)}{\partial t} \right], \end{aligned} \quad (23)$$

and because the coefficient of

$$\frac{\partial f}{\partial \sin^2 \theta_0} = \frac{d}{dt} (\sin^2 \theta_0),$$

we see from Eq. (23) that $\dot{\epsilon}$ vanishes for $\theta_0 = \pi/2$; i.e., $v_{\parallel} = 0$. Note that $\phi = 0$ at $s = 0$, where the subscript zero refers to midplane values, and that τ_B is the particle bounce time. For the special case of a parabolic well, $d/dt \sin^2 \theta_0 \approx \cos^2 \theta_0$.

Now to close these equations, we must compute $\partial V/\partial t$, which is obtained from the long, thin approximation, and $\partial \phi/\partial t$, which is obtained from the quasi-neutrality constraint.

Several runs (neglecting the ambipolar potential) were made; in each, the equilibrium evolved toward the marginally stable point of the mirror-mode and numerical problems were caused by the sharp magnetic-field profiles. The dynamics proceeded as follows: as the plasma β increased, the magnetic field profile sharpened, increasing the magnitude of the convective derivatives $(\partial/\partial t)$ so that the field profile was further sharpened (similar to a gravitational collapse).

We also encountered an interesting numerical instability problem that must be specially treated in these time-dependent problems. From Eq. (22), we obtain the energy balance equation (for a parabolic well and large mirror ratio):

$$\frac{\partial p_{\perp}}{\partial t} - C \approx -2\dot{\beta} p_{\perp} \approx -\frac{\beta}{1-\beta} \frac{\partial p_{\perp}}{\partial t}. \quad (24)$$

The right-hand side of Eq. (24) is obtained from the equilibrium constraint and relies upon the knowledge of the magnetic field, which is only known from the previous time step. Here the numerical algorithm is of the form

$$\frac{p_{\perp}^{n+1} - p_{\perp}^n}{\Delta t} - C \approx -\frac{\beta}{1-\beta} \frac{p_{\perp}^n - p_{\perp}^{n-1}}{\Delta t},$$

with an amplification $A = \beta/(1-\beta)$. Hence, if $\beta \gtrsim 1/2$ the scheme is unstable. The remedy is to treat f/B_0^2 as the independent variable, thereby canceling the right-hand side of Eq. (24).

Optimization of Mirror Reactor Design

Hall, Hooper, and Newcomb¹⁵⁰ have shown how to select pressure profiles by neutral injection distributed in velocity space. These so-called optimal profiles, which reach the mirror mode equilibrium limit along a section of a field line rather than at some central point, allow much higher β than the collisional profiles but require a correspondingly higher injection current to support them because many particles are injected quite close to the loss cone.

These simple analytic profiles have been used in estimating mirror reactor costs (including magnet, injector, energy convertors, and building costs). Because higher β achievable from optimal injection leads to larger final mirror ratios R , which in turn lower the adiabatic energy limits as $1/R(R-1)^{1/2}$, the field pressure B^2 and hence the magnet cost must be correspondingly increased. On the other hand, the

total neutron power is held constant in the optimization and therefore allows lower injection energies for the same fusion power output. Thus, by using appropriate scaling laws for the various costs and normalizing the formulae to the reference mirror reactor design,¹⁵ we find that optimal injection decreases the \$/kW cost of net electric power by about 25%. In a FERF or a tandem mirror plug device, one should optimize either the cost of neutrons or the cost of plasma density for a given coil set.

These simple calculations show that very useful improvements in the cost of mirror reactors can be made by closer coordination of coil and injector design. The final coupling of coil, Fokker-Planck, Monte Carlo diffusion, equilibrium, and stability codes remains to be carried out.

Time-Dependent Computer Model for the Flow of the Stream and Gas-Feed Plasmas in 2XIIIB

The time-dependent, axial-flow characteristics of the stream and gas-feed plasmas in 2XIIIB are now being modeled by solving the moment equations for axial flow. The equations of continuity, momentum, perpendicular energy, and parallel energy are being used. This work is an outgrowth of the steady-state calculations described in last year's annual report¹ for cold-plasma flow in a two-component mirror machine. Besides the time-dependent behavior, a potential-like term has been added to the momentum equation to represent the magnetic mirroring of ions in a varying magnetic field. This term reproduces in a qualitative way the experimental observation of a minimum in the stream plasma at the mirror throat.

A major reason for developing a time-dependent code is that it can be coupled with the one- and two-dimensional quasi-linear Fokker-Planck codes to give a self-consistent model for the behavior of 2XIIIB and future mirror machines. For the present quasi-linear calculations, the stream strength is not coupled to the electrostatic wave amplitude. However, such coupling probably exists because the waves heat the stream particles and thus change their magnetic moment. Also, the code is valuable because it gives the axial variation of the particle density of the plasma stream. Because the DCLC instability is determined by a line average along a magnetic field line of the "local" growth rate, axial variation of the particle density may be important. Axial variation could be especially crucial for a tandem mirror scheme when the stability of the end cells depends on the degree to which warm, central-cell plasma penetrates the end cells. This code may give meaningful values for the axial variation of the warm, central-cell plasma.

Numerical Simulation of the Plasma in the 2XIIIB Gas Box

We have completed calculations on the spatial profiles of the plasma density and temperature in the 2XIIIB cold-gas box.¹ The first results showed high-density ($\sim 10^{15}$ particles/cm³) peaks developing over a narrow region ($< 10^{-2}$ cm) at the outside edge; these peaks prevented sources from maintaining any plasma density inside the box. These profiles had the nonphysical characteristic of gradient scale lengths small compared to the Larmor radius. An approximate form for ion-ion particle diffusion was added to the calculations and resulted in more realistic solutions. Steady-state results were generated for a range of D₂ currents extending from 9 to 9000 A (equivalent) (Fig. 99). Qualitatively, the results showed that for low currents, low-density, uniform plasmas developed. As the current increased, the plasmas took on hollow shapes with high peaked wings. However, as the current further increased, the wings got thicker, tending to fill in the hollows.

One-Dimensional Radial Transport Calculations

An analytic model for finite Larmor radius effects, based upon an expansion that assumes large density gradient lengths compared to the Larmor radius, has been developed and included in the radial one-dimensional code.¹ A typical source term in the density equation has the form (for a centered, narrow, neutral beam)

$$S(r) = \sigma v \left(n_i(r) [n_o(r) + n_b(r)] A(r) - \frac{a^2}{4} \frac{\partial^2}{\partial r^2} n_i(r) [2I_1(r) - I_2(r)] + \frac{1}{r} \frac{\partial}{\partial r} n_i(r) [6I_1(r) \cdot I_2(r)] \right)$$

where

$$I_1(r) \equiv \frac{1}{\pi} \int_0^1 \frac{dz}{(1-z^2)^{1/2}} (1-z^2) \times \{n_b(zr) + n_b(-zr)\} H\left(z^2 \cdot 1 + \frac{D^2}{r^2}\right),$$

$$I_2(r) \equiv \frac{1}{\pi} \int_0^1 \frac{dz}{(1-z^2)^{1/2}} [n_b(zr) + n_b(-zr)]$$

Fig. 99. Steady-state plasma density profile in the gas-feed region for various neutral-beam currents.

$$\times H\left(z^2 - 1 + \frac{D^2}{r^2}\right),$$

$$A(r) = \frac{1}{\pi} \sin^{-1} \left[\min \frac{(D, r)}{r} \right],$$

and n_i is the plasma density, n_b is the neutral-beam density, D is the neutral-beam half width, a is the Larmor orbit, σv is the appropriate reaction rate, and H is the Heaviside step function. A typical loss term has the form

$$L(r) = -\sigma v \left\{ n_i(r) [n_g(-r) + n_g(r)] A(r) \right. \\ \left. - \frac{c}{\omega B} \frac{1}{r} \frac{\partial}{\partial r} r [n_g(-r) + n_g(r)] A(r) \frac{\partial n_i T_i}{\partial r} \right\}.$$

where ω is the Larmor frequency, B is the magnetic field, c and e have their usual meaning, T_i is the plasma temperature, and n_g is the neutral gas density.

We are concentrating on determining the physical regime in which the model gives valid results. Results so far suggest that even for initial conditions that violate the model assumption (i.e., steep density gradients), the solutions evolve toward profiles that satisfy the assumption (i.e., shallow density gradients). If this proves to be the case, the calculations should be good for all Larmor radii on the order of or less than the plasma radius, a limit that already exists for the basic fluid assumption.

Finite-Orbit Separation Theorem

For a two-dimensional, guiding-center plasma in the finite-orbit regime, it is possible to effect a complete separation of variables between the nonlinear equations of motion governing fluid modes, on the

one hand, and so-called drift modes on the other.¹⁵² The separation theorem has now been extended to three-dimensional systems of large aspect ratio. This makes possible a rational treatment of finite-orbit stabilization either in a large-aspect-ratio mirror geometry (with finite β) or in a screw pinch with a small ratio B_θ/B_z .

Effects of Weak MHD Instabilities of a Finite Larmor Radius

In many confinement configurations, MHD growth rates are weak because they arise from a small departure from a straight cylindrical configuration. Examples of such configurations are axisymmetric mirrors where the radius of curvature is very large compared to the plasma radius, the Syllac configuration where the aspect ratio and helical fields are small, and the stabilized pinch (screw pinch) where the stabilizing magnetic field in the axial direction is large compared to the magnetic field in the θ -direction.

Since these configurations are all characterized by a weak departure from a straight cylinder, stability is computed by expansion from the lowest-order solution, that of a straight θ -pinch. Namely, $\omega = 0$ (the eigenfrequency). In general, in such calculations the leading contribution to the eigenfrequency from the geometric distortion (of order ϵ_{geom}) is of order $\epsilon_{\text{geom}}^{1/2}$.^{153,154} Similarly, in computing the effects of finite Larmor radius (of order ϵ_{FLR}) the modification to the eigenfrequency is of order $\epsilon_{\text{FLR}}^{1/2}$.¹⁵⁵ (For the $\beta = 0$ case, see Ref. 156.) Equivalently, the eigenfunction expansion is given by

$$\psi = \psi_0 + \epsilon_{\text{geom}}^2 \psi_{\text{geom}} + \epsilon_{\text{FLR}}^2 \psi_{\text{FLR}}.$$

Hence, to obtain a complete theory one need only compute the geometry modification neglecting the finite Larmor radius to obtain a quadratic (variational form) and to that add the finite Larmor radius quadratic correction neglecting geometry. (Newcomb¹⁵⁷ has made a general proof of the additive character of the perturbations.) The variation of the total quadratic form then generates the Euler-Lagrange equation.

Now, since both pieces of this problem have been studied in some detail in the published literature, it is only necessary to extract those appropriate pieces.¹⁵⁸ As a representative case, we compare (see Fig. 100) calculations using this model with earlier numerical and analytic results.

Mechanism For Negative-Ion Production in the Surface-Plasma,

Negative-Hydrogen-Ion Source

We have reviewed the system parameters and surface adsorption conditions of the surface-plasma,

negative-hydrogen-ion source. A mechanism has been developed for the production of negative ions by incident, energetic-hydrogen atoms backscattering from a cesiated tungsten surface. The active electronic level during the course of the collision is approximated as the sum of the negative electron affinity of the cesium hydride, negative molecular ion and the image potential. The model predicts negative-ion formation for atomic collisions with all alkali-coated surfaces for alkalis from sodium through cesium. The model does not apply to lithium because the image potential approximation breaks down close to the surface. Negative-ion formation is also expected when incident positive ions backscatter from the substrate tungsten as neutrals. We have established the energy thresholds for incident atoms¹⁵⁹ and are now extending the calculations to include electron loss as the negative ion moves away from the cathode surface.

Interaction Cross Section of Cs^+ Ions

In selecting an ion for use in a system based on the fusion of heavy-ion pellets, care must be taken that the ion selected not have charge-exchanging reactions with like ions during the storage time in the storage ring. Specifically, we have examined the reaction

and have estimated the low-energy cross section for this process using the available interaction potentials appropriate to the left- and right-hand sides of the reaction. We estimate that cross sections are 10^{-15} cm^2 , small enough that this ion is a promising candidate for a pellet-fusion system.¹⁶⁰

Fig. 100. Comparison between present calculations of the electrostatic confinement of ions and earlier numerical and analytic results.

Nonadiabatic Behavior in Magnetic Fan Regions

Efficient conversion of the energy of ions that escape the mirrors is dependent upon (among other things) the ion energy being nearly entirely converted to energy parallel to the field lines. In fact, a simple expression for the reduction of efficiency $\Delta\eta$ of a Venetian blind direct converter due to $v \neq v_{||}$ is¹⁶¹

$$\Delta\eta = 6.9 \left(\frac{v^2 - v_{||}^2}{v^2} \right)$$

In terms of the magnetic moment of the ion μ , this becomes

$$\Delta\eta = 6.9 \frac{\mu B}{\mu_M B_M}$$

where the subscript M denotes conditions at the mirror.

If the magnetic moment is conserved as the ion travels in the fan region, $\Delta\eta$ can be made as small as desired by moving the direct converter into regions of lower B. Unfortunately, the curvature of the field lines increases as the magnetic field decreases, resulting in nonadiabatic motion of the ions.

To study this process for a particular case, the D-T fusion reactor, we have employed the particle code TIBRO-X,¹⁶² a much modified version of the TIBRO¹⁶³ code. A plot of $\mu B/(\mu_M B_M)$ for a typical triton that escapes is shown in Fig. 101. We see a steady decrease at first, followed first by an oscillation due to typical behavior in μ and then by an increase. Clearly, for the lowest $\Delta\eta$, it would be desirable to locate the direct converter at a radius of about 50 m from the center of the reactor. The field-line curvature also causes particle drift, which is

Fig. 101. $\mu B/\mu_M B_M$ for a typical ion trajectory in the magnetic fan of a D-T fusion reactor where the mirror is 8 m from the center of the reactor.

also computed by TIBRO-X; however, this can be compensated for by a shift of the direct converter.

Tokamak Microinstability

We have extended work on the nonlinear saturation of the dissipative trapped ion mode by mode coupling¹⁶⁴ (a tokamak problem begun at Princeton University) to a general, two-dimensional study. Analytic equilibria have been constructed, and a linear stability analysis has been performed. A two-dimensional fluid code has been built to directly integrate the time-dependent nonlinear equation of evolution. For a few special cases, we have verified the code by checking its results against analytic solutions: the code confirms that one-dimensional equilibria are unstable to transverse (radial) perturbations. We find stable two-dimensional analytical equilibria with values of $e\phi/T$ considerably smaller than our earlier one-dimensional results. Hence the associated anomalous transport is much weaker than our previous estimates and weaker than the Kadomtsev-Pogutse estimate.

Flute Instability of Pellet Expanding in a Magnetic Field

In LITE and Baseball II (BBII) experiments, a laser-irradiated pellet has been used for generating a target plasma for the neutral beams. One fear with such a method is that the plasma would develop flutes in the deceleration phase of the trapping. These flutes could penetrate the magnetic field to cause a high plasma loss. Last year¹⁶⁵ we described a snowplow model for the instability; the model showed that the flutes should steepen to form cusps, at which point the analysis is no longer valid.

To study the flutes for a longer time, we have employed the two-dimensional code ANIMAL.^{165,166} This code solves the MHD equations, with electrical and thermal conductivity, on an Eulerian grid. Cases typical of expected parameters in BBII were run with different wavelength perturbations for constant and minimum-B magnetic fields. As expected from theory, longer wavelengths dominate the behavior at long times. As the bulk of the plasma decelerates, the flutes continue into the magnetic field, their front surface forming a mushroom shape which "splashes" under the effect of the magnetic field (see Fig. 102). The fluted plasma also separates from the bulk of the plasma. Fig. 103 shows the trajectory of the front of a flute for two magnetic field cases with initial perturbation wavelengths of 1 cm. Times at which splashing occurs are indicated by arrows. We note that the expansion is faster for the case of a uniform field. From these results, we expect that the expanding plasma will be trapped by

Fig. 102. Successive snapshots of contours of constant density for pellet plasma expanding into a magnetic field: (a) $t = 5 \mu s$; (b) $t = 12 \mu s$; and (c) $t = 20 \mu s$.

the field, but at a larger radius than would be expected without fluting, and that the flutes will cause some "sloshing" of the plasma.

Laser Heating of Magnetically Confined Plasma

We have continued a study of some aspects of laser heating of magnetically confined plasma and more generally the resonant excitation of large-amplitude plasma waves.¹⁶⁷ The nonlinear effects of electrostatically trapped electrons on the scattering of laser light in "beat heating" or conventional Raman scattering are determined by a combination of analytic theory and particle simulation.

Exploratory Concepts: The Intense Ion Diode

Our goal is the development of extremely intense, pulsed, ion-beam sources. These sources could provide neutral beams that are intense enough to enable the buildup of energetic plasma in a mirror machine on a time scale of only a few gyroperiods. This rapid buildup capability may prove necessary to achieve field-reversed configurations in mirror plasma-confinement experiments.

Theoretical work has furthered our understanding of diode physics. Computational work has combined Poisson and Monte Carlo codes for the purpose of designing more efficient ion-generation sources.¹⁶⁸ These design studies, though incomplete, suggest that ~50% of the current supplied to the diode can be extracted as intense ion beam.

Fig. 103. Position of the front of the fluted plasma versus time for an initial perturbation wavelength of 1 cm. Curve (a) shows the constant-B field; curve (b) the minimum-B field with $dB/dx = 1 \text{ kG/cm}$; and curve (c) the position of the front of the unfluted plasma.

The results of a series of short-term experiments conducted at Physics International and Sandia Laboratories during the report period verified the basic concept of using reflex diodes to generate intense ion beams. At Physics International, a 50-cm² source generated ion current densities of 2 kA/cm² at 100 keV for 100-ns.¹⁶⁹⁻¹⁷¹ Experiments performed at Sandia Laboratories extended the duration of 100-keV ion generation up to 750 ns, although generator limitations meant an order of magnitude reduction in current intensity.¹⁷²

These experiments provided the basis for design of a 250-kV, 60-kJ generator and experimental facility for further development of the concept. The

goal for this experimental phase is the development of a 50- to 100-kV neutral beam with an equivalent current of 50 to 100 kA for 1 μ s. A contract for the

generator was awarded to Physics International in October 1976; completion of the full facility is scheduled for July 1977.

SECTION 4. CONFERENCES

Introduction

During the report period, two conferences of note were held at LLL: the US-USSR Symposium on Fusion-Fission Reactors and a Q-Enhancement Workshop.

US-USSR Symposium on Fusion-Fission Reactors

A US-USSR Symposium on Fusion-Fission Reactors was held at Lawrence Livermore Laboratory, July 13-16, 1976, as part of the US-USSR exchange of information on fusion power research and development. Approximately 75 scientists and engineers attended, including 3 from the USSR. Nearly all of the work in progress in the US and the USSR was reviewed at the meeting; the published proceedings¹⁷³ summarize the present understanding of fusion-fission reactor principles.

Considerable progress was reported in understanding the many engineering problems associated with using complex fusion devices as neutron sources for the breeding of fissile fuel. Early simple calculations indicate attractive fissile production rates when realistic engineering structures, cooling methods, and materials limitations are taken into account.

Q-Enhancement Workshop

A Q-Enhancement Workshop was held at Lawrence Livermore Laboratory September 13-17, 1976. There were 41 attendees from outside LLL, and a varying number of 20 to 30 attendees from LLL.

One of the objectives of the Workshop was to define appropriate experiments or calculations bearing on Q-related questions. To a certain extent this end was accomplished; however, the most useful objective of the Workshop was to spread interest in Q-related questions beyond the confines of LLL.

The first day of the meeting was a plenary session devoted to background talks on the present status of mirror research and on two Q-enhancement

topics. For the remainder of the week, attendees participated in one of three working groups:

- End Plugging
- Linked Mirrors and Alternate Geometry
- Field Reversal and High- β Effects

Additional plenary sessions were then held for seminars on topics deemed to be of general interest.

Brief summaries of the activities of each of these working groups follow. Table 11 contains evaluations of Q-enhancement methods.

End Plugging

The attention of the working group devoted to methods of plugging the ends of single-cell mirrors was focused primarily upon electrostatic means. A novel confinement scheme based upon this principle, described by T. K. Fowler and B. G. Logan, entails three mirror cells in tandem, with the ions of the central cell electrostatically confined between relatively dense, energetic plasmas localized to the two end cells. The Fowler-Logan tandem mirror was considered by the working group (and by the entire Workshop) to be a most promising Q-enhancement approach.

Some attention was devoted to past and current results on radio-frequency (rf) plugging, and a number of preliminary ideas were introduced. Radio-frequency plugging was considered to be limited by serious problems of rf wave penetration into the plasma at high density, the loss of rf power to the walls, and the possibility that the rf wave will couple to negative-energy ion-cyclotron modes within the plasma. Although an experiment on rotating plasmas at Novosibirsk was reported by V. Bocharov, this subject received relatively little attention, probably because of prevailing concern about the MHD stability of such systems. Rotating plasmas are currently conceived as having axial electrical contact with material structures both to stabilize interchange modes and to induce rotation via radial electron fields. This approach was seen to suffer from a prohibitive axial electron thermal conductivity and resulting low electron temperatures.

Table 11. Evaluation of Q-enhancement methods.

Method	Theoretical Q obtainable	Related experiments	Present understanding of physics	Reactor characteristics/ advantages	Foreseen difficulties/ disadvantages
Tandem mirror	Ignition	LLL proposal ³³	High	Direct conversion; high density, β ; low field and capital costs; clean with DD operation; ~GW.	Accumulation of reaction products.
Field reversal	Unknown, possibly high	ZXIB; Kurchatov; LASL; Cornell	Low	Low capital cost; small power; modular cells.	Transport due to small R_p/ρ_1 .
Toroidally linked minimum-B	4 to 5	None	Medium high	Few GW, must be $\int \frac{dQ}{B} \rho_1$ stable.	Costly magnetic field; costly to test principle.
Elmo Bumpy Torus	Ignition	ORNL	Medium high	Few GW.	High microwave power required for electron rings; under high- β conditions, there will be rapid energy exchange between rings and toroidal electrons.
Two-component	2	None	High	GW	>1 km length if not multiple mirrors.
Linear multiple mirror	< ignition	UCB; Novosibirsk; Sukhumi	Medium high	Must be $\int \frac{dQ}{B} \rho_1$ stable; 3 GW; 400 m long.	Radial diffusion in presence of enhanced scattering (e.g., non-adiabaticity).
Cusp and electrostatic	5	Kharkov	Medium	GW; circular coils	Hole size ρ_c must be maintained; breakdown due to extreme voltage; sheath stability and diffusion at high energies.
Ion Bumpy Torus	Ignition	None	Low	If MHD stable; ion rings should be better than electrons energetically; principle should be tested on single cell.	
MIRICLE	1.7	Cornell Proposal ¹⁷⁴	Medium	Modest Q gain	Toroidal and electron removal questions remain to be solved.
Rotating mirror	4 to 5	Novosibirsk	Medium low	Compact; ~GW size; axisymmetric.	Naturally MHD unstable; electrodes contacting plasma cools electrons.
rf plugging	1 to 2	Nagoya	Medium low	Compact; ~GW size.	Requires high rf power; wall loading; coupling to plasma modes.

Linked Mirrors and Alternate Geometry

This working group dealt with axially and toroidally linked mirror cells and with certain alternate geometries such as that typified by the multipole Surface Magnetic Confinement (Surmac) (A. Wong, at UCLA).

Devices based on linking minimum-B wells were described: C. J. H. Watson (Culham Laboratory) discussed toroidal linking and A. Lichtenberg (LBL) described axial linking.

Reactor concepts based on toroidal linking hold definite promise, with calculated Q values of 4 to 5. The chief difficulties with such schemes are the complexity of the magnetic field and the high cost of proof-of-principle experiments.

Axially linked systems rely on ion scattering in each mirror cell, traditionally taken to be Coulomb scattering, however, during the Workshop, non-adiabatic and rf scattering were considered. The simultaneous radial transport induced was seen to be a problem, and this subject requires further study. Lichtenberg reported on field designs that satisfy the maximum $\int df/B$ property required for MHD interchange stability.

At this stage, both the toroidally and axially linked systems show promise, particularly in combination with two-component operation.

The Surmac (Wong) approach was also discussed, particularly as to how it related to other multipole ideas. This approach confines plasma by a surface magnetic field generated by a very high-order multipole, and has the quite unique feature of being magnetic-field-free over much of the plasma volume. The working group concluded that the possibility of combining this with a multiple-mirror approach should be pursued.

Field Reversal and High- β Effects

Discussion of high- β Q-enhancement was subdivided into three broad topics:

- Theory of guiding-center equilibrium and stability at high β ,
- Stability and transport properties of reversed-field configurations,
- Improvement of electron physics in particle simulation codes at high β (SUPERLAYER at LLNL and the Cornell code), and
- Experiments, measurements, and diagnostics.

Guiding-Center Equilibrium and Stability at High β . It was generally agreed that the limiting- β values calculated using current guiding-center codes disagreed with experimental results. It was felt that the relaxation of the mirror-mode restriction was probably a Larmor orbit effect. Such an effect comes in several ways; for example, at a few Larmor

orbits in the cross section, the guiding-center description is breaking down, and in this small radius limit there may be appreciable energy in rotation that alters the stability picture. Crude ways of including the influence of the finite Larmor radius are

- To average equilibrium quantities over the guiding-center motion which for 2XIIIB conditions reduce the effective β to half its peak value, and also
- To include finite Larmor radius terms in the stability analysis, thereby relaxing the beta limit. Similar arguments could be made for the Alfvén ion-cyclotron instability. The consensus was that analytic and computational work was required. In particular, these effects should be studied on a particle code such as SUPERLAYER.

Reversed-Field Configurations. Because reversed-field configurations are unstable in the MHD limit, it appears that only plasmas having aspect ratios of order unity and a size equivalent to a few Larmor radii can be stable. A thin non-MHD limit is difficult to obtain analytically; it was generally agreed that a modification of a code such as SUPERLAYER could handle the theory. Specifically, it was suggested that a two-dimensional, axisymmetric code with linear perturbations in the direction of symmetry would have the dominant physics. To assure interchange stability, it was thought that it would be reasonable to use a stabilizing artificial gravity to simulate the quadrupole field. Finally, the importance of better electron physics was emphasized.

Particle Simulation Codes. There was extensive discussion of just how to follow electrons in a particle code. Since the frequency of the electrons is generally unimportant, the dominant motion of electrons is the EXB drift. The high conductivity of the electrons along field lines should force the parallel electric field to be zero. There was (at the time of the Workshop) no agreement as to how the electron motion in the zero magnetic field region should be modeled. One popular idea was to include an effective conductivity that would become large in the region of the reversing field. Analytic and code results will be needed to guide the model.

Experiments, Measurements, and Diagnostics. In the session on experiments, it was agreed that, if equilibrium, stability, and scaling could be achieved, field-reversed reactor prospects were very encouraging due to advantageous cost, size, and modular construction. The Cornell electron-ring experiments and the USSR/German θ -pinch experiments have provided the experimental basis for field-reversed equilibrium.

New experiments of interest include the 2XIIB neutral-beam, ion-ring experiments to test equilibrium, stability, electron effects, and microstability. The LASL reversed-field θ -pinch experiments would also test R/a_i scaling. Also men-

tioned was the desire to study transport properties in field-reversed equilibria, possibly in internal-ring devices. It was agreed that detailed diagnostics of field-reversed equilibria need development, although global or indirect techniques exist.

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