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MAGNETIC FUSION ENERGY QUARTERLY REPORT

January through March 1978

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

April 22, 1978

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LAWRENCE LIVERMORE LABORATORY

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NOTICE

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Frontispiece. The Mirror Fusion Test Facility (MFTF) coil winder pictured in the last *Magnetic Fusion Energy Quarterly Report* will be used to wind about 80,000 feet of Nb-Ti and Cu wire around the coil frame. Using procedures established during test winding on the test-coil frame shown here, we can then begin winding the twin coils that will create the magnetic field needed to confine the plasma in the \$94 million MFTF.

PREFACE

Effective with the beginning of FY 1978, the *Magnetic Fusion Energy Annual Report* for the Magnetic Fusion Energy (MFE) Program at the Lawrence Livermore Laboratory (LLL) was replaced by quarterly reports; this is the second in the new series.

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

The information in each *Quarterly* is presented in the same sequence as in the *Form 189* submissions prepared for the U.S. Department of Energy; the three main sections are Open Confinement Systems, Development and Technology, and Applied Plasma Physics. Each of these sections is introduced by an overall statement of the goals and purposes of the groups reporting in it. As appropriate within each section, statements of the goals of individual programs and projects are followed by articles containing summaries of significant recent activity and descriptive text.

The last *Quarterly* in each fiscal year will contain a list of all publications and presentations prepared by MFE personnel during that year.

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*LLL Participating Guest employed by the Pacific Gas and Electric Company.

MAGNETIC FUSION ENERGY QUARTERLY REPORT

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1. OPEN CONFINEMENT SYSTEMS

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

There are three confinement systems now in operation or under construction at LLL: the 2XIIB, the Tandem Mirror Experiment (TMX), and the Mirror Fusion Test Facility (MFTF).

- 2XIIB relies on magnetic fields to confine a hot, dense plasma for a short time. It features C-shaped magnetic coils that form the confining magnetic field. Their unique shape (in what is known as a yin-yang geometry) stabilizes the confined plasma by creating a magnetic field (a magnetic well) that increases in every direction from the plasma center.

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

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

2XIIB

The 2XIIB magnetic-mirror machine was built to study the scaling of plasma confinement with ion energy. We have raised the mean plasma ion energy to 13 keV and the peak energy confinement parameter $\hat{n}_e \approx 10^{11} \text{ cm}^{-3} \cdot \text{s}$. After reaching high betas ($\beta = 8\pi n W_i / B_{\text{vac}}^2$), experiments attempting to achieve field reversal reached a field-reversal factor $\Delta B/B = 0.9$. Experiments attempting to improve the microstability of mirror-confined plasma, to increase plasma radius, and to further increase beta are underway.

Large-Diameter Experiment

The diameters of 2XIIB plasmas have been doubled in a series of experiments begun this quarter. Improved electron energy confinement and an apparent reduction in anomalous ion losses were observed when the plasma radius was increased.

Introduction and Parameters Achieved. (2XIIB team)

The large-diameter plasma experiment initiated this quarter was the principal 2XIIB experiment during the quarter. Larger-diameter plasmas are produced in 2XIIB by aiming the neutral beams off-axis so that, when the beams have been ionized, the ion guiding center is displaced further from the axis, thus increasing the diameter of the plasma. This "paramagnetic" aiming is to the opposite side of the

axis than that used in field-reversal experiments ("diamagnetic" aiming).

Figure 1 shows radial density profiles of beam attenuation, Thomson scattering, and charge exchange. These measurements indicate a mean plasma radius of 13.6 cm. Since in these experiments beams were operated with hydrogen, this plasma has a size of seven gyroradii. Diamagnetic-loop measurements give further evidence that a large, hot-ion plasma has been produced.

That plasmas with larger radius can be produced means that stabilization via the streaming-plasma technique works for plasmas with radii larger than 2 to 3 gyroradii; this is not a trivial result, since it means that finite-gyroradius effects were not responsible for the stabilization of the earlier, smaller-diameter plasmas.

Fig. 1. Radial density profiles of large-diameter 2X11B 10-keV hydrogen plasma ($B = 0.77$ T).

We have been conducting beam-aiming experiments over a wide range of conditions (see Ref. 1) and with different ion species in the neutral beams and streaming plasma. Table I summarizes data from our highest-beta shots. As can be seen (see also Fig. 2), the plasma beta decreases with increasing plasma radius. This is expected without a dramatic increase in $n\tau$, since the beams are filling a much larger volume. The electron temperature decreases more slowly. A simple classical electron temperature model, where T_e is electron temperature and n is plasma density, gives a $T_e/n^{4/5}$ theoretical scaling factor, whereas in earlier 2X11B operation, we found that T_e/n was an experimental scaling factor that indicated the quality of electron confinement. In either case, we see that both $T_e/n_e^{4/5}$ and T_e/n_e have improved with larger radius.

Figure 2 shows that the product $\hat{n}\tau_E$ of mean energy confinement time τ_E times central density $\hat{n}$ is independent of radius.* Since T_e is decreasing, it appears that the anomalous losses decrease with increasing plasma radius (note that $\hat{n}\tau_E/(2\sqrt{2}n\tau_{\text{drag}})$ increases with radius).

These experiments will be completed in April; we are obtaining considerable data and shall continue our analysis of it.

Radio-Frequency Probe. (D. P. Grubb and T. C. Simonen)

We have inserted a perpendicular, 13-tip rf probe in 2X11B in the east (vertical) fan 160 cm from the midplane. By inserting or withdrawing the probe,

we can measure the radial profile of the rf fluctuations and map the recorded profile back to the midplane. For each data shot, not only the envelope of the high-frequency oscillations during the entire shot is stored but also a 40- μ s-long, high-speed transient record is stored. With the number of amplifiers and transient recorders available, we can study five spatial locations on each shot. Fast Fourier transform routines² are used for frequency analysis of the data from the transient recorders.

The results of a radial scan of the rf fluctuations present in a large-diameter (large R_p/a_i) hydrogen plasma with a vacuum field strength of 0.77 T are summarized in Figs. 3 through 6. The plasma density and electron temperature profiles are shown in

Fig. 2. 2X11B parameters vs R_p/a_i . The data are for deuterium plasmas except for the right-most point.

*This comparison is not at constant beta. Further work will concentrate on comparisons of $n\tau$ with radius for constant beta.

Table 1. Results of 2XIIB plasma-radius scaling experiments.

	Experiment			
	Field reversal 9 12 77: shot 27 at 6 ms	Head-on injection 9 19 77: shot 15 at 6 ms	Large R_p/a_i (deuterium) 2 24 78: shot 30 at 4.5 ms	Large R_p/a_i (hydrogen) 1 25 78: shot 47 at 7 ms
Conditions:				
Beam offset	3 cm	0 cm	140 A at 0 cm 270 A at -3 cm	130 A at 0 cm 250 A at -3 cm
Beam current (A)	510	500	410	380
Streaming plasma:				
Guns	3, 4, 5, 6	3, 4, 5, 6	5, 6, 7, 8	5, 6, 7, 8
Gas	25-Torr D_2	25-Torr D_2	None	None
Results:				
$\int ndl$ (10^{15} cm^{-2})	1.4	1.1	1.3	0.9
R_p (cm)	6.4	11.7	14	14
L (cm)	16	20	20	20
A_s (10^{13} cm^{-3})	12.1	5.3	5.3	3.5
W_i (keV)	13	13	12	12
β	1.5	0.6	0.5	0.4
T_e (eV)	130	115	93	100
$\Delta\phi/\phi$ (10^{-3})	3.4	3.5	3.5	2.0
a_i (cm)	3.6	3.5	2.3	2.3
R_p/a_i	1.8	3.3	4.9	6.0
$B(T)$	0.67	0.67	0.77	0.67

Fig. 3. The amplitude of the rf fluctuations as recorded by the rf envelope and the autocorrelated probe-tip signal are shown in Figs. 4 and 5 respectively. These data are taken with a five-tip probe on several shots. The data points connected with lines are from one shot for both Figs. 4 and 5. Both figures show a reduced rf amplitude near the center of the plasma, though the effect is more pronounced in Fig. 5. This reduction may reflect the fact that the rf oscillations recorded in Fig. 5 are only those at the cyclotron frequency, whereas the rf envelope may be made up of signals with many different frequencies.

The radial profile of the frequency spectrum is shown in Fig. 6. Within shot-to-shot reproducibility, the mode exhibited a single, unique frequency ($10 \text{ MHz} \pm 0.1 \text{ MHz}$) over the entire diameter of the plasma. The observed frequency appears to be consistent with the β -corrected cyclotron frequency.

For the data reported above, the plasma was unstable to only a single mode. However, on several occasions during the large-diameter plasma experi-

Fig. 3. Radial profile of 2XIIB plasma in which rf measurements were made.

Fig. 4. Radial profile of average rf envelope signal from 4 to 6 ms.

ments, we observed that the plasma was unstable to two modes with nearly the same frequency at the same time (Fig. 7). By varying the neutral-beam current at a constant vacuum field strength, we measured the frequency shift of these modes as a function of the central plasma beta $\beta(0)$. The frequency shift of both modes shown in Fig. 8 appears to be between a "long-thin" plasma approximation

$$f \approx f_{\text{vac}} [1 - \beta(0)]^{1/2},$$

and a "bounce-averaged" model,

$$f \approx f_{\text{vac}} [1 - \beta(0)/2]^{1/2},$$

although the frequency of the low mode may not be the vacuum field value in the limit that $\beta(0) \rightarrow 0$.

That the rf amplitude is localized on the edge of the plasma and that the plasma may be unstable to more than one mode at the same time are new observations that will receive more study during the next quarter.

End-Loss Analyzer. (D. P. Grubb)

The 2-in.-diam end-loss analyzer (ELA) developed by Molvik³ has been used to measure the flux of plasma particles impinging on the west-end wall of 2XIIB during the large-diameter plasma ex-

periments. In its present location, the ELA samples plasma from an ellipse that is approximately 5 cm high by 1/2 cm wide and centered at the midplane.

By varying the voltage of the ion repeller grid inside the ELA, we have measured the energy distribution of the plasma entering the ELA. The energy distribution of the plasma from the streaming-plasma gun is shown in Fig. 9(a); most of this plasma has an energy less than 250 eV. The energy distribution of the plasma reaching the ELA when the same streaming-plasma guns are fired in conjunction with the neutral-beam sources is shown in Fig. 9(b). Once again, there is a large contribution to the end-loss current by particles with energies less than 250 eV, but there is now a significant current of ions with energies greater than this amount. During the next quarter, we shall measure a third energy distribution: that of the plasma built up by the neutral beams and by only those streaming-plasma guns on the east end of 2XIIB. By comparing these data with those in Fig. 9(b), we can measure the amount of streaming-plasma that is reflected by the potential created by the hot, trapped ions.

Under the same conditions, i.e., plasma buildup by the east streaming-plasma guns and by neutral beams, we can compare the current of ions measured by the ELA at energies less than ~ 3 kT_e.

Fig. 5. Radial profile of ω_{ci} averaged over $40 \mu s$ (starting at 4 ms).

Fig. 6. Radial profile of observed frequency and the calculated β -corrected ω_{ci} cyclotron frequency (for density distribution of Fig. 3 and H^+ plasma).

Fig. 7. Amplitude vs frequency for autocorrelated probe-tip signal.

Fig. 8. Observed frequencies of two modes present at the same time as a function of the central plasma beta $\beta(0)$ (D^+ plasma). For curves marked (a), $f = f_{vac}$; (b), $f = f_{vac} [1 - \beta(0)/2]^{1/2}$; and (c), $f = f_{vac} [1 - \beta(0)]^{1/2}$.

with predictions of the minimum current required to maintain the DCLC mode at marginal stability. However, this requires that the energy distribution of the ion current to the ELA be determined as plasma conditions change. To sweep out the energy distribution of the current several times during a single data shot, during the next quarter we shall

Fig. 9. Energy spectra of end-loss current: (a) streaming-plasma guns only, and (b) both streaming plasma guns and neutral-beam injection.

build a voltage-controlled power supply and ramping circuit capable of biasing the ion repeller grid from 0 to 1 kV in less than 200 μ s and operate it with the ELA.

End Calorimeter Measurements. (G. M. Melin)

We have measured the end-loss energy leaking through the 2XIIB fans during the large-diameter

plasma experiments by using calorimeters located at each end of the machine (Fig. 10). Each calorimeter consists of an array of five copper plates ($2\text{ cm} \times 6\text{ cm}$), the central plate being divided into three smaller plates ($2\text{ cm} \times 2\text{ cm}$). The east calorimeter, when centered on the machine center line, magnetically maps into a rectangular shape (about $30\text{ cm} \times 1\text{ cm}$), parallel to the x -axis at the $z = 0$ midplane (see Fig. 10), while the west calorimeter maps into an equivalent shape parallel to the y -axis. We can evaluate the total end-loss energy through a fan as follows:

- The energy collected by a calorimeter, where the energy profile is defined by the five plates, may be considered as having been emitted by the associated rectangular area at the $z = 0$ midplane.

- The end-loss energy is then calculated by assuming azimuthal symmetry.

In most experiments, the hot-plasma radius is smaller than the radial extent of the calorimeter mapping area ($\sim 15\text{ cm}$). The energy losses corresponding to a radius larger than 15 cm are then small and neglected in this end-loss energy evaluation.

Experimentally, we find the following:

- Most of the energy exits along or near the flux tubes of the streaming-plasma guns.

- The energy profile is broader than that of the streaming-plasma gun flux with no hot plasma present.

- Equal energy depositions are observed on east and west calorimeters when symmetrically placed streaming-plasma guns are located on both ends of the machine.

- The energy received by the calorimeter during a shot is consistent with other measurements in the end regions:

- flux of particles and electron temperature from Langmuir probe data,

- ion energy by a retarding potential, gridded analyzer.

Figure 11 shows typical results obtained with a deuterium plasma when the neutral-beam current is varied: the total end-loss energy evaluated by calorimetry is plotted vs the total energy deposited by the beams during a shot. Only about 50% of the beam energy goes to the ends. The discrepancy raises several questions about the nature of other possible losses:

- Losses via high-energy particles that go to the ends but miss the calorimeter because of their large Larmor radii; and

Fig. 10. Locations of end-loss calorimeters.

Fig. 11. End-loss energy (data points) vs deposited beam energy for various neutral-beam currents.

● Radial losses at the midplane resulting from some rf activity, i.e., either rf-enhanced radial diffusion or rf heating of ions that are charge exchanging with cold gas at the plasma boundary.

The classical Spitzer value for the average $n\tau$ product $\langle n\tau \rangle = 4.4 \times 10^7 T_e^{3/2}$ (eV) agrees well with the experimental $\langle n\tau \rangle$ inferred from diagnostics measurements at low beam current; however, it is no longer relevant at high beam current. This behavior is similar to that found in the gas-box experiments reported elsewhere.⁴ We are investigating the role of rf fluctuations and comparing experimental results with calculated results from a buildup code.

Radial Fokker-Planck Calculations. (A. H. Futch)

We have modified the radial Fokker-Planck code (RFPC) to include quasi-linear diffusion. The Fokker-Planck coefficients were modified by adding additional terms calculated by integrating the quasi-linear coefficients derived by Rognlien for the HYBRID II code⁵ over a normal-mode distribution in angle. The Holdren solution to the normal mode was used.⁶ A spatial diffusion term, which was added separately, was based on the cross-field diffusion coefficient of Kaiser.⁷

The quasi-linear terms caused a major change in most parameters calculated by the RFPC. For example, radial profiles were changed significantly. Also, previous runs in which the plasma decreased in radius as thermal gas eroded away the plasma surface before collapse occurred were stabilized by diffusion that moved the excess ions trapped in the

plasma interior to the surface to compensate for the large charge-exchange losses.

Quasi-linear diffusion significantly reduced the electron temperatures, plasma potential, and particle lifetimes. These calculations assumed an $m = 1$ mode and a perturbed potential consistent with experimental measurements. Calculations based on spatially constant Fokker-Planck codes give electron temperatures of approximately one tenth the ion temperature. For 2X113 parameters, previous Fokker-Planck results would lead one to expect an electron temperature T_e of approximately 1 keV; typical runs with the RFPC give temperatures of about 150 eV.

Since a number of physical effects not previously studied were included in the new results, it was desirable to remove these effects one by one from the code and then observe the change in the calculated parameters. Figure 12 shows the effect on electron temperature at the center of the plasma when this is done. The results shown were obtained

Fig. 12. Effect on calculated electron temperature at the center of the plasma of removal of various physical effects from the radial Fokker-Planck code.

by readjusting the injected currents after each change until a new equilibrium was obtained at the same density.

We found that charge exchange with thermal gas had negligible effect on the electron temperature at the plasma center $T_e(0)$. The greatest change in electron temperature occurred when quasi-linear diffusion was removed from the code. The large change in T_e results simply from an increase in the ion lifetime, and therefore the electron lifetime τ_e , as turbulence is turned off. The electron temperature was found to be proportional to $\tau_e^{2/5}$. A normal run consisted of three beams at full energy, half energy, and one-third energy. When the half- and third-energy beams were turned off, T_e increased by another 14%. The last increase in T_e resulted when the magnetic field was increased from 0.67 to 4.0 T, thereby decreasing the gyroradius and increasing the center density. The center density increases because the ions trapped at the center contribute to the density over a smaller volume as the gyroradius decreases.

Figure 13 shows a comparison of the calculated electron temperature and density with experimental values obtained from a shot during the last quarter. The calculated electron density is in good agreement with measurements during the buildup and at equilibrium, but decays much slower than measured values after the beams are turned off. The calculated electron temperature is in reasonable agreement with the only measured point at equilibrium. The calculated electron temperature increases sharply after the beam is turned off because quasi-linear diffusion is set equal to zero to agree with the experimental observation that the instability stops immediately with beam turn-off. The faster experimental decay after beam turn-off indicates other cooling mechanisms such as cooling by the streaming plasma must be included to obtain agreement at low electron temperatures and following beam turn-off.

Preliminary Study of Cross-Field Plasma Injection in 2X11B

(C. W. Hartman and D. V. Cheng*)

Results of preliminary experiments in using cross-field plasma injection to achieve field reversal in 2X11B are encouraging enough to merit further investigation.

These experiments in cross-field plasma injection were motivated by the possibility of achieving field reversal in 2X11B by transverse injection of plasma from a coaxial plasma gun. A recent reassessment of

the requirements to obtain field reversal in 2X11B by neutral beams alone, taking into account electron effects, suggests that either the neutral-beam current or the confinement time must be increased by about a factor of 3 over present 2X11B values. Alternately, auxiliary injection of approximately 6-kJ energy such as by transverse injection from a coaxial plasma gun might substantially reduce the required neutral-beam current.

The 2X11B experiment provides a high-quality environment in which to study cross-field injection using a coaxial plasma gun. Two important environmental aspects are the minimum-B magnetic-mirror field configuration and the high-vacuum, fast-pumping technology made possible by large, gettered surfaces located near the containment region. Furthermore, 2X11B has a complement of plasma diagnostics. Accelerated plasmas having 10's of kilojoules of energy are available from coaxial plasma guns, as compared with the 1-kJ plasma energy that is present in a typical 2X11B experiment.

To assess the feasibility of cross-field injection, we began a preliminary series of experiments using a deflagration-mode, coaxial gun developed at the University of Santa Clara. These experiments were conducted for roughly 5 days during this quarter. Although the gun operated poorly, only low-beta plasmas were trapped, and field reversal was not achieved, the results encourage us to continue these investigations. Figure 14 shows the measured line densities. The plasma trapped when both guns are fired simultaneously exceeds that trapped when the guns are fired individually.

Fig. 13. Comparison between electron temperature and density values obtained experimentally and calculated with the radial Fokker-Planck code (RFPC).

*University of Santa Clara.

Fig. 14. Line density vs time for stream and coaxial guns alone as well as stream and coaxial guns together.

Low-Voltage Ion-Source Test

(J. E. Osher)

High-voltage breakdown of a prototype streaming-ion source during early tests on the 2XIIB has led to modifications and plans for additional testing.

In January, we installed and began testing the prototype streaming-ion source. This source, which has a 10 cm × 15 cm extraction area, was installed on-axis at the west end of the 2XIIB. An initial problem in which the 2XIIB fringe magnetic field interfered with the operation of the electromagnetic gas valve of the source was corrected by encasing the valve within magnetic shielding and orienting the magnetic axis of the valve so that it was perpendicular to the field of the 2XIIB end fan.

With this modification, we tested the source for operation in 2XIIB guide fields of 0.05 T to 0.3 T, with up to 25-A peak extraction supply drains. When we fired Bank 6 for the main 2XIIB field, operation did not appear to be adversely effected. However, firing the Ti washer-stack streaming-plasma guns for startup generally resulted in relatively prompt breakdown of the high-voltage extraction system. Reducing startup to the use of only a single streaming-plasma gun on the west end at best only delayed breakdown (irregularly) by 2 to 5 ms.

We had considered the possibility of such a breakdown problem, and that was a basic reason for early testing of the low-voltage source on 2XIIB; however, the problem was sufficiently severe to prevent useful operation with the 2XIIB hot plasma. We had designed the three-electrode extraction geometry for the low-voltage ion source for output currents up to 200 mA/cm²; however, because of a relatively large decel gap, we expected it to handle incident plasma at only up to ~50 mA/cm² without breakdown. Thus, in early February we removed

the source from 2XIIB for examination and modification.

Our examination of the fine, tungsten-mesh, ground-potential screen revealed that it had worked loose (because of heat cycling?) and ultimately been damaged (developed holes) from contact breakdown with the molybdenum wire grid of the decel. Also, the source face showed discoloration, presumably because the plasma from the streaming-plasma guns had been concentrated into ~2-cm-thick bands at the source location. This nonuniform concentration of plasma probably also explains part of the unexpectedly severe high-voltage breakdown problem.

The ground screen has now been rebuilt of a heavier tungsten-mesh material and tightly stretched. It has a reduced decel gap that we expected can handle plasma currents of at least 120 mA/cm² before breakdown. Further tests are planned on 2XIIB. If breakdown problems still persist, use of this type of source would probably be restricted to regions of lower plasma density (perhaps the plasma boundary).

Status of Continuing Developments

Electron Gun for the Stabilization of the Drift-Cyclotron Loss-Core Mode. (B. G. Logan, J. D. Williams, D. P. Grubb, and G. G. North)

Because of the encouraging results of the electron-beam stabilization experiments at MIT⁸ and on the basis of theoretical predictions by Baldwin and Logan, we have developed an electron gun (Fig. 15) for stabilization of the drift-cyclotron loss-core mode (DCLC) in the 2XIIB experiment.

The gun is designed to provide 30 A of electron current at 20 kV using a dispenser cathode that can be regenerated after exposure to air.⁹ The cathode (Fig. 15) is a tapered cone with a total emitting surface area of 6.6 cm². In a uniform magnetic field, the electron beam from this cathode is a 0.2-cm-thick annulus with a 2.5-cm inner diameter. It is powered by a 1-ms-long pulse-forming network that is capable of supplying 30 A at 20 kV into a matched load with a maximum default current of 60 A. The body of the gun has been made long enough that the cathode assembly can be inserted inside the mirror throat if desired.

This electron gun has been built and tested. On a test stand, the gun has exceeded its design specifications, supplying 31 A at 23 kV for 1.1 ms. It is now ready for operation in 2XIIB.

Measurements of Impurities in 2XIIB. (R. P. Drake)

Extreme ultraviolet studies during this period, performed by the Johns Hopkins University, included further observation of known impurities and

Fig. 15. The 2X11B 20-kV, 30-A electron gun.

a study of neon penetration from the end fans. To increase understanding of impurity distributions, densities, power loss, and sources, spatial and spectral scans of oxygen, carbon, and titanium were performed. The plasma was stabilized with neon gas arc guns; neon emissions were observed from the central plasma; and end losses were measured. As a result of recent work, we now believe that the neutral beams are the dominant source of oxygen in the 2X11B, and that streaming-plasma impurities penetrate in small relative quantities and high ionization states.

HCN Laser Interferometer Diagnostic. (B. W. Stallard)

A new diagnostic being developed for 2X11B is a combined Faraday rotation and interferometer diagnostic using 337- μm radiation from an HCN laser. During this quarter, we tested the interferometer arm with plasma.

The probing beam path is shown in Fig. 16. Measurements were made both with streaming-plasma gun stabilization at both ends of the hot plasma and with stabilization only at the end opposite to the laser beam input. A comparison of line density measured with the HCN laser and with neutral-beam attenuation, measured perpendicular to the plasma axis, is shown in Fig. 17. The HCN laser data have been corrected for a longer beam path length by taking into account the plasma shape. As expected, the HCN line densities are somewhat greater than for beam attenuation since

the probing beam passes through stabilizing plasma exterior to the hot plasma.

Computer System. (W. F. Cummins)

The principal addition to the 2X11B data acquisition and processing system during the last quarter was a computer system that will serve as the executive and principal data processor for the TMX computer network. It can also be linked, if desired, to the future Beta II experiment.*

The primary elements of this system are a central processing unit containing 128 thousand words of memory, 14.7 million bytes of system disc memory, and 50 million bytes of disc data storage. For archival purposes, a nine-track magnetic-tape drive is included. To improve our graphics display capability, a "smart" terminal and a TV display interface were procured. An improved operating system was part of the package.

Our problem in linking the various computers in Building 435 stems from the fact that they are of differing vintages extending back 10 years. During March we adapted and configured a distributed system software package to our network requirements. This allows us—within a few days—to

*In FY 1979, we propose to bring 2X11B back into operation after transferring some components of the present system to the TMX facility in FY 1978. Our objective is to provide an experimental facility to investigate single-cell physics questions related to MFTF, such as startup and stability. This experimental facility will be called Beta II.

Fig. 16. 337- μm beam path in 2XIIB.

reconfigure the executive and satellite computers according to the demands of the experimental effort.

During the next quarter, our efforts will be directed toward defining and constructing a better management system for the data base than presently in use; the present search and retrieval procedures can be markedly improved. Applications programming support will continue for 2XIIB experimental physics operations.

40-keV Neutral-Beam Testing. (*D. L. Correll and R. H. Munger*)

To facilitate tests of the TMX battery-arc system, we have modified the 2X test stand by the addition of a TMX-source gate valve on the side of the vacuum vessel. Late in January, the 2XIIB 10-ms power supplies were discontinued and we began operation with the prototype TMX 25-ms supplies. Most of the remainder of the quarter was spent solving many complex electronic problems associated with the 2XIIB 10-ms power supplies and also the prototype 25-ms supplies for TMX. The successful zero-offset (Z-0) flat-grid set was used much of the time rather than the prototype TMX spherical grid, both to protect the latter from harm and to separate grid and electronic problems.

Because of the difficulty of localizing the electronic problems, we began a systematic investigation of the entire system. The operation of such

Fig. 17. Line density measured by the HCN interferometer (data points) and beam attenuation. Plasma stabilization is at both ends of the hot plasma.

components as the core stack (which protects the grid against damaging high-current surges during breakdowns) was examined in detail.

Many electronic problems were corrected in the timing chassis, in the arc charge, fire, and crowbar

Fig. 18. Installation of the central vacuum chamber and solenoid magnets on the TMX support structure.

firing circuits, and in the accel fire and crowbar firing circuits. Most of these problems were cured by filtering and biasing circuits that were too sensitive to turn-on by noise.

The circuit that reduces the arc density during accel startup was found to contribute to the electronic problems. Consequently, startup without this circuit as proposed for the TMX battery-arc system was demonstrated when proper timing of the arc relative to the accel turnon was provided and the rate of rise of accel voltage was near that of the arc. This was made possible by the use of new control amplifiers.

Tandem Mirror Experiment

The Tandem Mirror Experiment (TMX)^{4,10} will test a new principle for improved plasma confinement in mirror systems. The basic idea is to reduce the plasma loss rate by electrostatically plugging the ends of a solenoidal central confinement region using the high positive ambipolar potential generated in minimum-B end plugs. Each end plug will be driven by the injection of neutral beams from 12 source modules, in a manner similar to that used in the 2XIIB experiment.

When the power supplies operated more reliably, the Z-0 grid was run up to 37.6 kV and 25-ms pulse length; then the spherical grid was installed and operated. This grid ran up to 36.3 kV, at low accel current, with some difficulty; then later to 29 kV with very good accel current. It was removed for examination because of voltage limitation, and the Z-0 grid was replaced. The Z-0 grid was then run up to 40 kV with very good accel current.

A problem with the prototype spherical grid was found to be an internal breakdown between the #2 grid lead-in wire and ground. The grid is being repaired; it will be installed and tested again next quarter.

The TMX has three fundamental objectives:

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

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

The key physics parameters projected for the TMX experiment are listed in Table 2.

Table 2. Key physics parameters for the TMX experiment.

Parameter	Value
Electron	
Temperature, T_e	0.20 keV
Confining potential, Φ_e	1.1 keV
Plug	
Density (assumed uniform over V_p), n_p	$5 \times 10^{13} \text{ cm}^{-3}$
Average energy, E_p	26 keV
Radius of plasma half-maximum, r_p	7 cm
Central magnetic field, B_p	1.0 T
Confinement product, $(nr)_p$	$3 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$
Central cell	
Density (assumed uniform over V_c), n_c	$1.2 \times 10^{13} \text{ cm}^{-3}$
Ion temperature, T_e	0.080 keV
Confining ion potential, Φ_c	0.29 keV
Length, L_c	5.5 m
Radius, r_c	31 cm
Magnetic field, B_c	0.05 T
Confinement product, $(nr)_c$	$3.1 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$

Magnet Alignment Requirements

(J. H. Foote)

The accuracy necessary when installing the TMX magnet coils has been determined from magnetic-field and particle-trajectory calculations.

We have completed a series of drift-surface and magnetic-field calculations in which we estimated the accuracy with which the elements of the TMX magnet set must be magnetically aligned,¹¹ for a 0.05-T field at the center of the solenoid.¹

One might think that misalignment of the magnet elements could distort the curvature of the magnetic-field lines in the solenoidal section enough so that radial drifts of the trapped ions, and even

radial losses, could occur. Radial shifts indeed take place; however, our calculations show that the drift surfaces of ions magnetically trapped in the solenoidal section provide an insensitive indicator of misalignment problems. The intersections of these drift surfaces with the solenoidal midplane tend to remain closed and to shift with respect to the solenoidal axis by an amount comparable to or less than the misalignment shifts of the plugs and transition C-coils.

The more sensitive measure of the required alignment accuracy is either the position of a drift surface at a plug midplane calculated for ions that pass through the solenoid and reflect at the outer mirror

regions of the plugs or, similarly, the mapping along magnetic-field lines of the plasma cross section at the solenoidal midplane to a plug midplane. The solenoidal plasma should map to the region of the plug plasma so that ions escaping from the solenoid can be reflected by the plasma potential of the plug. If we use as the criterion that a 31-cm-radius circle at the solenoidal midplane (representing the plasma there) should map into an approximate circle (with about a 7-cm radius) at the plug midplane with the center shifted by not more than 1.0 cm from the magnetic axis of the plug, then a plug set (baseball plus nested C-coils) and the corresponding pair of transition C-coils must be aligned with respect to one another to within about 0.5 cm. The combination of the plug set and transition C-coils, when well aligned with respect to one another, can be misaligned with respect to the solenoidal axis by a considerably larger amount and still satisfy our criterion.

An additional observation made during the series of drift-surface calculations summarized here is that we must guard against slight dips in $|B|$ in the nearly uniform solenoidal magnetic-field region. Such magnetic-field fluctuations can temporarily trap ions with pitch angles near 90° , which in turn can cause the particles to drift radially and be lost. A smoothing of the solenoidal magnetic field eliminates this problem.

Construction

(C. C. Damm, A. K. Chargin, M. O. Calderon, L. J. Mooney, A. L. Hunt, R. S. Hornady, and R. K. Goodman)

At the end of this quarter, the TMX construction project was about 65% complete, with debug operation of the system scheduled for October 1, 1978.

An engineering description of TMX by subsystem has been given in Ref. 10; the status of each subsystem is summarized here.

Magnet System. All coils for the magnet system are either wound or in the process of being wound; the status of the coil fabrication is shown in Table 3.

A finite-element stress analysis of the restraining structure of the plug magnet assembly verifies that the design is conservative. The structure is now being fabricated.

The solenoid magnets have been installed, Fig. 18; installation of the other coils, which is keyed to the assembly sequence of the vacuum tanks, will start in May.

Vacuum System. The central-cell tank has been installed on the support structure, Fig. 18. The fabrication of the plug tanks is underway; we expect delivery of the first sections in mid-May. The liquid-nitrogen-cooled (LN-cooled) panels are being fabricated, and delivery should meet the assembly schedule to begin in May. Fabrication of the

Table 3. Status of TMX magnet construction.

Magnet	Winding fixtures	Potting case	Winding	Potting	Vacuum case	Cap and leak check
C-coil No. 1	done	done	done	done	done	done
C-coil No. 2	done	done	done	done	done	done
C-coil No. 3	done	done	done	done	done	done
C-coil No. 4	done	done	done	done	in progress	in progress
86° trans. No. 1	done	done	done	done	parts due March 31	
86° trans. No. 2	NA	done	done	done	parts due March 31	
180° trans. No. 1	available	done	done		parts due April 1	
180° trans. No. 2	NA	done	in progress		parts due April 8	
Baseball No. 1	done	done	done	done	done	
Baseball No. 2	done	done	in progress		available	
Octupole No. 1	done	done	done		parts due April 21	
Octupole No. 2	NA	done	in progress		parts due April 21	

vacuum feedthroughs for these panels is also in process.

The titanium getters have been designed and are being procured.

Injector System. The 40-keV source modules consist of an arc chamber and an extractor assembly. Components for the arc chamber are in hand and assembly has started. Parts for the extractors are due from the vendor early in May. The fixtures for assembling and servicing the injector magnetic shield and neutralizer assembly have been completed and are in use.

Mounting fixtures for the streaming-plasma guns are being fabricated and a gas-box design is complete. The prototype piezoelectric valve for the gas box has been successfully tested; the valve opens in < 1 ms. with a gas flow rate of ~ 47 Torr-litre s^{-1} .

We have received for testing two more accelerator-modulator power supply units. The design of the battery power supply for the filaments and prototype testing is complete and production is proceeding. The battery power supply for the arc is in a final testing stage, with minor rework of the controls underway.

Facilities. The support structure for the vacuum tanks has been installed in the TMX pit, Fig. 18. All power-supply tiers have been completed, as has a complete grounding-plane system.

The installation of the control racks and the raised floor is complete and the racks are being wired. The electrical installation contract for high-voltage power and other general utilities is in the procurement cycle, with work expected to begin in May. Power for general assembly requirements in the TMX pit has been installed.

Design work is proceeding with the LLL LN supplier for the installation of two 11,000-gal tanks to replace an existing 7,500-gal tank that has insufficient capacity for the TMX requirements.

Controls. Design of the magnet control system is complete, fabrication of components has begun, and software is being developed. The design and fabrication of the safety monitor chassis and master timing distribution amplifier have been contracted and are underway.

The neutral-beam control chassis, including controls for battery filament, battery arc, and accel/decel power, is being designed. The telemetry unit design is complete, with prototype testing dependent on delivery of parts.

Diagnostics.

Thomson Scattering System. The four-pulse ruby laser is on hand; only one electronic problem remains to be corrected before the laser is accepted from the vendor. We have decided to locate the laser power supplies on the shelf at the east end of

the pit. The basic optical design of the Thomson scattering system is well along, and the 66 individual components are now being specified and ordered. Mechanical designs of the subsystems that hold and enclose these optics are progressing close to schedule. The design and specification of associated electronic components and interfacing has begun. A suitable photomultiplier tube has also been selected, and a set of these tubes will be ordered soon.

Heavy-ion Probe. During this period, a contract was signed with Rensselaer Polytechnic Institute (RPI) to assume technical responsibility for the implementation of a heavy-ion beam-probe system to measure the radial potential profile in the TMX midplane. Under this contract, RPI will provide information and design to LLL for the construction of the necessary components and supply personnel at LLL to activate and operate the system when TMX begins operation.

An ion source based upon RPI designs and approved by LLL was constructed and is being tested on RPI's test stand. Calculations by LLL and RPI have identified suitable locations for the effective source point and the secondary-ion detector. Detection grids using these locations have been calculated by both groups for the vacuum field so as to establish a base line against which system operation may be compared.

Once we knew the source and detector location, we began designing the necessary vacuum chambers that will contain various beam apparatus and be mounted on the TMX center-cell tank.

Also, a control system was conceptually designed in sufficient detail to allow purchase of the majority of the necessary commercial components. A processor and some supporting modules have been sent to RPI for systems development. The design of special necessary interface boards has also begun.

For the axial beam system, we acquired an ion source and recovered suitable vacuum tanks and pumps from surplus equipment. Because the control system will be identical to that for the transverse system, its design is progressing. Most of the necessary power supplies are also available from LLL surplus. We expect to test the axial beam source during the next reporting period.

Low-energy Ion Analyzer. This diagnostic provides the energy spectrum of the electrostatically confined ion distribution in the central region between the plugs.

We reviewed the originally proposed experimental method¹⁰ (the time-of-flight method) and retained it with some modifications dictated by calibration of the low-energy neutral-deuterium atom detector. The neutral beam incident on the plasma has been increased from 1-keV to 20-keV to

take advantage of the previous development and current availability of the LBL 50-A source. The resulting charge-exchanged neutral flux from the plasma will be interrupted by a chopper wheel rotating at 24,000 rpm, with a slit width corresponding to a 1- μ s transmission time, and a 2-m flight path, as described in Ref. 10. The neutral-deuterium atom detector at the end of the flight path has been changed to a microchannel plate with an electrically grounded front face. This unit is commercially available as a component of an imaging electron multiplier. The potential advantage of this detector is a significant reduction in noise, an important attribute at the anticipated counting rates. All detectors must be calibrated over the energy range of the incident deuterium neutrals because of the variation of the electron emission coefficient of the detector surface with incident atom energy. Assignment of a kinetic temperature to the ion energy distribution is based upon the measured detector response as illustrated in Fig. A-5, Ref. 10. The selected calibration method requires a direct measurement of the microchannel plate response to a deuterium ion beam of known energy over the

energy range from 50 eV to 500 eV. We then assume, with some justification from the literature, that the neutral-deuterium atoms will produce an identical detector response as a function of energy over the same energy interval. A constant difference in detector response between the ion and neutral atom will not affect the calibration.

As much as possible of the time-of-flight neutral analyzer will be preassembled and tested. It will then be attached as a unit to the central vacuum chamber of TMX late in the assembly schedule. This will reduce the time interval between the end of the construction phase and the acquisition of plasma data as well as ensure prompt assembly on TMX. We have acquired major portions of the vacuum system for the 2-m flight path. The chopper motor is being vacuum tested and a small ion source is being assembled for early tests of the microchannel plate detector. In addition to reviewing the physical principles of the diagnostic, we have completed the necessary engineering functions of cost estimation and scheduling. We have ordered long lead-time items necessary to the primary TMX assembly.

Mirror Fusion Test Facility (MFTF)

As a result of major experimental successes in the LLL mirror program on startup and stabilization of plasmas in minimum-B magnetic geometry, a Mirror Fusion Test Facility (MFTF) was proposed.¹² The MFTF will be used to bridge the gap between present-day small mirror experiments and future fusion reactor activity based on magnetic mirrors. The MFTF will investigate advanced engineering problems such as those associated with superconducting magnets, neutral-beam injectors, plasma-wall interactions, disposal of neutral particles and ions escaping from the plasma chamber, and high-speed vacuum pumping techniques.

Approval for the project has been given, and both operating and line item funding have been authorized for the MFTF. Construction of the facility began on October 1, 1977, with completion scheduled for July 1981. The operating budget activities include R & D and fabrication and installation of apparatus for the first experiment in MFTF. The project is proceeding on schedule.

Technical Support

The objectives of the MFTF Technical Support Group are

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

Neutral-Beam Requirements. (*G. D. Porter, F. H. Coensgen, R. S. Devoto, G. Leppelmeier, A. W. Molvik, J. E. Osher, J. W. Shearer, and K. I. Thomassen*)

An assessment of the neutral beam requirements indicates that 24 source modules will sustain the plasma as required.

Our reassessment of the neutral-beam current requirements for the MFTF included an examination of the expected performance of the 80-keV source operation based on the most recent results of development work at LBL. Because the molecular mix of these sources is somewhat poorer than in the 20-keV 2XIIB sources, the LBL source modules will produce more neutral current than previously anticipated, but the average beam energy will be 50 keV rather than 60 keV. We evaluated the current requirements for two plasma radial profiles and found that a diffuse (Gaussian) profile required more than 50 source modules to sustain a plasma with $\langle\beta\rangle = 0.5$ and $[(a_i/n)(\partial n/\partial r)]^{-1} \geq 13$ over a volume that contains one-half of the plasma. The current requirements are somewhat more modest for a flat-topped profile. Then, a plasma with $\langle\beta\rangle = 0.5$ and $R_p/a_i = 13$ can be sustained with 28 source modules. The 24 modules we expect to use will sustain a plasma with $\langle\beta\rangle = 0.45$. This corresponds to a peak beta of $\beta_0 = 0.65$ and is considered adequate for the MFTF goals.

Status of Continuing Developments

Target-Plasma Production. (*G. D. Porter*)

We have continued the design of the field-enhanced streaming-plasma gun that was discussed in the previous quarterly report.¹ We found that the magnet described there was too large and hence too expensive to fabricate for the MFTF. A smaller magnet designed during the past quarter fits around the standard 2XIIB streaming-plasma gun, and the entire assembly can be inserted through a 6-in.-diam valve into the vacuum chamber. Detailed design of this assembly was completed and fabrication has begun. This field-enhanced streaming-plasma gun will be tested in the 2XIIB.

Ion Beam-Dump Development. (*R. C. Ling and A. W. Molvik*)

We continued the study of beam dumps for the unneutralized ion beams. We have completed the development of a code that enables us to visualize the particle orbits in the fringing field of the MFTF magnet. We believe that the most probable beam-dump configuration is a set of louvers that surrounds the neutral-beam channel. The dump must be made of louvers to permit pumping the gas that will evolve from the surface. A code (GFUN) is being developed that will enable us to evaluate the ef-

fect of the magnetic shielding on the ion trajectories.

Neutral-Beam Development. (*A. W. Molvik*)

The detailed design of the 80-keV arc chamber and accelerator was completed. We are continuing a lower level design effort to correct problems found during the assembly and testing.

The arc chamber has been partially assembled to check that parts fit. Minor problems were found. These will be corrected and the arc chamber parts will be cleaned and reassembled.

The accelerator parts were manufactured. The insulator-electrode stack was bonded together and finish-machined. Then, the gradient grid was assembled in the stack. The entrance grid was assembled, and the exit grid is ready to be assembled. The major delay in the accelerator is in obtaining the suppressor grid wire. LLL and Thermal Electron Corporation are working on wires in parallel. Both are close to the desired cross section, and the wires appear to be adequately straight. However, LLL found, after forming the wire, that the initial molybdenum stock had cracks. Therefore, the wire must be reformed using other wire stock. Thermal Electron must procure the wire to a 7-m radius, then produce enough wire for one source.

Vacuum Accessories. (*F. Dixon*)

Design was completed for the isolation valves, gimbals, bellows, support structure, neutralizer duct, and high-voltage test stand (HVTS) adapters. Hardware delivery will start in April to provide the test equipment needed to interface the MFTF neutral-beam source with the HVTS. Investigation of magnetic shielding requirements led to a reduction in estimated shield weight. Optimization of the shield requirements was initiated with computer analysis for the MFTF neutral-beam injector arrays.

80-kV Model. The development model of the MFTF 80-kV power supply was integrated and debugged. The accel dc power supply was assembled and malfunction of the variable-voltage transformer was corrected. The unit is ready for 480-V ac low-voltage switching transient tests. Modulator tests were performed in March, with preliminary high-voltage testing on major subsystems of the accel switching modulator.

The gradient grid and dummy load were assembled. A seismic hazard analysis required design upgrade of the dummy load stand with work scheduled for early April. With the accel dc, modulator, gradient-grid, and dummy-load nearly complete, we plan development tests and integration with the sustaining neutral-beam source module for the next quarter.

Controls. Work in this area was mainly centered on research concerning an effective man-machine

interface and on the development of software for automatic conditioning of the 80-kV neutral-beam sources.

Research on the man-machine interface focused on two areas: touch panel graphics and console hardware layout. A microcomputer has been coupled to a color TV monitor and programmed to enable a user to generate and vary displays at will. It is being used to study various schemes for information display and touch-panel control. To maximize operator ease and effectiveness, we have ordered a console cabinet in which display and control equipment will be configured in a variety of ways. These studies are leading to a control system philosophy based on human interaction with the proposed color touch-panel displays.

The software organization for controlling the 80-kV model is complete. Software development is continuing. The necessary computer equipment began arriving in March; system debugging will begin in May when the last components are delivered.

Construction

(V. N. Karpenko)

During the second quarter of the MFTF project, six of the scheduled key project milestones were completed to give a total of eight accomplished. A project review was held in January followed by detailed examination of the reestimated system and facility costs in February. Two major system procurements were initiated and design work started by two architect-engineer firms, in addition to many smaller procurements. Removal and demolition progressed in Building 431. Some delays were experienced, but rescheduling of tasks covered most of the critical activities. Deferral of some noncritical efforts resulted in the rescheduling of the third milestone for award of a contract to Pacific Gas & Electric Co. for the 230-kV, 250-MW power line with no major impact foreseen for the MFTF construction project.

Preliminary design efforts by LLL resulted in an increase in vessel size to provide more volume for cryopanel in order to increase vacuum pumping required for plasma stabilization with a gas box scaled up from the successful 2XIIB experiments. Also, the increased distance to the ends of the vessel significantly reduced the end-loss energy flux. The distance was extended from 6 m to 9 m from the center of the magnet to the inside of the vessel dome, a 50% increase.

The cryogenic system capacity was increased to provide the needed pumping speed with a revised arrangement of the cryopanel and an increase in surface area. The redesign provided 500 m² of panel array vs the earlier one-sided array of 340 m². The

helium liquifier capacity to support this subsystem was revised to 3000 W. The liquid-nitrogen system usage rate was adjusted from 4700 to 5800 litre/h during MFTF operation. More specific project activities are identified below.

Magnet System. In February, we obtained results from the weld-sample tests of type 21-6-9 stainless steel that we plan to use in the magnet case. The filler metal was inconel 625 produced using the shielded metal-arc process. Two-inch plates were welded, and samples were sectioned for strength and toughness tests at liquid-helium temperature of 4 K. We find that the weld metal has good strength, ductility and toughness at 4 K. The heat-affected zone has higher strength and lower but adequate toughness; the 21-6-9 base metal has higher strength and toughness. The test results provide positive support for the base material and filler metal for the magnet case. We are continuing to work on weld development to enable selection of the best assembly techniques.

A rectangular cross section has been selected for the MFTF coil and we have chosen a support-system design.

A coil form for practice winding has been ordered. Fabrication of the superconductor core has begun, and we have selected a tension-control system for the coil winder. The superconducting test-coil winding was completed.

Design and procurement were completed for construction of the superconductor wraparound assembly line. The procurement package was forwarded to DOE/SAN for approval.

Our engineering studies on the magnet included seismic analysis and analyses of support structure, of case structure, and of the temperature gradients and stress resulting from cooldown. We also examined the possibility of reducing the thickness of the stainless-steel case from 3 to 2 in. in some areas; very favorable results include the promise of significant reduction in the weight of the magnet case.

Fusion Chamber System. In January, we sent a request for proposal (RFP) for the fusion chamber system to eight interested companies. A pre-proposal conference and site visit by interested companies resulted in clarifications and changes that were transmitted in Amendment No. 1 to the RFP, dated March 13, 1978. Five more amendments resulting from additional questions were also issued in March.

We have begun to adapt a Monte Carlo code for calculating the effective pumping speed of the cryopanel subsystem for the fusion chamber system. Initial results, expected by mid-April, will provide analytical inputs to the technical evaluation of the

proposals. One result will be an improved estimation of chamber pressures during gas injection.

The helium recovery compressors and helium storage bottles now being removed from the Nevada Test Site will all be delivered by the end of April.

The site of the cryogenic system has been shifted from the southwest side of Bldg. 431 to the northeast corner to allow access of fire-fighting equipment to another experiment area in Bldg. 431. This relocation greatly improved both component accessibility and flexibility of use.

Sustaining Neutral-Beam Power Supply System.

The specification was developed for the MFTF sustaining neutral-beam power supply and reviewed by the LLL Electrical Engineering Department. The 80-kV system incorporated the design and development efforts mentioned above for the 80-kV model. We have identified three different ways to meet the modulator-switch requirements for this system. These alternatives help reduce the implied risks to potential subcontractors. Further definition and test activities have increased our confidence in system designs with some cost reductions.

In April, personnel at Rome Air Force Base will perform tests on the preferred tube for the switching modulator based on our established plans. The results are expected to provide design data for response to our RFP issued in March to industry; proposals are expected in June.

Control and Diagnostics System. Bids were opened in March for the MFTF computer system procurement. Seven proposals were received for the supervisory control and diagnostic system computers; five were received for the local control computers. We expect to complete our evaluation of these proposals by May 1978.

A rough draft of the preliminary operator's manual for the supervisory control and diagnostics system is 50% complete.

Starting with the control and diagnostics system, we are using a wide acceptance band, no-protocol interface. This interface choice reduces vendors' risk and provides for maximum standardization.

Software development work continued to support the line-item design efforts.

Bldg. 431 Modifications. A new detailed cost estimate was completed for Bldg. 431. Demolition work continued and is progressing according to plan. A project schedule has been received from the architect/engineer (A/E) for the Bldg. 431 modifications. The following relocations have been made:

- The control room and diagnostic area are being relocated at the northwest corner of Bldg. 431 to

avoid the high magnetic field environment in the middle of the second floor area. We are studying the effect of this change on computer, peripheral equipment, experimental diagnostics, and central control arrangements.

- Exterior cryogenic systems equipment will be located in Room 1060 of Bldg. 431.

- The pulse power substation providing 480 V from the 230/13.8-kV source will be located at the southeast corner of Bldg. 431.

Pulse Power. The final environmental impact statement for the 230-kV power line was received from PG&E and reviewed at LLL.

Design work continued on the temporary power line. Interface definition with the power supplies was established. Work continued on design and planning of feeder transfers for power modifications to Bldg. 431.

The power-factor correction requirements were negotiated with PG&E for the 230-kV power contract. The factor range of 0.975 lagging to 0.85 leading for full load and 0.95 lagging to 0.80 leading for half load is considerably less stringent than the previous 0.99 for leading or lagging.

A requisition for additional engineering prepared by PG&E is being reviewed by LLL.

Building 441. A/E negotiations were completed, and an orientation meeting was held. Meetings are now being held with the LLL program staff. A required audit of the mechanical subcontractor has delayed the awarding of the A/E contract award to April.

Project Management. The MFTF Configuration Management Plan was prepared by LLL and approved by the Project Manager on February 24th. Following review by the DOE San Francisco Projects office, the document was revised to provide additional detail on configuration approval and change control within the LLL project and contractor efforts. Project level reviews of the specifications, work statements, terms/conditions and RFP instructions were conducted prior to release of invitations for the fusion chamber system and for the magnet analyses and design proposals. Following a review of the procurement package for the sustaining neutral-beam power-supply package by the Livermore Project Office (LPO) Standing Review Committee and the LPO staff, the purchase requisition was signed and the RFP was issued. With issuance of the RFP, key milestone #9 was completed on schedule.

The MFTF Performance Measurement System was implemented on MISTER, thereby providing a subsystem schedule network for the magnet system.

Revised inputs were made to correct computer output and activity updates for the various systems. The magnet network was rerun with updated and corrected inputs. The other task inputs are now being updated.

In the first *Quarterly Cost/Schedule Status Report*, a management condition indicator was employed to show the green, yellow, or red status condition of each level 3 of the work breakdown structure element. These status conditions were defined in the *MFTF Monthly Cost and Schedule Report* for December 1977.

Activity during the quarter also included the following:

- The *MFTF Contingency Plan* was approved by the FLL Project Manager and submitted to DOE.

- The preliminary *Safety Plan* issued in February was updated in March to include comments received from SAN. The improved *Safety Plan* will be issued as an MFTF document in April.

- The *MFTF Quality Assurance Plan* was issued in March, meeting the planned milestone.

The construction activities are progressing with minimum variances in the key milestone schedules. Preliminary design activities have provided a sound basis for procurement planning. Detailed technical requirements evolved, with some changes in systems designs providing improved confidence in meeting the overall experimental requirements. Design integration and interface definition activities increased. Inputs from the superconducting test coil program and progress on the 80-kV power supply development model further enhanced the overall MFTF design base.

2. DEVELOPMENT AND TECHNOLOGY

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

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

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

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

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

Several key problems on tritium control and handling that must be solved for any large D-T fusion device are being investigated in the LL tritium laboratory; emphasis is on cleanup of low tritium concentrations in reactor containment buildings and on the containment of tritium by using various low-permeability barriers and coatings to be applied to metal walls.

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

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

Magnet Systems

Superconducting Magnet Development
(D. N. Cornish)

The technology of superconductors and superconducting magnets is of vital importance to the building of present-day plasma physics facilities and to the planning and study of future experimental mirror

machines and reactors. We are developing a Nb-Ti conductor for the Mirror Fusion Test Facility (MFTF) winding and Nb_3Sn conductors for future mirror devices.

MFTF Development. We have completed the winding of the test coil for the Mirror Fusion Test Facility (MFTF) using 6,500 ft of prototype conductor. Valuable experience was gained in learning

how to wind and join this conductor. The cold-welding of the core presented no problems, and all the joints appear to be sound. However, we encountered problems in soldering the stabilizing jacket over the joined core, principally because the latter had a strong tendency to curve as soon as the jacket was removed. The problems were overcome by modifying the splicing arrangements of the jacket and by twisting the conductor so that its natural direction of curvature matched that of the winding.

Strip heaters of lengths varying from a few centimetres upwards were attached to three adjacent layers so that the equivalent of about 1-1/6 turns of the magnet winding carried a heater. These heaters are designed to enable us to investigate the propagation and recovery characteristics of initial normal zones, which vary in size from a few centimetres of a single turn to several full turns. Several joints were also fitted with heaters so that their performance could be studied and related to that of the main body of the windings. Strain gages were also incorporated, largely to check their performance under these operating conditions.

The completed coil was then assembled between two similarly sized coils that had been wound previously for the high-field test facility (HFTF). Fig. 19 shows the coil assembly, with its array of diagnostic leads, about to be coupled to the top-plate assembly of the cryostat. The main and diagnostic wiring has been completed, and the whole assembly is ready for lowering into the 2-m-diam cryostat for its first cool-down.

We have completed the fabrication and installation of associated equipment, including lifting facilities for 10 tons, power supplies, control and protective systems, and an extension to the helium-recovery system; cool-down is scheduled to commence at the beginning of April.

High-Field Test Facility. The power supply, protective systems, and controls required to operate the first two sections of Nb-Ti backing coils together with the MFTF test coil have now been fabricated and installed and are ready for commissioning.

The superconductor ordered from Supercon for the remaining two backing coils is late; we now expect the first consignments to arrive in early April.

Nb₃Sn Conductor Development. Airco is proceeding with the development and fabrication of a prototype length of stabilized conductor as outlined in Ref. 13. The first-stage billet consists of a 188-mm finished diameter, 13 wt% Sn bronze casting, drilled with 187 7.04-mm-diam holes into which the Nb rods will be inserted. This bronze billet was vacuum-induction melted and cast on a previous development contract; when machined and

drilled, it was found that internal porosities connected the internal seven or eight holes in the central region of the upper half of the billet. The billet was therefore given two hot-vacuum bakes to remove any residues from the machining and drilling operations before the Nb rods were loaded into it. This billet is scheduled for extrusion during the first week in April.

The second-stage billet will consist of a 250.2-mm o.d., 142.6-mm i.d. copper billet loaded with 1777 hexagonal rods drawn from the first-stage billet. A two-piece sheet-Ta liner with overlapped edges will separate the "hex-pack" from the copper can.

Because the hex-pack is surrounded by a thick, relatively soft Cu layer, there is a danger that "center-bursting" might occur during the extrusion process unless parameters such as die angle are exactly correct. There could also be problems associated with the wrapped Ta barrier, and there is some doubt about whether annealing is required after each or after every two passes through the drawing dies. To check these uncertainties and to make any necessary modifications before the expensive billet is processed, a dummy billet has been processed ahead of it. This billet consists of a central 13 wt% Sn, 138.2-mm-diam, 552-mm-long bronze rod that is wrapped with Ta sheet and loaded into a 250.2-mm o.d., 142.6-mm i.d. Cu can. The billet has been extruded and to date has been drawn down to a 32.5-mm diameter. Although detailed examinations have not yet been carried out, it appears to be satisfactory. Processing will continue to the finished size of 5.4 × 11.0 mm, and detailed evaluation will be made. It will then be used for trial runs to check the proposed method of adding the stabilizer.

During 1977, Supercon attempted to scale up their Nb tube/bronze process from 2-in.- to 8-in.-diam billets. The first-stage billet was successfully extruded, and samples were drawn down to produce satisfactory 0.027-in.-diam wire. However, many irregularities and broken filaments were found in the extruded rod from the second-stage billet. There is some doubt as to the reason for this failure. Possible causes include faulty control resulting in too low an extrusion temperature, possible loss of vacuum in the billet due to a fall during shipment, or too great an extrusion reduction ratio.

The total cost of developing any process to the final goal—the economical fabrication of filamentary Nb₃Sn conductor on a large-scale production basis—is very substantial. Furthermore, the spending rate accelerates as the billets increase in size and cost. Since the overall funding for this development activity is strictly limited, its allocation is continually under review. During FY 1977, we

Fig. 19. MFTF test coil assembled between coils for the High-Field Test Facility.

had shown that the strain characteristics of the bronze-matrix Nb₃Sn conductor were acceptable for the large fusion magnets. It was at that time, therefore, considered to be in our best interest to concentrate on the further development of that conductor. However, although we plan to carry out strain measurements on samples previously supplied by Supercon during the next quarter, we do not propose to continue to fund the development of this Supercon type of conductor.

The preliminary study at M.C.A. to assess the feasibility of scaling up the powder metallurgy approach to the fabrication of commercial Nb₃Sn filamentary conductors has continued. A 25-mm-diam 165-mm-long billet containing six Ta-clad, Sn-infiltrated, 11.7-mm-diam sintered-Nb rods was extruded to a 6.2-mm diameter. This rod was severely fractured both internally and externally. We believe that this poor ductility resulted from the relatively poor vacuum ($\sim 5 \times 10^{-5}$ Torr), which was the best that could be achieved during the sintering; a value of 10^{-6} Torr or lower was used during the preliminary work at LBL.

Plasma Engineering

LLI/LBL Neutral-Beam Development

(E. B. Hooper and R. V. Pyle)

The LLL/LBL Neutral-Beam Development Group has the responsibility for developing neutral-beam injection systems for mirror and tokamak experiments. Modules with beam energies of 20 to 40 keV have been used on the 2XIIIB and Adiabatic Toroidal Compression (ATC) devices. Current near-term development efforts are directed toward 80- to 120-kV injectors for the MFTF (80-kV), Doublet III (D-III) (80-kV), and Tokamak Fusion Test Reactor (TFTR) (120-kV) experiments. The total beam power from each accelerator module will be 6 to 7 MW, in 0.5-s pulses. The users want to place orders for production models in about 1 year. Development goals for the longer term are near steady-state operation, higher energy, and better efficiency; this part of the program is centered on negative-ion production, acceleration, and neutralization. We hope to have 200- to 400-kV injectors based on negative ions developed in time for application in the mid- to late-1980's.

Development for near-term and mid-term applications (based on positive-ion technology) continues to dominate our efforts. Although there is still much quantitative work to do on the TFTR, MFTF, and D-III injectors, we have made sufficient progress in the past quarter to give us considerable confidence that it is technically possible to meet the development goals for these experiments.

Positive-Ion Program. Our positive-ion-based work had the following highlights:

The full-scale TFTR prototype ion source (basically similar to MFTF and D-III sources) operated on test stand IIIB (TS IIIB) at 100 kV, 70 A in a short-pulse (15-ms) mode with hydrogen. The goal is 120 kV, 65 A, 0.5 s with deuterium. (Most of our testing is with hydrogen because of neutron problems associated with deuterium use.)

Testing for the full pulse length will be done on the HVTS facility later in the year, after we have demonstrated 120-kV, 63-A, 23-ms operation with deuterium on TS IIIB.

We have built a "magnetic bucket" plasma source having a square cross section suitable for fractional-area (~ 15 A) 80- to 120-kV source operation and have measured its plasma properties. The external surface of the arc chamber is covered with suitably positioned permanent magnets that produce a multipole field within the arc chamber. The magnetic field slows the loss of charged particles from the plasma to the chamber walls. On the basis of our previous measurements with a cylindrical magnetic bucket and on experience at Oak Ridge National Laboratory (ORNL) with cylindrical buckets, we expect that this new plasma source should have a higher fraction of atomic ions than our present sources have. Preliminary operation the last day of the quarter (with hydrogen) on a fractional-area TFTR source confirmed that the atomic fraction is indeed higher, but we have so far obtained little quantitative data.

Draper Lab personnel successfully demonstrated fully-automated runup of a newly assembled 80-kV source.

Beam-plasma interactions can occur in the neutralizer of a neutral-beam system, possibly affecting the optical properties of the beam in an adverse way. Optical and Langmuir-probe measurements in the neutralizer of our 120-kV TS III system indicate that some such interaction may be taking place, and that the beam divergence may be approximately doubled as a result. Because the final neutral beam still meets the specifications of present users, this potential problem will be investigated with low priority.

An energy-recovery try by the direct-recovery group was attempted with a 120-kV injector on TS IIIA. Poor vacuum caused by beam-surface gas evolution prevented a successful demonstration; they will try again during the next quarter.

Studies of possible radiation effects on cryocondensation pumping systems were started at the U.C. Berkeley Triga fission reactor.

Negative-Ion Program. Negative-ion workers pursued two paths:

- Continuation of the work to produce a negative-ion beam by accelerating positive ions to low energies, passing them through cesium vapor to convert a fraction to negative ions, and then accelerating the negative ions to high energies. Most of the effort was devoted to developing better low-energy positive-ion sources, both conventional accelerators and energetic arcs. Construction began on the cesium cell to house the new cesium jet.

- Development of alternate techniques for producing negative ions, e.g., production on surfaces. Most of our studies during this quarter were concerned with surface production.

Facilities. The high-voltage power supply for the HVTS was operated at 60 kV. Also, we completed plans for modifying TS IIIA for 2-s operation.

Direct Conversion

Beam Direct Energy Conversion. (*W. L. Barr, G. W. Hamilton, and R. W. Moir*)

Apparent discrepancies between results from two tests of the beam direct converter are tentatively ascribed to desorption of gas from the electrodes and beam dump.

The most recent test (February 1978) of the beam direct converter on the 120-keV beam line at LBL was done with He^+ ions to avoid molecular (and hence fractional-energy) ions. The results with either magnetic or electrostatic electron suppression differed only slightly from earlier (October 1977) results. The main difference was that the initial self-bias on the collector did not stop at 40 kV (1/3 energy) as before, but got as high as 75 kV under some conditions (e.g., when the collector was floating). The collector current and voltage decreased to zero within 300 ms after the initial fast rise. The maximum average collector current was 0.37 A, while the net electrical current decayed from a maximum initial value of 0.3 A. These results indicate that the cancelling electron current increased during the pulse as the gas density increased. The maximum collection efficiency is about 10% at the beginning of a pulse.

We believe we have now identified the cause of the discrepancy as being the desorption of gas from the electrodes and possibly also from the LBL beam dump. A Langmuir probe located near the first aperture indicated a cold plasma with $T_e \approx 4$ eV and a density that increased to $2 \times 10^9 \text{ cm}^{-3}$ by the end of a pulse. A gas analyzer showed that H_2 is produced in the direct converter at a rate comparable to that of He from the beam. The beam is pure He, but H_2 might be selectively reabsorbed between shots from the gas mixture that exists in the LBL vacuum system. The vacuum system is shared with beam line IIIB, which operates on hydrogen.

We are working on solutions to the outgassing problem that appears to be common to both electrostatic and magnetic electron suppression.

Reactor Materials

RTNS-II

(*J. E. Osher, C. Hanson, and J. C. Davis*)

The RTNS-II facility will provide the neutrons required to determine the response of potential fusion reactor materials to 14-MeV neutron irradiation. Areas of research to be explored with this machine include radiation effects on superconductors, damage-rate studies, changes in observable microstructure, and changes in physical properties. A major emphasis of this work will be to develop the knowledge and methods required to relate data from other radiation sources to the fusion-neutron environment. We anticipate some effort in measuring neutron and gas production cross sections.

During the second quarter of FY 1978, we met two major goals of the RTNS-II project:

- The prototype accelerator became fully operational for tests with ion beams, and
- The project staff moved into the newly completed Building 292 to begin installation and assembly of the neutron source components.

The acceleration column is shown in a close-up view in Fig. 20 and installed on the prototype accelerator in its test enclosure in Building 212 in Fig. 21. Without beam, the acceleration column has been tested to its full operating voltage of 380 keV; with H^+ beam, operation has been limited to ~30 to 40 mA at energies up to 250 keV by the lack of radiation shielding around the accelerator. A rotating target is now being installed on the prototype for target tests. All accelerator diagnostic and control systems have been tested successfully.

With the start of installation activities in Building 292 in March, initial operation of the first source in Building 292 is expected in July 1978. Experimenters will have access to the RTNS-II Facility at that time to develop irradiation experiments.

14-MeV Neutron Irradiation Studies

Radiation Damage In Superconductors. (*R. M. Scanlan*)

In designing the magnet shielding for magnetic fusion reactors now in the planning stages, we must know the effects of radiation on candidate superconducting materials as a function of fluence. Calculations for a tokamak reactor predict a total neutron flux of between 4×10^{12} and $4 \times 10^{13} \text{ n/m}^2 \cdot \text{s}$ at the superconductor. These flux calculations are based on perfect shielding; as more refined calculations are

Fig. 20. RTNS-II acceleration column.

made that incorporate neutral-beam injection ports, etc., the flux values at localized areas of the magnet will increase. Because the magnets must be used for many years, the radiation tolerance of the magnets may become the controlling factor.

The work in progress has the following three objectives:

- Determination of the effects of neutron irradiation (from about 4 MeV to 14 MeV) on the critical current of Nb_3Sn , Nb-Ti, and other superconductors at liquid-He temperatures and in the presence of magnetic fields up to 12 T,
- Correlation of the electrical properties of these materials with both initial microstructure and radiation-induced changes in microstructure, and
- Measurement of the recovery of the changes in the critical current during annealing at temperatures up to room temperature.

During the past quarter, Nb-Ti superconductor samples were irradiated and results were compared with those from an earlier test. Critical current inconsistencies must be resolved in future tests.

Our previous results on radiation damage in Nb-Ti (see Ref. 4) showed some unusual behavior in that upon annealing after irradiation the critical current first decreased and then recovered at higher temperatures. To substantiate this behavior, we repeated the experiment at the RTNS-I.

Two samples of Nb-Ti superconductor were irradiated to a fluence of $8 \times 10^{20} \text{ n/m}^2$ at the RTNS-I. One sample had been irradiated previously to a fluence of $8 \times 10^{20} \text{ n/m}^2$, and the other sample was unirradiated. The results of this most recent irradiation were totally unexpected: the critical currents of both samples remained unchanged during the irradiation, whereas we had measured a 26% decrease in critical current at the same fluence in the previous experiment.

To evaluate differences between the two irradiations, we examined the autoradiography to check sample alignment during the irradiations and the dosimetry to determine the neutron fluences; there were no significant differences. At this time, we conclude that the most recent experiment (which

Fig. 21. RTNS-II power supply and high-voltage enclosure.

showed no change in critical current to a fluence of $8 \times 10^{20} \text{ n/m}^2$ is correct. One possible explanation for the observation of a decrease in critical current in the previous irradiation is that the thermal contact between the specimens and the copper block changed with irradiation and the specimen temperature therefore increased during the irradiation. However, because there are no data available on the effects of irradiation on thermal conductivity of organic insulation, we cannot at present verify this explanation.

The best way to resolve the differences between these experiments is to continue the irradiation to higher fluences and to measure the critical current change with fluence. This experiment will be performed at the U.C. Davis Be(d,n) source as soon as funds are available.

Effect of Helium on Mechanical Properties of Nb and Nb-1%Zr. (*W. L. Barmore and R. R. Vandervoort*)

The mechanical properties of materials used in fusion reactors are changed by large concentrations of internally generated helium. Because of high (n,a) cross sections, significant quantities of helium will be produced in fusion reactor materials irradiated by 14-MeV neutrons in a relatively short time span. For example, a concentration of 25 to 50 atomic ppm helium will be produced internally in niobium by a fusion neutron flux of $\sim 10^{18} \text{ neutrons m}^{-2} \text{ s}^{-1}$ with 1 year's exposure. Helium atoms produced at a high concentration in a host matrix having low helium solubility

are thermodynamically unstable and have a high driving force to coalesce in the microstructure at various defects. Thus, helium atoms tend to migrate to dislocations, precipitates, grain boundaries, impurity particles, and microcracks and to coalesce into bubbles. These helium-induced defects generally cause embrittlement.

We have developed an optimized process for doping Nb and Nb-1%Zr specimens with helium using the tritium-decay method. Tritium is dissolved in the metal at 400°C to give a resultant Nb to ^3H ratio of 20 and an equilibrium partial pressure of 1.33 Pa over the specimens. The tritium decays by the reaction $^3\text{H} \rightarrow ^3\text{He} + \beta^-$ at a rate that produces about 7 atomic ppm helium per day in the host microstructure. Using this technique, we can successfully dope specimens to 500 atomic ppm ^3He in less than 10 weeks. During the past quarter, we determined the tensile properties of Nb-1%Zr with helium concentrations of 0 to 100 atomic ppm and at temperatures up to 800°C.

We are investigating helium effects that are separate from combined helium and displacement-damage effects by doping Nb and Nb-1%Zr specimens with ^3He by the tritium-decay method to as high as 500 atomic ppm and studying changes produced in the mechanical properties.

The tensile properties of Nb-1%Zr at temperatures up to 800°C as a function of helium concentration are given in Table 4. The strengthening effects and losses in ductility caused by helium are

Table 4. Tensile tests on Nb-1%Zr.

Helium (atomic ppm)	Test temperature (°C)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (%)	Reduction in area (%)
0	23	150	260	53	95
25	23	165	279	46	95
100	23	234	355	36	65
0	200	106	202	43	95
25	200	92	194	45	95
100	200	158	275	30	85
0	400	102	202	27	95
25	400	92	194	33	95
100	400	147	244	30	75
0	600	70	222	32	95
25	600	85	208	31	95
100	600	116	235	25	55
0	800	65	204	31	95
25	800	78	221	27	65
100	800	185	292	12	30

pronounced, particularly at a concentration of 100 atomic ppm. Note the loss in ductility at 800°C in the specimen containing 100 atomic ppm helium. The combined effect of temperature and deformation may lead to the rearrangement of helium in the metal matrix, the result being deleterious changes in the microstructure. Electron microscopy observations showed a homogeneous distribution of helium in as-charged specimens at 25 atomic ppm, however, as the helium concentration increased, there was a greater tendency for helium bubbles to form on grain boundaries.

Fusion Systems Engineering

Reactor Design Studies.

Performance Parameters for Fusion-Fission Power Systems. (D. J. Bender)

A comparatively near-term application of present-day fusion research, the hybrid (or fusion-fission) reactor, has recently received increased attention because of its potential to serve as a supplier of fuel to the nuclear power industry.¹⁴⁻¹⁶ Because the hybrid produces a source of neutrons external to the fission process, it is a highly flexible nuclear breeding option that permits the use of a wide variety of nuclear fuel cycles.

We have developed goals for the following parameters: plasma power amplification and hybrid unit capital cost ratio.

Fortesque¹⁶ recently proposed a set of parameters that could be used to compare the fissile breeding performances of the hybrid and the fast breeder reactor. We have elaborated on the analysis of Fortesque to reflect considerations that we have found important in our studies of the hybrid reactor. Our objective is to evolve a set of general performance parameters that will permit comparison of diverse hybrid reactor designs and fuel cycles on a common basis. Here, we present a summary of the full analysis.¹⁷

The fusion-fission symbiosis under consideration is represented in Fig. 22. We assume a driven fusion reactor that produces a gross electrical power P_{eb} (based on one unit of electrical input power to the plasma heating equipment). The hybrid also produces fissile fuel to provide fuel makeup requirements for a group of fission converter reactors having electrical output P_{ec} . The model used for the hybrid power flow is diagrammed in Fig. 23. We considered two hybrid configurations:

- "On-line" operation in which the thermal energy from the hybrid is converted to electrical output, and
- "Fuel factory" operation in which all thermal energy from the hybrid is rejected ($\eta_{tb} = P_{eb} = 0$).

We propose the following parameters to describe the fusion-fission power system:

Fig. 22. Electrical power flow for the entire fusion-fission system.

Fig. 23. Power flow in the fusion reactor.

- Fusion power multiplication in the converters:

$$r = \frac{\text{converter thermal power}}{\text{fusion power}}$$

- Thermal power ratio:

$$R_1 = \frac{\text{converter thermal power}}{\text{breeder thermal power}}$$

- Electrical energy multiplication

$$Q_E = \frac{\text{system gross electrical output}}{\text{breeder electrical input}}$$

- System unit capital cost ratio

$$R_c = \frac{\$/kW(e) \text{ for system}}{\$/kW(e) \text{ for converter}},$$

which is expressed as a function of the breeder unit capital cost ratio

$$\kappa = \frac{\$/kW(t) \text{ for breeder}}{\$/kW(t) \text{ for converter}}$$

Expressions for these performance parameters are derived in terms of the power-flow parameters appearing in Figs. 22 and 23.

We have considered two examples, the first based on the U/Pu fuel cycle and the second on the Th/²³³U fuel cycle. Power-flow parameters were selected from the results of our hybrid reactor studies,^{18,19} and the formulation was used to develop target performance parameters for plasma power amplification Q_p and for the hybrid unit capital cost ratio κ .

The variation of the system unit capital cost ratio is shown in Fig. 24 as a function of the plasma power amplification. Here, the Th/U fuel cycle is used with the hybrid in the "on-line" configuration. The unit capital cost ratio for the hybrid κ is treated as a parameter that varies from one to three. The following significant information is displayed on this figure:

- For $Q_p = 1$, the system capital costs are within 10 to 15% of the asymptotic values achieved with an ignition plasma ($Q_p = \infty$), thus demonstrating the adequacy of $Q_p = 1$ to 2 for hybrid reactor applications; and

- Even for hybrid capital cost ratios as high as $\kappa = 3$, attractive system capital costs can be achieved ($R_c \gtrsim 1.25$) with modest plasma performance.

The following results are obtained from the two examples:

- Scientific feasibility, or breakeven ($Q_E = 1$), occurs for the fusion-fission power system at $Q_p \approx 0.1$.

- If we select $R_c = 1.25$ as an economically competitive value, this condition is achieved by the on-line hybrid for plasma power multiplication of $Q_p \approx 1.2$ and hybrid unit capital cost ratios of $\kappa \approx 1.5 - 2.5$.

- The fuel factory configuration, at the same value of Q_p as the on-line hybrid, must have a capital cost reduction of ~ 2 to achieve comparable economics.

The Field-Reversed Mirror Reactor. (G. A. Carlson)

It may be possible to sustain a field-reversed, mirror-confined plasma using neutral beams. This would make possible small fusion reactors. We have completed a design study showing how several field-reversed cells can be assembled to make a commercial reactor.

Fig. 24. Variation of system unit capital cost ratio as a function of the plasma power amplification for a Th/U cycle and on-line operation, where κ is the capital cost ratio for the breeder unit.

The reference case field-reversed mirror (FRM) reactor²⁰ is a multicell configuration with 11 field-reversed toroidal plasma layers arranged along the horizontal axis of a long superconducting solenoid (see Fig. 25). Each plasma layer requires the injection of 3.6 MW of 200-keV deuterium and tritium and produces 20 MW of fusion power. The reactor has a net electric output of 74 MW(e).

The parameters of the reference case design result in part from somewhat arbitrary physics assumptions and in part from optimization procedures. We constructed an analytic model of the FRM reactor, encompassing physics, engineering, and economics, to permit investigating the effects of various assumptions and parameter variations. The optimization procedures were directed towards minimizing the estimated direct capital cost divided by the net electric power [$\$/kW(e)$]. The principal parameters that were optimized were the injection energy and the reactor cell length. The estimated direct capital cost for the reference design reactor is $\$1200/kW(e)$.

We considered a number of possible startup scenarios for the field-reversed plasmas; however, the choice of a specific startup method for the conceptual design was deferred pending experimental demonstration of one or more of the schemes in a mirror machine. Basic to our plasma model is the assumption that, once created, the plasma can be stably maintained by injection of a neutral-beam current sufficient to balance the particle loss rate. Two important physics assumptions for our reference case are that the particle confinement time is proportional to the ion-ion collision time and that the ratio of plasma minor radius to ion gyroradius ($S = a/\rho_i$) is limited by stability to about 5. The parametric analysis showed that less conservative

Fig. 25. The 11-cell field-reversed mirror reactor.

assumptions, such as classical confinement and/or $S = 10$, result in considerably improved reactors.

The individual reactor cells for the reference design are 2 m long and have a cylindrical first-wall radius of about 60 cm. The main magnetic field of 4.1 T is provided by Nb-Ti superconducting solenoids with a mean radius of 3.4 m. The plasma layers are held separate and stable by shallow axial and radial magnetic wells produced by normal Cu mirror coils and Ioffe bars placed at the first wall. The neutral beams are injected between sections of the main solenoidal magnetic through ports in the blanket and shield. The individual reactor cells weigh about 550 tonne and can be removed for refurbishing or replacement by a gantry crane located over the reactor centerline.

The Moving-Ring Field-Reversed Mirror Reactor.

(A. C. Smith, Jr.)*

The moving-ring field-reversed mirror (FRM) reactor would produce power by burning magnetically field-reversed rings of fusion fuel that are trapped in the trough of a magnetic mirror well. This device (see Fig. 26) would use a pulsed startup mechanism (such as intense ion-beam sources, plasma guns, or relativistic electron beams) to generate an initial, field-reversed minimum-B magnetic-confinement volume filled with fuel plasma in a relatively low background magnetic field (the ring former shown in Fig. 26). A local moving mirror (provided by sequentially energizing sets of push coils located in the wall of the reactor) would then drive the plasma ring into the high magnetic field of the burner solenoid section, thereby compressing the ring and heating it to the initial burn temperature.²¹ Experimental and theoretical understanding of the precise heating to be expected is somewhat sketchy, but if C is the compression ratio of a characteristic linear dimension of the ring, then the plasma temperature after compression T_f should scale from the initial temperature T_i roughly as $T_f/T_i \approx C^n$, where $1 \lesssim n \lesssim 2$.

The moving-ring FRM reactor could equally serve as a startup mechanism for the steady-state FRM described in Ref. 22. The distinction between the two concepts is in what follows compression in the moving-ring FRM reactor: whereas in the steady-state FRM reactor the confined plasma ring would be located in a fixed magnetic well and injected with high-energy neutral beams for refueling and sustenance of the diamagnetic currents, in the moving-ring FRM reactor there would be little additional energy invested in the plasma; instead, the burning plasma ring would be transported (using

push coils) down the solenoidal burner section of the reactor. During its transit of the burner section, the ring could be refueled with cold plasma (either as pellets or via low-energy streaming-plasma guns); moreover, moving the ring down the axis of the reactor would clear the way for the next ring in the procession to enter the throat of the burner. Cold-ion refueling allows the power produced by the plasma ring to be held constant—or varied, as the case may be—by controlling the ion temperatures and densities. Without refueling by energetic beams, the field-reversed confinement—in the absence of anomalous effects—will be sustained by the self-inductance of the ring. For fusion rings of interest, this time can easily be of the order of tens of seconds. Therefore, diffusive particle losses will determine the overall ring lifetime. The moving rings could be radially centered in the burner by either wall eddy currents or by a quadrupole field.

Depending on the fuel composition and purpose of the reactor, heat could be extracted in the conventional manner from the shield and blanket. When the plasma burn is nearly quenched (because of the cold-ion refueling), the plasma rings may be exhausted out the expander end of the device (Fig. 26) into a direct converter. Although plasma-burns in the moving-ring FRM reactor are indeed transient events, the device could be designed to permit a fairly uniform wall heat load, as though the plasma energy source were stationary and the burn steady state.

Preliminary calculations indicate that initial burner-section plasma temperatures of 50 to 100 keV will be required (depending on the particle diffusion loss rates). The total radiated power per ring can probably be maintained at about 20 MW, with an overall plasma energy gain $Q \approx 5$ to 8 and ring lifetimes of about 1 s for rings confined in a burner with a 0.8-T magnetic field.

Tritium Control and Handling.

Tritium Processing and Control Using Active Metal Getters. (M. F. Singleton)

We are evaluating a commercially available getter pump for the Tokamak Fusion Test Reactor (TFTR). In the current TFTR design, these pumps will be used to collect the deuterium and tritium pumped from the torus between each 5-min pulse. The deuterium and tritium will then be recovered off-site from the pump cartridges.

The getter pump being evaluated for the TFTR contains an intermetallic compound of 84 wt% Zr-16 wt% Al that has been powdered and pressed onto an iron substrate in a proprietary process. A photomicrograph (Fig. 27) of the powder on a substrate reveals a very thin ($\sim 2\text{-}\mu\text{m}$) phase at the interface. More metallographic work on this material is

*LLL Participating Guest employed by the Pacific Gas and Electric Company.

Fig. 26. The moving-ring field-reversed mirror reactor. (Illustration reproduced with the permission of PG&E.)

500 X

Fig. 27. Photomicrograph of 84 wt% Zr-16 wt% Al powder pressed onto substrate material used in getter pump.

now in progress. Pellets of pressed bulk material have been prepared for hydriding followed by metallographic analysis.

The thin plates of Zr-Al are arranged so as to optimize the surface-to-volume ratio and the pumping speed. The result is a circular cartridge of concentrically arranged plates placed at 4° angles to each other (Fig. 28). This cartridge is mounted on a rod-shaped heating element that is used to activate the Zr-Al at 750°C and to keep it at 400°C during operation. A water jacket around the outside is to shield personnel from heat and is not necessary for proper pump performance. The pump is open to the system at only one end, and it must be evacuated from this end during the activation process. When the pump is in service, it acts as a dead-end trap.

Our evaluation will include a comparison between the pumping speeds obtained with each hydrogen isotope: hydrogen, deuterium, and tritium. The effect of low-level impurities (helium, nitrogen, carbon dioxide, argon, and methane) on the hydrogen pumping speed will also be assessed.

These getter pumps have fairly high pumping speeds for the active gases, but their capacity is fairly limited. Many of these impurities cause a decrease in hydrogen pumping speed, and some may inhibit it completely. The radiolysis effects due to beta decay of the tritium may effect either pumping speed or the integrity of the getter material.

The experimental system has recently been completed, and our preliminary results on the pumping speed with deuterium are in excellent agreement with those of the manufacturer. However, we had a number of problems with heater failure when we first activated the pumps, and we feel the design will need modification for service with tritium. At present, we must open the pumps and remove the cartridge in order to repair or replace the heater. This could pose a hazard to the operator if tritium has been in the pump.

Tritium Processing and Control Systems. (A. E. Sherwood)

Proposed fusion reactors will have a large tritium inventory. Containment and cleanup systems will be needed to limit personnel exposures and population dose. Also, fusion research facilities presently being designed will require tritium cleanup systems. Tritium can be removed from effluent air by catalytic oxidation followed by water adsorption. However, available performance characteristics and basic data for the design of tritium/air cleanup systems are inadequate. Our program has the following objectives:

- To develop mathematical models for the engineering design of tritium cleanup systems,
- To obtain data on the kinetics of oxidation and adsorption bed dynamics, and

Fig. 28. Getter pump, showing (left to right) water jacket, cartridge, and heater with flange.

- To develop the instrumentation for real-time discrimination of tritium gas and tritiated water vapor.

In March, we successfully completed the first catalyst-evaluation experiments for the TFTR in our redesigned maintenance enclosure.

Our first successful experiments on the evaluation of low-temperature catalysts for the TFTR were performed during the last week of March. The experiments were carried out in the redesigned maintenance enclosure using a Pd/kaolin clay catalyst.

The experimental setup is shown in Fig. 29. Note that ion chamber 1 measures tritium as gas and water, while ion chamber 2 measures tritium gas only (we assume that the intermediate adsorbent bed catches all the water). Gas/water discrimination was confirmed with our first tritium run: we introduced a small amount of tritiated water into the enclosure: chamber 1 registered $\sim 500 \mu\text{Ci}/\text{m}^3$, and chamber 2 registered nearly zero $\mu\text{Ci}/\text{m}^3$. The tritiated water had been picked up, as expected, by the main adsorbent bed during the overnight run.

For the next run, we introduced a pulse of tritium gas into the enclosure (at $\sim 20,000 \mu\text{Ci}/\text{m}^3$ concentration) and started circulation through the cleanup system. The catalyst, loaded in the as-received condition, did not convert any tritium at all (to three significant figures) in a several-hour period.

Before the next run, we activated a batch of catalyst pellets for about 4 h at 400°C in a hydrogen gas flow and then allowed overnight cooling in a continuing hydrogen-flow stream. The activated catalyst was then loaded into the cleanup system,

the pump was turned on, and a pulse of tritium gas was released into the enclosure. Ion-chamber readings for the 10-h duration of this run are shown in Fig. 30. The rapid changes in the first 10 min are caused, we believe, by a lack of uniform initial mixing. There is a gradual change in slope from 10 to 100 minutes caused in part, by a slight increase in air temperature: The air started at 23.0°C , rose to 25.0°C at 200 min, and reached 25.1°C at 400 min.

The catalyst gave almost constant conversion from 100 to 400 min. From the slope of the curve, given the flow rate (146 litre/min) and the enclosure volume (5450 litre), we calculate 65% conversion per pass. From this, we compute an overall pseudo-homogeneous first-order rate constant of 1.7 s^{-1} based on the above flow rate and a catalyst volume of 1.53 litre.

Note in Fig. 31 that ion chamber 1 shows a tailing effect starting about 100 min before chamber 2. This is consistent with the presence of a small amount of tritiated water. Eventually, chamber 2 starts to tail off also, but we are then close to instrument background and accuracy is low.

In summary:

- The apparatus in the maintenance enclosure is operational, leak-tight, and appears to be working well,
- The catalyst requires activation for tritium use, and
- Reasonable catalytic conversion was achieved for about 8 h at 25°C and low tritium levels (10^2 to $10^4 \mu\text{Ci}/\text{m}^3$) in air at ambient humidity.

Fig. 29. Experimental tritium-maintenance enclosure system for the TFTR.

Fig. 30. Tritium conversion by catalytic oxidation at 25°C.

Cryogenic Properties of D-T. (P. C. Souers)

Work continuing on the compendium *Cryogenic Hydrogen: Properties Pertinent to Magnetic Fusion Energy*. The main structure of the document is now complete.

The compendium *Cryogenic Hydrogen Properties Pertinent to Magnetic Fusion Energy* is intended to gather in a convenient reference book all pertinent data on the hydrogen isotopes of interest to fusion technology. Thirteen new sections have been completed:

- Tritium Radioactivity
- The Melting Curve

Fig. 31. Hot- and cold-ion density profiles in 2XIIIB calculated for 5,000 A of gas current by the PHLOW code for use in the Monte Carlo calculation.

- The Liquid under Low Pressure
- The Solid Under Low Pressure
- Liquid Thermal Conductivity
- Quadrupole Energy and Heat Capacity
- Sound Velocity in the Solid and Liquid
- Dielectric Constant of the Liquid and Solid
- Debye Temperatures
- Solid Self-Diffusion and Quantum

Corresponding States

- Zero-Pressure Kinetic Gas Data to 30 K
- Nuclear Magnetic Resonances
- Hydrogen-Helium Mixtures

The early section titled "Saturated Vapor Pressures" was redone to provide consistent equations, for the first time, across all liquid and solid isotopes. Also, we have made a good start on determining the low-pressure equation of state (EOS) for H₂ with direct application to the liquid jet program at Physics International in San Leandro, CA. A first, simple, EOS model has been developed that shows a very narrow window for adiabats in compressing fluid H₂.

3. APPLIED PLASMA PHYSICS

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

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

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

Fusion Plasma Theory

Time-Dependent Tandem-Mirror Confinement Studies

(R. H. Cohen)

We have used the TAMRAC code to study startup conditions in the Tandem Mirror Experiment and alpha-particle buildup in a tandem mirror reactor.

The tandem-mirror rate code TAMRAC integrates rate equations for number and energy of an arbitrary number of species in a tandem-mirror machine. In addition to sources and end loss,^{23,24} the code includes models for enhancement of plug loss due to the drift-cyclotron loss-cone (DCLC) mode and for externally supplied streaming plasma to stabilize the DCLC mode, supplemental electron heating, species-dependent radial diffusion, and provision for injecting hot (not electrostatically confined) ions into the solenoid. We have used TAMRAC for the following two studies:

- A study of startup in the Tandem Mirror Experiment (TMX) that indicates that near steady-state conditions can be achieved on a time scale allowed by the power supplies if the gas feed is suitably programmed, and
- A study of alpha-particle buildup in a tandem mirror reactor, and ways of preventing buildup to a level that seriously degrades reactor Q. One particular means of eliminating hot alpha particles, nonadiabatic scattering (magnetic moment stochasticity), has been studied in detail.

Superadiabatic Ion Motion in the Presence of an Electrostatic Wave in a Mirror Machine

(G. R. Smith, J. A. Byers, and L. L. Lodestro)

Studies of ion motion in an axisymmetric magnetic-mirror field show that superadiabaticity affects ions with perpendicular energy greater than 8 keV.

Rosenbluth²⁵ and Timofeev²⁶ showed that a monochromatic flute mode at the ion-cyclotron frequency causes ions with low perpendicular energy $W_{\perp}$ to move stochastically, while ions with high $W_{\perp}$ move superadiabatically. We have improved their model by including the azimuthal ∇B -drift. Also, we used Rosenbluth's method and developed a new, more general method for determining the boundary in velocity space between stochastic and superadiabatic motion. The new method is based on the overlap of the bounce resonances defined by $\omega - kv_D = \Omega - 2n\omega_b$, where $\omega - kv_D$ is the wave frequency, Doppler-shifted by the ∇B -drift, ω_b is the frequency of bouncing between mirrors, Ω is the bounce-averaged cyclotron frequency, and n is any integer. Both theoretical methods predict that ions with $W_{\perp} > W_{\perp s} \approx 8$ keV move superadiabatically; this result agrees with the behavior of calculated ion orbits in a model magnetic field. The value of $W_{\perp s}$ depends only weakly on the axial and radial scale lengths of the magnetic field and on the amplitude ϕ of the flute mode ($W_{\perp s} \propto \phi^{0.21}$). Such a low value for $W_{\perp s}$ disagrees with experimental results that, apparently, indicate stochastic motion of ions with $W_{\perp} = 40$ keV.²⁷ This discrepancy cannot be resolved, we believe, either by including the collisional drag by electrons, or by replacing the present slab model by a cylindrical one. However, inclusion of effects of the quadrupole field may significantly alter the above results.

Simple Rotating-Field Reversed-Plasma Equilibria

(B. McNamara)

We have examined models of rotating equilibria that will be useful in studying the stability of the reversed-field theta pinch.

We have surveyed rotating equilibria, such as are generated in the Los Alamos Scientific Laboratory

(LASL) reversed-field theta pinch, as a function of five parameters: plasma beta, pressure profile, rotation velocity, aspect ratio of the theta pinch, and the mirror ratio of the vacuum field. Several models have been examined, the simplest of which is the one-fluid, scalar-pressure, rigid-rotator model. The equilibrium is described by two equations: a Bernoulli-type relation between the density ρ and the electric potential $\phi(\psi)$,

$$\mathbf{B} \cdot \nabla \left[C_s^2 \ln \rho - \frac{r^2}{2} \left(\frac{\partial \phi}{\partial \psi} \right)^2 \right] = 0,$$

where C_s is the speed of sound; and the radial pressure balance equation for the poloidal magnetic flux ψ ,

$$\Delta^* \psi + 4\pi C_s^2 r^2 \partial \rho(\psi, r^2) / \partial \psi = 0.$$

These equilibria represent a starting point for magnetohydrodynamic (MHD) stability studies of the reversed-field theta pinch and for the more complicated two-dimensional equilibria in tandem-mirror devices.

Rotational Instabilities in Reversed-Field Configurations

(L. D. Pearlstein and L. Lodestro)

Our calculations of rotational instabilities in reversed-field theta pinches agree with observed mode frequencies but not with rotational velocities.

Reversed-field theta pinches disrupt because of an $m = 2$ rotational instability. In these configurations, L (the plasma length) $\gg R$ (the plasma radius); thus, $B_z \gg B_r$ except where the field lines turn. Equilibrium satisfies the "long-thin" approximation, $2p_\perp + B^2 = B_{vac}^2$, and $B = B_z$ almost everywhere. Since rotational modes are flutes, we average over closed field lines, neglecting contributions from where the field lines turn. This produces the differential equation (for rigid rotation at frequency Ω)

$$\frac{d}{d\eta} (\eta^2 + \eta_0^2) \ell(\eta) \rho T \frac{d\psi}{d\eta} - \left[\frac{m^2 - 1}{4} \rho T + 2\omega^2 \eta \frac{\partial \rho}{\partial \eta} \right] \ell(\eta) \psi = 0.$$

Here, η is a function of the flux such that $B^2 = B_z^2 \tanh^2 \eta$ and η_0 is the value of η at the last closed field line, $\ell(\eta)$ is the length of a field line, and

$$\rho T = (\omega - \Omega) \left[\omega - \Omega + \omega_* \left(1 + \frac{1}{2 \sinh^2 \eta} \right) \right] \frac{1}{\cosh^2 \eta}.$$

The singularity at $r = 0$ disappears because of averaging. Note that ($\eta = 0$) now becomes a boundary point where $E_\theta = 0$ (perfect conduction), but $\psi = E_\theta/B$ is indeterminate. To resolve this ambiguity, one can include a B_θ in equilibrium that suggests $\psi = 0$. Alternatively, one can solve the boundary-layer problem where the FLR expansion is not valid.

To date, we have only compared stability boundaries from a variational procedure and a shooting procedure with the boundary conditions $\psi^{(0)} = 0$. Results for $\psi = 0$ indicate that the frequency of the mode agrees with that observed. However, instability is predicted to occur at a rotational velocity considerably in excess of that inferred experimentally from Doppler-shifted impurity radiation.

Orbital Resonances in Quadrupole-Stabilized Mirror Configurations

(R. H. Cohen, D. V. Anderson, and C. Sharp)

Calculations suggest that the orbital resonances manifested as sudden losses of plasma ("bursts") in RECE-Berta should be considerably smaller in 2X-IIB.

Using analytic techniques and the particle-orbit code ORBXYZ, we have demonstrated that a quadrupole field added to an axisymmetric, non-vacuum mirror configuration significantly couples the radial, azimuthal, and axial motions of single particles, and that this effect may account for the bursting and nonbursting anomalous losses observed in the relativistic electron compression experiment (RECE-Berta) at Cornell.²⁸ At particular values of the plasma self-field, a class of resonant particles can experience sizable excursions from an initial set of radial and axial oscillation amplitudes. If the plasma radius is defined by a limiter, as in RECE-Berta, then resonant particles hitting the limiter would give rise to a sudden loss of plasma. From our analytic estimates of the resonance conditions and resonance widths, we have estimated the size of a burst. Orbit-code calculations in steady-state and time-varying fields are used to show the effect. Between bursts, resonances mainly affect particles away from the limiter, giving rise to an enhancement of classical diffusion, such as is also observed in RECE-Berta. In 2X-IIB, resonance effects

should be considerably smaller at a given fraction of field reversal, and should not be manifested as bursts.

Spatial Eigenmodes for the Alfvén Ion-Cyclotron Instability in Finite-Length Plasma

(D. C. Watson and T. D. Rognlien)

Calculations of spatial eigenmodes and stability limits based on a finite-length plasma agree with earlier deductions and calculations.

We have investigated improvement in Alfvén ion-cyclotron (AIC) stability brought about by finite-length plasma and we have also examined the eigenmode (E-field) structure. For ease of investigation, we chose a finite-length plasma model where ions are confined by a parabolic electrostatic potential well and lie in a uniform magnetic field. The electrons maintain quasi-neutrality. The Maxwell-Vlasov system was solved in full, including the ion bounce motion.

First, we derived heuristic dispersion relations; second, we calculated exact stability limits; third, we displayed the important eigenmodes. We found that modes with spatially even E-fields have resonances at $\omega = \omega_{ci} \pm 2n\omega_{bi}$, whereas modes with spatially odd E-fields have resonances at $\omega = \omega_{ci} \pm (2n - 1)\omega_{bi}$. Here, ω_{ci} and ω_{bi} are the ion cyclotron and bounce frequencies, respectively.

The lowest-order odd mode is the most unstable. The onset of instability roughly agrees with that deduced from the infinite-medium dispersion relation and the requirement that a half-wavelength should fit in the plasma. These results are in accord with those from Byers' linearized particle-simulation code, which uses the same finite-plasma model. Byers' code²⁹ has a linear-polarization constraint that introduces additional resonances with $\omega_{ci} \rightarrow -\omega_{ci}$ in the equations above. This leads to the complication of double resonances when $\omega_{bi} = \omega_{ci}/n$.

Electron Effects in Ion-Current Field Reversal

(D. E. Baldwin and M. E. Rensink)

Using a simple model, we have determined situations in which significant electron currents develop in an axisymmetric plasma composed of more than one ion species.

Existing calculations of field reversal driven by ion currents have neglected all electron effects other than ion energy loss. These have assumed that the generation of a current by ionization of neutral-beam atoms results from the charge separation induced by the magnetic field; all plasma currents are

carried by the ions. However, electron currents can be generated by two means:

- Electron-ion momentum transfer tends to equalize the average velocities of these particles, partially cancelling the ion current. This mechanism is particularly effective at a field null, and

- Radial electric fields are set up by the charge separation that results from ionization or unequal transport rates. In these fields, electrons can drift in a way that cancels the ion current.

Using a simple model of electron-ion momentum transfer, we have calculated electron currents in the presence of assumed ion species. We find the following general conclusions for an axisymmetric configuration:

- The existence of a field null in steady state requires a net current at the null. This can arise in a plasma composed of more than one ion species where the ions have different charges and average velocities. Most simply, a nonrotating species offers a resistive background so that the electrons cannot accelerate to nullify the current of a rotating ion species.

- Away from a field null, an azimuthal electron drift velocity arises only because of a radial electric field.

- On open magnetic lines, electron end-conduction to grounded boundaries constrains the variation in potential to the order T_e/e . Azimuthal electron drift currents are small compared with the ion current and are justifiably neglected.

- On closed magnetic lines, large potentials can develop between magnetic flux surfaces, and the possibility of significant cancellation of the ion current by drifting electrons exists.

A quantitative assessment of these effects requires a prescription for calculating electric fields and electron currents in ion-particle codes such as SUPERLAYER at LLL. This is being implemented.

Axial Profile of Electron Temperature via Monte Carlo Electrons

(T. D. Rognlien)

We have developed a Monte Carlo electron code to calculate the axial electron heat flow in 2XIIIB.

The electron temperature T_e measured in the 2XIIIB experiment shows that the central temperature can increase from 50 eV to 150 eV as the plasma density is increased. In contrast, the electron temperature is considerably lower in the region outside the mirror throat and gas box, with T_e ranging from 20 eV to 40 eV. The theoretical description of axial electron heat flow is complicated by the fact that the mean free path for electrons is of the same

order as the scale length of density variation in the system. Consequently, neither a classical fluid description nor a bounce-averaged Fokker-Planck description of the electron heat flow is valid. To treat this problem properly, we have developed a Monte Carlo computer code for the electrons.

A basic outline of the Monte Carlo electron code is as follows:

- The electron orbits are followed in assumed or previously calculated magnetic and electric fields.
- The electrons are randomly scattered at each time step according to their Coulomb scattering coefficients.
- The average energy of such electrons is calculated at a number of axial positions and for many time-steps.

This sequence gives statistically meaningful information about the axial temperature profile. Details of the various parts of the calculation follow.

The electron orbits are followed along a magnetic field line; we assume that the magnetic moment is conserved between collisions. The electron equation of motion is thus

$$m_e \frac{d^2 z}{dt^2} = m_e \frac{dv_z}{dt} = e \frac{\partial \Phi}{\partial z} - \mu \frac{\partial B}{\partial z}, \quad (1)$$

where z is the axial position, m_e is the electron mass, e is the electronic charge, Φ is the electrostatic potential, B is the magnetic field, $\mu = m_e v_\perp^2 / 2B$ is the magnetic moment, and $v_\perp$ is the velocity perpendicular to B . The fields $\Phi(z)$ and $B(z)$ are taken from the axial fluid code PHLOW, which describes the axial flow of cold plasma from the gas box. For given hot-ion density and electron temperature profiles, the PHLOW code calculates a self-consistent $\Phi(z)$, $n_e(z)$, and $n_c(z)$, where $n_e(z)$ is the electron density and $n_c(z)$ is the cold-ion density.

After an electron is pushed one time step Δt according to Eq. (1), its velocity components are changed to reflect the effect of Coulomb collisions. A velocity coordinate system is formed in which the electron velocity vector lies along the $w_\parallel$ -axis. The electron is then scattered in this coordinate system according to

$$w_\parallel \rightarrow w_\parallel + \langle \Delta w_\parallel \rangle \Delta t + \left(3 \langle \Delta w_\parallel^2 \rangle \Delta t \right)^{1/2} R_1 \quad (2)$$

$$w_x \rightarrow (1.5 \langle \Delta w_x^2 \rangle \Delta t)^{1/2} R_2 \quad (3)$$

$$w_y \rightarrow (1.5 \langle \Delta w_y^2 \rangle \Delta t)^{1/2} R_3 \quad (4)$$

Here, $R_{1,2,3}$ are random numbers uniformly distributed from -1 to 1. The scattering coefficients are obtained from Spitzer³⁰

$$\langle \Delta w_\parallel \rangle = -A_c [2n_e \ell_c G(\ell_c v) + n_h \ell_h G(\ell_h v) + n_c \ell_c G(\ell_c v)] \quad (5)$$

$$\langle \Delta w_\parallel^2 \rangle = \frac{A_c}{v} \{ n_c G(\ell_c v) + n_h G(\ell_h v) + n_c G(\ell_c v) \} \quad (6)$$

$$\langle \Delta w_\perp^2 \rangle = \frac{A_c}{v} [n_c H(\ell_c v) + n_h H(\ell_h v) + n_c H(\ell_c v)] \quad (7)$$

where $v = (v_z^2 + v_\perp^2)^{1/2}$. Other quantities are

$$G(x) = [\text{erf}(x) - x \text{erf}'(x)] / 2x^2, \quad (8)$$

$$H(x) = \text{erf}(x) - G(x), \quad (9)$$

$$A_c = 8\pi e^4 \ln \Lambda / m_e^2, \quad (10)$$

$$\ell_a^2 = (2kT_a / m_a)^{-1}. \quad (11)$$

The subscripts e , h , and c refer respectively to electrons, hot ions, and cold ions, and $\ln \Lambda$ is the Coulomb logarithm. The spatial profiles of particle densities n_e , n_h , and n_c are taken from the PHLOW code. After the electron is scattered in the w -velocity space, its velocities are converted back to the v_z and $v_\perp$ space. The process is then repeated with the electron advanced according to Eq. (1).

We now have a version of the Monte Carlo code that calculates the electron temperature profile for fixed profiles of n_e , n_h , n_c , and T_e . Shown in Fig. 31 is a sample of the profiles used as obtained from the PHLOW code for a high-current case of $I_{\text{gas}} = 5,000$ A. Recall that $n_e = n_h + n_c$; n_e is therefore omitted from the figure. The T_e profile is assumed to be 50 eV at the left-hand wall and to rise to 100 eV in the center. The initial temperature profile and that of the Monte Carlo electrons is given in Fig. 32.

The statistical fluctuation is evident. Note that the temperature does not depart greatly from the assumed T_e profile because the electron-electron interactions are stronger than those causing hot-ion heating and cold-ion cooling. The temperature in the center of the profile is ~ 105 eV; that at the end is ~ 50 eV. The heating in the center arises from hot ions; the cooling at the ends is from electron sheath losses. We emphasize that our results are not final, but rather that they show the information that can be obtained from the Monte Carlo code.

Our next step will be to iterate the Monte Carlo code and the PHLOW code until the $T_e(z)$ profiles are the same in each. This self-consistent result is the ultimate goal of the calculation.

A Local Theory of Nonlinear Ion Dynamics in a Drift-Cyclotron Mode

(B. I. Cohen, N. Maron, and T. D. Rognlien)

Nonlinear perturbation theory and a new hybrid model (fluid electrons and particle ions) for one-dimensional, fully electrostatic computer simulation have been used to study the nonlinear theory of the drift-cyclotron instability.

The interaction of the ion diamagnetic-drift wave with an ion Bernstein wave can lead to the well-known drift-cyclotron instability. In mirror machines, the drift cyclotron mode becomes important because it can persist as a residual instability after electrostatic turbulence (resulting from the DCLC mode) and externally introduced streaming plasma have partially filled the loss cone in velocity space.³¹ Local theory³²⁻³⁴ has suggested that nonlinear ion dynamics induced by a single wave can stabilize the drift-cyclotron mode by disrupting the necessary frequency synchronization between the mode frequency ω , the nearest cyclotron harmonic $N\omega_{ci}$, and the ion diamagnetic frequency ω^* . We consider three particular regimes: near linear marginal stability $\omega \approx N\omega_{ci} \approx \omega^*/2$,³² near the simultaneous resonance $\omega \approx \omega^* \approx N\omega_{ci}$,³³ and in the regime of ion trapping.³⁴ We have reviewed the theories of the stabilization caused by a nonlinear frequency shift^{32,33} within our own analytical framework and have found significant discrepancies. We have derived a nonlinear equation of the form

$$[(\partial^2/\partial t^2) - \gamma^2]\psi + \alpha|\psi|^2\psi = 0$$

where $\psi = e\Phi/T$, γ = the linear growth rate, and α is a coupling coefficient associated with the nonlinear (specifically quasi-linear in origin) corrections

to Poisson's equation at third order in the mode amplitude. A nonlinear dissipation shift acts as a stabilizing influence ($\alpha > 0$) on both the drift-cyclotron and DCLC instabilities. There is a concomitant shift in the real part of the mode frequency at saturation, which is the order of the linear growth rate in magnitude.

To confirm theoretical predictions and further understand the role of nonlinear ion dynamics in the stabilization of drift-cyclotron and DCLC instabilities, we have developed a hybrid model (fluid electrons and particle ions) for one-dimensional, fully electrostatic computer simulation. The algorithm suffers no restriction due to electron-cyclotron or plasma-frequency time scales, and is only required to accurately follow lower-hybrid and ion-cyclotron frequencies (Fig. 33). We are using

Fig. 32. Comparison of initial electron temperature and the first iteration of the Monte Carlo electron temperature.

Fig. 33. Numerical dispersion properties of the one-dimensional slab, hybrid simulation code. The theoretical grid-corrected linear dispersion relation for small-amplitude lower hybrid waves in a cold, uniform plasma is plotted, $\omega/\omega_{ci} = (\omega_h/\omega_{ci}) [\sin(k\Delta x/2)/(k\Delta x/2)]^{3/2} \cos^{1/2} k\Delta x/2$, with data obtained from simulation superposed for comparison $[\omega_h = \omega_{ci}/(m_e/m_i + \omega_{ci}^2/\omega_{pi}^2)^{1/2}]$.

Fig. 34. Simulations of the drift-cyclotron instability confirming linear theory. The complex frequency ω/ω_{ci} is plotted as a function of scale length L_n/a_i for $N = 1, 2$ where $\text{Re } \omega \approx N\omega_{ci}$ and $ka_i = 7$, $\omega_{pi}^2/\omega_{ci}^2 = m_i/m_e = 100$, and $\omega_{ci}\Delta t = 0.05$. Increasing turbulence occurs as L_n/a_i decreases. The real part of the frequency has not been measured in simulations where there is an early onset of non-linear behavior.

the simulations to study the stability of systems that could be stabilized by a complex frequency shift in the regime of weak instability where our analytical theory is expected to be valid. In regimes of strong instability we expect ion trapping. So far, our simulations have confirmed the linear theory of the drift-cyclotron instability (Fig. 34) and have evidenced ion trapping in the nonlinear regime. When the electric field amplitude is sufficiently weak so that trapping does not occur, simulations of a single unstable mode confirm our theoretical description of saturation by means of a nonlinear frequency shift. However, preliminary multi-mode simulation results suggest that this saturation mechanism may fail in the presence of other modes (Fig. 35).

Experimental Plasma Research

The Intense, Pulsed Ion-Neutral Source (IPINS)

(D. S. Prono)

Our principal goal is to develop intense, pulsed, neutral-beam sources (IPINS) for the mirror program. The generation of a reversed-field configuration in a 2XII-B-scale experiment with rapid (microsecond time scale) buildup times would be the main near-term application of this technology, and the current research is focused on the achievement of the performance levels required by this application.

The major test stand is now operational. Our experiments have emphasized

- Diagnostic fabrication, installation, and debugging;
- Initial studies of beam divergence; and
- Studies of how geometrical changes in the diode affect the rapid anode-cathode closure observed in this system.

Because the data are preliminary, we shall not attempt a detailed discussion of our results to date. Briefly, this system has exhibited the low-impedance ion-flow mode with the diode voltage remarkably constant (as the current changes and the gap closes) and with the voltage level controlled by the properties of the anode foil. This behavior is, of course, in good accord with the simple one-dimensional steady-state theory. The major problem is the short duration of the ion-flow mode, which is terminated by diode closure after a much shorter time (closure velocities $> 10 \text{ cm}/\mu\text{s}$) than with the small test stand. Although we do not understand the origin of this rapid anode-cathode closure, we have demonstrated how the inherent "two-dimensionality" of the diode geometry of the small test stand (asymmetric current in the foil and a small B_z field) lessens the closure speed there. For a number of reasons, operation in this fashion may not be desirable, and we are therefore attempting to extend the ion-flow duration by expanding the anode-cathode gap.

We are designing a modification to the diode geometry that will allow larger anode-cathode spacings, improved access to and visibility of the diode region, and a revised vacuum insulator support structure. The last should alleviate the flashover difficulties that occur with a longer ion-flow pulse length. The modified design should be installed early in the next quarter.

Fig. 35. Nonlinear evolution of a drift-cyclotron mode in the presence of other modes. Plotted here is the electric field energy density for a single mode $ka_1 = 7$ as a function of time for $\omega_{pi}^2/\omega_{ci}^2 = m_i/m_e = 100$, $L_\perp/a_1 = 4.9$, and $\omega_{ci}\Delta t = 0.05$. There are other linearly unstable modes present that apparently destabilize the single mode shown subsequent to its saturation at $\omega_{ci}t \approx 20$ with an amplitude $(E_k^2/8\pi)_{sat}$, in fairly good agreement with our nonlinear perturbation theory. The instability late in the simulation is preceded and accompanied by considerable ion trapping.

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