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MAGNETIC FUSION ENERGY ANNUAL REPORT October 1976 through September 1977

Scientific Editor: M. A. Harrison
General Editor: L. Gottlieb

January 4, 1978

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CONTENTS

Abstract	1
Section 1. Confinement Systems	3
Introduction and Summary	3
2XIIIB Experiment	3
Introduction	3
Field-Reversal Experiment	5
Thomson-Scattering Measurements	17
Plasma-Diamagnetism Measurements	19
Power-Balance Measurements	20
Neutron Measurements	20
Zeeman-Effect Magnetic-Field Diagnostic	21
Faraday Rotation (Interferometer Diagnostic)	21
New Diagnostics: Magnetic Probe	23
Reaction-Ion Analyzer Diagnostic	25
Improvements to Thomson-Scattering System	25
Langmuir-Probe Measurements	26
Neutral Beams	29
40-keV Neutral-Beam Extractors	29
80-keV Source Design for Mirror Fusion Test Facility	30
Computer Control	31
Data Acquisition and Processing	32
Streaming-Plasma 1-kV Ion-Source Development	32
Radially Dependent Fokker-Planck Code	37
rf-Heated Gas Box	38
Electrical Engineering Support	38
Mechanical Engineering Support	39
Mirror Fusion Test Facility	40
Introduction	40
Technical Capabilities and Objectives	40
Research and Development Activities	40
Project Design Update	43
Tandem Mirror Experiment	51
Introduction	51
Physics Parameters	51
Engineering Description	52
Section 2. Development and Technology	56
Introduction and Summary	56
Superconducting Magnet Development	58
Direct Energy Conversion	60
Beam Direct Conversion	60
Advanced-Fueled Fusion Reactors Suitable for Direct Energy Conversion	62
Neutral-Beam Conceptual Studies	63
Reactor Studies	64
Field-Reversed Mirror Reactor	64
Preliminary Design Study of the Tandem Mirror Reactor	66
Fusion-Fission Hybrid Reactor Studies	66
Small Mirror Reactors	69
Neutral-Beam Development and Technology	70
Introduction	70
Test Facilities	70
Positive-Ion-Based Program	73
Efficient Beams	74
Prototype Beam Lines	79
Technology Transfer	79

Rotating-Target Neutron Source-II	81
Radiation Damage	82
Correlation of Neutron Damage with Neutron Sources	82
Helium Effects on Mechanical Properties	89
Radiation Damage in Superconductors	90
Resistivity Measurements of Radiation-Damage Rates	91
Computer Modeling of Radiation Damage	94
Rotating-Target Neutron Source-I Irradiations and Dosimetry	95
Tritium Handling and Control	96
Tritium Containment and Blanket Designs for a Mirror Fusion Central Power Plant	96
Tritium Control in Mirror Hybrid Reactor	96
Tritium Processing and Control Systems	98
Tritium Processing and Control Using Active Metal Getters	99
Improved Equipment and Production Procedures for Rotating-Target Neutron Source-II Tritide Targets	101
Section 3. Research	102
Theory and Computations	102
Introduction and Summary	102
Quasilinear Codes for Ion Transport in Mirrors	103
Marginal-Stability Studies of Drift-Cyclotron Loss-Cone Mode	104
M = 1 WOBBLE Instability Driven by Rotation	108
Electron Effects in Ion-Current Field Reversal	108
Reassessment of Requirements to Obtain Field Reversal in Mirror Machines	109
Theory for Tandem Mirror Experiment Proposal	109
Monte Carlo Neutral-Transport Code	109
Monte Carlo Simulation of the Effects of Drift-Cyclotron Loss-Cone Turbulence on Single-Particle Orbits	110
Adiabaticity in Tandem Mirror Systems	112
Potential-Aided Confinement in Mirror Machines	113
Tandem Mirror Rate Code	114
Basic Studies of Dynamical Systems	114
Axial Flow Code for Warm Plasma in a Mirror Machine	115
Monte Carlo Simulation of Neutral Particles	115
Adiabatic Invariants by Lie Transforms	116
Tandem Mirror Studies	117
Conversion of Bounce-Average Code to μ -J Space	119
Magnetohydrodynamic Equilibrium and Stability of Minimum-B Mirror Traps	120
1b <i>Intra</i> Multiconfiguration/Self-Consistent Ground-State-Potential Energy Curves	121
Formation Processes and Secondary-Emission Coefficients for Negative-Deuterium Ion Production on Alkali-Coated Surfaces	121
Radiation Losses in 2X11B Using the Prono Source	121
Computer Calculations of 2X11B Field-Reversed Mirror Configurations	121
Tokamak Microinstability	126
Computer Simulation of High-Beta Mirror Plasmas	126
Laser Interactions with Plasma	128
Alfvén Ion-Cyclotron Mode	129
3-D Calculations of Mirror Equilibria with the Finite-Element Vector-Potential-Equilibrium Code (YEPEC)	130
Preliminary Planning for a 3-D Multifluid Magnetohydrodynamic Mirror-Plasma Simulation Code	131
Accurate Single-Particle Orbits in Realistic 3-D Minimum-B Mirror Fields	132
Parameter Studies of Axisymmetric Reversed-Field Vlasov Equilibria for the 2X11B Regime with the CYLEQ Code	132
Calculation of 2X11B Self-Fields from Experimental Data	132
2-D Axisymmetric Fluid Simulation of Plasma Production and Flow in Ion Beams	133

Implementation of Incomplete Cholesky Conjugate-Gradient Method	133
3-D Plasma Equilibrium	134
Exploratory Concepts: Intense Pulsed Ion-Neutral Source (IPINS)	135
Section 4. Talks and Publications	137
Talks	137
Publications	145
Journal Articles	145
Preprints for Journals	147
Reports	148
Proposal	148

MAGNETIC FUSION ENERGY ANNUAL REPORT

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ABSTRACT

This year we moved beyond the straightforward magnetic mirror experiments (of 2XIIB and Baseball II-T) to substantially larger ones. These new experiments, the Tandem Mirror Experiment (TMX) and the Mirror Fusion Test Facility (MFTF), will bring us closer to reactor concepts and to issues that must be settled before reactors are built.

Our confinement-systems activities featured improved operating and plasma parameters in 2XIIB, the start of TMX construction, and extensive engineering design on MFTF. We upgraded the performance of 2XIIB's neutral-beam sources, doubling injected current and electron temperatures. Also, we achieved even higher values for peak beta (plasma pressure/magnetic pressure). The higher beta implied a close approach to a field-reversed state. Along with the construction start on TMX, we performed further computations relating to this promising idea. On MFTF, we completed the design of its large coil winder and development of its coil conductor.

To support our mirror-confinement experiments, we furthered the development of state-of-the-art technologies in many areas. Our superconducting magnet program saw successful operation of a production line for adding a "wraparound" stabilizer to the MFTF coil's superconducting core. We successfully developed a cold-weld technique for making superconducting joints. As a result of mechanical strain tests, we concluded that the superconducting material niobium tin could tolerate practical strain and be used in high-field magnets. After meeting our goals at 15 keV in the direct energy conversion program, we built and installed a 120-keV beam-direct convertor in Lawrence Berkeley Laboratory's IIA test stand. In the area of reactor studies, several designs were completed: a conceptual design of a 100-MWe vertical-stacked multicell reactor, a preliminary design of a 1000-MWe tandem mirror reactor, and a reference conceptual design of a fusion-fission hybrid reactor based on a classical mirror plasma and a depleted uranium blanket. Our neutral-beam program reported significant improvements in two major test facilities. On the IIA stand, we successfully evaluated "magnetic core snubbers" for spark-damage control; the IIB stand became operational, powering and controlling our first full-current neutral-beam source for the Tokamak Fusion Test Reactor. Construction continued on the RTNS-II (Rotating-Target Neutron Source), a new 14-MeV neutron source to obtain data on reactor materials at higher doses. Using RTNS-II and beryllium(d,n) sources, we explored the nature and magnitude of radiation damage effects produced by their neutrons. The tritium technology group continued its studies to control tritium emissions and clean up tritium in both fusion and hybrid reactors.

The theory program had improvements in the linear theory of drift cyclotron loss cones and in the concomitant quasilinear theory. We delineated the major theoretical problem areas for tandem mirrors and performed first-cut analyses of many of these. Field-reversal studies led to an understanding of the role electron currents play on the buildup to and maintenance of this configuration. Our computational group focused on understanding field reversal in 2XIIB and on modeling for TMX. A large effort went into applying the

SUPERLAYER computer code to modeling rf drift-cyclotron loss-cone diffusion. We undertook a variety of parametric studies to accurately model 2X11B and to determine model sensitivities. Development continued on physics models and new simulation methods that describe important electron physics features in a high-beta plasma. Using a 2-D multispecies Fokker-Planck code, we began a number of studies on tandem mirror systems. A 3-D fluid-equilibrium code, McGus, was applied to studies of MFTF, the TMX end cells, and several reactor designs.

SECTION 1. CONFINEMENT SYSTEMS

Introduction and Summary

Our main confinement-related developments concerned further improvements in 2XIIIB operating and plasma parameters and design and construction of two new mirror facilities, the Tandem Mirror Experiment (TMX) and the Mirror Fusion Test Facility (MFTF).

By upgrading the performance of the neutral-beam sources in 2XIIIB, we doubled the injected current—from 250 to 500 A. As a result of this increased current and of improvements in the vacuum pumping and other parameters of 2XIIIB, electron temperatures also roughly doubled—up to a maximum value of 180 eV and routinely attained values of 140 eV. That such elevated values could be obtained was especially significant from a plasma physics standpoint for the following reason: demonstration of such values removed a possible ambiguity in the interpretation of heat-conduction effects between the hot plasma and the outside world. At 60 to 80 eV it might have been claimed that electron temperature (T_e) was being controlled by classical electron thermal conduction, a process that would represent a "clamp" on further increases in T_e . The achievement of 140-to-180-eV electron temperatures implied a substantial degree of decoupling present between the interior plasma and the exterior regions. Though we would expect this result from our picture of the physics of mirror confinement, its direct demonstration, refuting the pessimistic interpretations, was gratifying.

Another result of the upgrading of 2XIIIB parameters was the achievement of even higher values for peak beta (plasma pressure/magnetic pressure): up to 2.5. This implied a close approach to a field-reversed state. Experimentally, the field-reversal parameter ($\Delta B/B$) = 0.9 ± 0.1 ($\Delta B/B > 1.0$ corresponds to field reversal). While we do not know whether further increases in $\Delta B/B$ will be possible with 2XIIIB as it stands, we were encouraged by the achievement of such high beta values with the present facility. We formulated plans for additional upgrading to push further toward field reversal, including the possibility of higher current, pulsed neutral-beam sources.

Construction began on TMX, and further computations relating to this promising idea were performed. The planned TMX completion date is October-November 1978.

We completed the design of the large coil winder and development of the coil conductor for the large mirror facility, MFTF. Extensive engineering

design was also performed on MFTF, which is planned for completion in 1981-1982.

Thus, we vigorously pursued implementation of new directions for mirror research, the tandem mirror, and the field-reversed mirror, as outlined in the last progress report.

Author

R. F. Post

2XIIIB Experiment

Introduction

During FY 1977 we directed our activities toward the investigation of field-reversal geometries in mirror-configured plasmas. Simultaneously, we developed new diagnostics, improved existing ones, and started supporting projects in such areas as new plasma-stream sources and higher energy neutral beams.

Using existing high-current neutral-deuterium-beam injectors¹ and stabilizing the drift-cyclotron loss-cone (DCLC) instability,² first with streaming-plasma injectors³ and then with a gas-feed system,⁴ we achieved an unprecedented high β (plasma pressure/magnetic pressure) = $8\pi n\bar{E}_i/B_{vac}^2$ (n = plasma density, $\bar{E}_i$ = mean ion energy, B_{vac} = vacuum magnetic-field strength) in our 2XIIIB series of magnetic mirror plasma-confinement experiments. With gas-feed stabilization⁴ the peak beta (β) at the plasma center exceeded unity. This development, together with the recognized necessity of enhancing the Q (fusion power output/neutral beam injected power input) of reactor schemes based on the mirror machine concept,⁵ led to the field-reversal experiments on the 2XIIIB device described here. Fokker-Planck calculations of classical mirror transport, with all the plasma confined on open field lines, predicted Q values close to unity.⁶

A preliminary study of a field-reversed mirror reactor (FRM), in which the bulk of the plasma is confined on field lines closed by plasma diamagnetic currents, predicts $Q \approx 5$,⁷ assuming transport dominated by classical collisions. The concept of the FRM differs from the earlier Astron scheme⁸ in that field reversal is maintained by bulk plasma-diamagnetic currents rather than by a separate layer of energetic electrons or ions. Other approaches to field reversal include the ion-ring compressor,⁹ field-reversed ion rings formed by cusp injection,¹⁰ field-reversed theta pinch,¹¹ and adiabatic compres-

sion of plasma-gun-injected vortices.¹² To date field reversal, in the sense of internal magnetic field opposite applied field, has been achieved by trapping relativistic electron rings in gas,¹³ cusp injection of a relativistic electron beam into gas¹⁴ or preionized plasma,¹⁵ and in field-reversed theta pinches.¹¹

We directed the 2XIIIB experiments described here toward obtaining the largest reversal of the vacuum magnetic-field strength with our existing set of neutral-beam injectors and a streaming-plasma/gas-feed-stabilization method. Principal changes in 2XIIIB operation compared with earlier experiments were

- Increased neutral-beam injection power achieved mainly by installation of improved neutralizers.

- Off-axis aiming of the beams tangential to trapped ion gyro-orbits to enhance the axis-encircling component of the ion-diamagnetic current and to increase the plasma energy density.

Table I summarizes the best results obtained for three particular data runs. Shown in Table I for each data run are B_{vac} at the center of the minimum-B magnetic well, I_{beam} = injected neutral-deuterium (D^0) current in equivalent amperes, R_p = mean plasma radius, m = total plasma magnetic dipole moment, $\bar{E}_i$ = mean ion energy, T_e = electron temperature, and the estimated field-reversal parameter (ξ) = $\Delta B/B_{vac}$. (ξ is the change in field strength at the plasma center divided by the vacuum-field strength.)

For the internal field point opposite the vacuum field and closed field lines to form, ξ must exceed unity. Measurement of this parameter requires an internal nonperturbing measurement of magnetic-field strength. Two methods being developed for this measurement on 2XIIIB—a Faraday rotation measurement¹⁶ and a resonance fluorescence Zeeman probe¹⁷—are unavailable for the data reported here. The values of ξ in Table I are estimated from the bulk plasma dipole moment (m), measured by a large diamagnetic loop around both the plasma volume and R_p . Internal probe measurements are not possible because of nonlocal destruction of plasma confinement and melting of probe material.

Table I. Summary of 2XIIIB field-reversal experiments.

Date	B_{vac} (kG)	I_{beam} (A)	R_p (cm)	m (MA·cm ²)	$\bar{E}_i$ (keV)	T_e (eV)	$\frac{\Delta B}{B}$
3/30/77	6.7	400	8.7	18	12.5	75	0.4
4/14/77	4.35	400	6.5	14	10.0	50	0.9
9/12/77	4.7	500	6.5	14	12.5	30	0.6

For the first data run, shown in Table I, we injected up to 400 A D^0 at a mean energy of 14 keV into a 6.7-kG vacuum field (mirror ratio = 2.0) achieving an estimated $\xi = 0.4$. Subsequently, we attempted to reverse a lower vacuum-field strength of $B = 4.35$ kG (mirror ratio = 1.8); this produced the best result ($\xi = 0.9$).

Reducing the field further is not effective because it lowers the electron temperature (not unless the mirror ratio is held constant) and results in poor ion confinement owing to Spitzer drag. This trend can be seen in the first two rows of Table I, where T_e dropped from 75 to 50 eV as B_{vac} decreased from 6.7 to 4.35 kG and where the increased Spitzer drag caused $\bar{E}_i$ to drop from 14.5 to 11.8 keV.

The next series of experiments sought to improve ξ by raising T_e . Our motivation for increasing T_e was twofold. First, the ion energy loss rate of the earlier experiments could be accounted for by classical Spitzer drag on the electrons, and this was reduced by raising T_e . Second, the particle-simulation computer code SUPERLAYER¹⁸ predicted an increase in ξ for an increase in T_e , provided the ion loss rate was dominated by Spitzer drag. We raised T_e by increasing the neutral-beam injection current to 500 A (primarily by installation of improved neutralizers), by using stabilizing streaming-plasma injectors on the radial boundary of the plasma rather than the center, and by returning to the 6.7-kG vacuum field. As can be seen in the third row of Table I, $T_e = 130$ eV was attained, a nearly two-fold increase compared with the earlier experiment at 6.7-kG; the estimated ξ increased 50% to 0.6. However, the field reversal attained was not as high as the $B_{vac} = 4.35$ -kG experiment and it fell below the expectation of the SUPERLAYER code,¹⁸ which predicted $\xi > 1$ for $T_e = 130$ eV and $I_{beam} = 500$ A.

Examining the data in more detail reveals that ion-energy confinement, although improved compared with the earlier experiments at lower T_e , does not continue to increase with increasing T_e above $T_e \approx 80$ eV, contrary to what would be expected if classical Spitzer drag were dominant. The saturation of ion-energy confinement correlates with an increasing level of ion-cyclotron fluctuations having the same spectral character as the fluctuations stabilized by streaming-plasma injection. This suggests the presence of ion losses due to the DCLC mode.

The experiments summarized in Table I indicate the way to attain increased field reversal by neutral-beam injection into a mirror machine. T_e should be increased, thus reducing ion losses due to classical Spitzer drag. Simultaneously, fluctuations due to

the DCLC mode should be suppressed, so that Spitzer drag is the dominant ion-loss process. Recent experiments on 2XIIIB, at a lower ξ than reported here, indicated that T_e may be raised independently of the magnitude of B_{vac} by increasing the mirror ratio.

In addition to exploring combinations of the stream-gun and gas-box stabilization methods, we may consider electron-beam stabilization recently reported by Klinkowstein and Smullin at MIT¹⁹, or we may consider field reversal in a mirror end cell of the Tandem Mirror Experiment (TMX),²⁰ with the end cell stabilized by the Maxwellian solenoidal plasma. Other possibilities for field reversal in a mirror machine include using one of the fast-pulsed methods—electron beam, field-reversed theta pinch—to create a field-reversed target for neutral-beam trapping.

Since the experiments described here were initiated, there was an intensive theoretical effort²¹ to assess the requirements of reaching field reversal by neutral-beam injection into a mirror machine. We aimed these investigations primarily at the question of electron cancellation of the ion current at the field null $B = 0$. We demonstrated that (1) for a field-reversed state to exist, a finite current density must flow at the field null; (2) in a fully ionized

deuterium plasma, finite current at the null requires an admixture of high-atomic-number (Z) ions; (3) for $\xi = \Delta B/B < 1$ (i.e., a field null does not exist), electron currents may be ignored as in the present SUPERLAYER simulation work; and (4) for $\xi = \Delta B/B > 1$, electron currents must be included in a simulation of fully ionized plasmas. The role of the high- Z ions is to scatter the electrons, preventing them from being accelerated up to the mean ion velocity of the $Z = 1$ component. A rough prescription, given by Baldwin and Fowler, to achieve field reversal in 2XIIIB-like conditions is that plasma radius equals four vacuum-field Larmor radii (about twice the radius of present experiments) and that the injection current or ion-energy confinement be improved a factor of about three.

Field-Reversal Experiment

The plasma in the 2XIIIB Experiment (Fig. 1) is driven by 12 Lawrence Berkeley Laboratory, 20-kV, 50-A neutral-beam modules,¹ arranged six on each side of the experiment. Up to 7 MW of neutral-beam power have been injected. For the densest plasmas, 4.5 MW are absorbed by the plasma, 1.5 MW are trapped by ionization, and 3 MW are reradiated as energetic charge-exchange flux. A

Fig. 1. A view of 2XIIIB Experiment, showing the two vacuum vessels that house 12 Lawrence Berkeley Laboratory neutral-beam modules. Also seen are the ceramic high-vacuum chamber, the yin-yang minimum-B coil set, and the streaming-plasma guns used for startup and stabilization.

nonconducting ceramic vacuum chamber surrounds the plasma, which is confined in the minimum-B magnetic well of a yin-yang coil. The plasma is stabilized against ion-cyclotron fluctuations by (1) plasma-stream injection along a solenoidal guide field to the mirror-confined plasma and (2) by gas injection into a box with elliptical apertures just outside the mirror opposite the stream guns.

Figure 2 shows the most important diagnostic equipment for the data reported here. A 90° Thomson-scattering system measures electron temperature (T_e); a 15-channel charge-exchange

analyzer measures ion energy (E_i). Radial scans of T_e can be made from $r = -2$ cm on one side of the vertical plasma midplane to $r = 6$ cm on the other side. The charge-exchange flux can be scanned from $r = -12$ to $+12$ cm. We measure plasma line density with a 2-mm microwave interferometer and plasma-density shape with a crossed array of collimated detectors that measure neutral-beam attenuation along chords through the plasma. Adjacent channel separation is 2 cm for the vertical array and 5 cm for the horizontal array. The spatial resolution of all these diagnostics is 1 cm at the plasma. Plasma

Fig. 2. Principal diagnostic equipment used on 2X11B.

diagnetism is measured by a large loop wound around the vacuum-chamber wall and three small loops inside a thin wall tube 25 cm from the plasma axis. Since the area of the large loop is $\sim 1 \text{ m}^2$ compared with a typical plasma cross section $\sim 150 \text{ cm}^2$, the large loop measures the total plasma magnetic dipole moment and is insensitive, for constant dipole moment, to changes in scale length of the order of plasma dimensions. The small loops at $r = 25 \text{ cm}$ and $z = 0, 8$, and 22 cm are sensitive to the radial and axial scale lengths of the plasma-current distribution. We aim the neutral-beam injectors and measure the neutral-beam injected power with a calorimeter that can be extended into the plasma-confinement region.

For experiments that have obtained the highest field-reversal parameter, the neutral beams from opposite sides of the experiment are offset $\Delta = 4 \text{ cm}$, as in Fig. 3(a), so that ions tend to be trapped on orbits encircling the magnetic axis. Head-on injection with $\Delta = 0$, as in Fig. 3(b), improves beam-trapping efficiency but results in increased plasma radius; so the field reversal attained is less than in Fig. 3(a). Calorimeter profiles of injected beam power, averaged over the six beams on each side, appear in Fig. 4. The $7 \times 35\text{-cm}$ extraction grids of the beam modules are oriented with the 7-cm slots in the vertical direction so the vertical height of the

beam footprint at the plasma is much smaller than the horizontal width. The vertical profiles have a 3-cm halfwidth measured to the $1/e$ point so that the beams are well focused compared with the 4-cm vertical offset.

Experimental Data. In this section we will present the experimental data regarding field reversal: the scaling of plasma line density, mean plasma radius (R_p), peak plasma beta (β), and estimated field reversal parameter (ζ) = $\Delta B/B_{vac}$ with injected neutral-beam current (I_{beam}). To satisfactorily understand this data, particularly the degree of field reversal achieved, requires a theoretical model compatible with all the observations. Such a complete theoretical simulation does not presently exist; this poses some difficulty in organizing the remainder of the data to be presented in a useful way.

Ion confinement is clearly important since, if magnetohydrodynamic stability is assumed, it plus the injected beam power will determine the degree of field reversal achieved. For this reason, we present the scaling of electron temperature (T_e) with I_{beam} so the classical Spitzer flow of energy from ions to electrons can be calculated. We also compute the mean ion-energy confinement parameter ($\langle n\tau \rangle_{E_i}$). It will then become apparent that $\langle n\tau \rangle_{E_i}$ does not scale as the classical $T_e^{-3/2}$; in particular, above $T_e \approx 80 \text{ eV}$, $\langle n\tau \rangle_{E_i}$ is nearly independent of T_e . Similarly, a simple rate equation for the ion power balance based on the scaling of line density with I_{beam} implies that ion-energy confinement is not limited by electron drag. This leads to consideration of ion-loss mechanisms other than electron drag.

One possibility is that the drift-cyclotron loss-cone mode at the high densities reported here was

Fig. 3. Beam-injection arrangement. (a) For field-reversal experiments, the beams were aimed tangentially with a vertical offset of $\pm 4 \text{ cm}$ that trapped ions on orbits encircling the magnetic axis, thus producing diamagnetic currents. (b) In comparison, head-on injection improves the beam trapping but results in lower diamagnetic currents.

Fig. 4. Beam-injection profiles. (a) Vertical profiles have a 3-cm halfwidth measured to the e-folding point. (b) Horizontal profiles have an 18.5-cm halfwidth measured to the e-folding point.

not sufficiently stabilized with the present stream guns and gas-feed system; so there were additional ion losses due to ion-cyclotron fluctuations. Evidence of this is the amplitude of ion-cyclotron oscillations detected by a 2-mm microwave beam that increases with increasing T_e .

Secondly, recent electron-ring experiments at Cornell²² have identified an anomalous electron-loss rate dependent on the strength of the quadrupole field. Since the minimum-B field strength of the 2XIIB Experiment has a large quadrupole component, it has been suggested²² that this quadrupole loss may appear here as an ion loss. In an experiment reported later (see "Variation of Quadrupole Component of Vacuum Magnetic Field"), we have varied the strength of quadrupole field but have not observed a significant variation of ion confinement.

Plasma Line Density, Plasma Radius, Beta, and Field-Reversal Parameter. Figure 5 provides scaling of plasma line density and mean plasma radius with

neutral-beam injection current (I_{beam}) for two values of central-vacuum magnetic-field strength, $B_{\text{vac}} = 4.35$ and 6.7 kG. For these experiments, the solenoidal-guide field was 2 kG with the remaining field supplied by the yin-yang coil. The mirror ratio at radial position, $z = \pm 75$ cm is $R = 1.8$ and 2.0 for the central field's 4.35 and 6.7 kG, respectively. This data was taken with the tangential beam-aiming arrangement shown in Fig. 3(a). For both sets of data, the line density increases approximately linearly with I_{beam} as it increases by a factor of two. Mean plasma radius, defined as the 1/e point of the line-density profiles, is nearly independent of I_{beam} for $B_{\text{vac}} = 4.35$ kG and increases slowly with I_{beam} for $B_{\text{vac}} = 6.7$ kG. Data for head-on beam injection, as in Fig. 3(b) and with $B_{\text{vac}} = 6.7$ kG, showed similar scaling. The mean plasma radius, however was larger, i.e., $R_p \approx 11.5$ instead of 6.5 cm. The maximum line density was the same as for tangential injection.

Beta. The data in Fig. 5 can be combined with

Fig. 5. Plasma line density and radius for two vacuum magnetic-field strengths, with tangential beam aiming as seen in Fig. 3(a). (a) Line density increases linearly with neutral-beam current; (b) Plasma radius increases slowly or is independent of beam current.

charge-exchange measurements of mean ion energy ($\bar{E}_i$) to compute the peak plasma beta ($\hat{\beta}$) at $r = 0$ according to the formula

$$\hat{\beta} = 8\pi \frac{\hat{E}_i}{B_{vac}^2} = 8\pi \frac{\int n dl}{\sqrt{\pi} R_p} \frac{\bar{E}_i}{B_{vac}^2} \quad (1)$$

The scaling of $\hat{\beta}$ with beam current (I_{beam}) is in Fig. 6. Since $\bar{E}_i$ and mean plasma radius (R_p) did not change appreciably with increasing I_{beam} , the variation of $\hat{\beta}$ vs I_{beam} comes from the linearly increasing line density (ndl). For both values of vacuum magnetic-field strength (B_{vac}), $\hat{\beta}$ increases with I_{beam} reaching $\hat{\beta} \approx 2.2$ for $B_{vac} = 4.35$ kG and $\hat{\beta} \approx 1.2$ for $B_{vac} = 6.7$ kG. There is no evidence of a saturation of $\hat{\beta}$ as I_{beam} increases. It is noteworthy that reducing B_{vac} resulted in higher $\hat{\beta}$. This is evidence that a $\hat{\beta}$ -limit has not been reached in the high-field $B_{vac} = 6.7$ -kG experiment, in which case $\hat{\beta}$ would have decreased by a factor $(6.7/4.35)^2 \approx 2.4$ as the field was lowered.

Models of field-reversal parameter. For a plasma with an axial scale length (L_p) that is large compared with the radial scale length (R_p), or equivalently negligible field-line curvature near the plasma midplane, $\beta > 1$ would imply $\Delta B/B_{vac} > 1$ on axis. For the plasmas under consideration, since we have $L_p/R_p \sim 2.5$, it is essential that the finite length be taken into account when estimating the field-reversal parameter ($\Delta B/B_{vac}$). This has been

done with two simple models, both yielding essentially the same result.

The first is an equivalent-cylinder model of the plasma-current distribution, supposing that the current flows in a thin cylinder of radius R_p and length $2L_p$ with a total magnetic dipole moment (m) $= I\pi R_p^2$, where I is the total circulating current. For this model

$$\frac{\Delta B}{B_{vac}} = \frac{1}{B_{vac}} \frac{\mu_0}{2\pi} \frac{m}{R_p^2 \sqrt{R_p^2 + L_p^2}} \quad (2)$$

Here R_p and L_p are taken as the $1/e$ halfwidths of line-density profiles. The total m is related to the measured large diamagnetic loop voltage by

$$V_{loop} = \frac{1}{RC} \sqrt{\pi} \mu_0 \frac{m}{(4h^2 + \pi l^2)^{3/2}}, \quad (3)$$

where $RC = 0.1$ s is the integration constant and h and l refer to the large diamagnetic loop dimensions shown in Fig. 7.

The second model is a rigid rotor, supposing that the observed approximately Gaussian plasma line-density profiles rotate about the plasma axis at a frequency $\Omega < \omega_{ci}$, leading to a field change on axis:

$$\frac{\Delta B}{B_{vac}} = \frac{1}{B_{vac}} \frac{\mu_0}{2\pi} \frac{m}{R_p^3} \left(\frac{L_p}{R_p} \right), \text{ where } \quad (4)$$

Fig. 6. In this comparison of low and high fields, peak plasma beta increases with beam current, $\hat{\beta} = 8\pi \hat{E}_i / B_{vac}^2 = 8\pi \int n dl / \sqrt{\pi} R_p \cdot B_{vac}^2$.

Fig. 7. Large diamagnetic-loop geometry. (a) Diamagnetic-loop of Fig. 2 is shown with m equal to the total plasma dipole moment, $h = 64.8$ cm, and $H = 38.1$ cm. (b) With an equivalent circular loop of radius $R_{\text{Loop}} = h/\sqrt{2}$, the total magnetic flux, $\Delta\phi = \int \Delta\mathbf{B} \cdot d\mathbf{a}$, can be equated to $\Delta\phi = 4\pi \mu_0 m h^2 / (4h^2 + \pi R_{\text{Loop}}^2)^{1/2}$.

$$\frac{1}{R_p} \left(\frac{L_p}{R_p} \right) = \frac{4}{\sqrt{\pi}} \int_0^{\infty} \frac{d\eta}{\eta^2 + \epsilon^2} \int_0^{\infty} d\eta \left[\frac{\eta^3 e^{-\eta^2 - \eta^2}}{\eta^2 + \epsilon^2} \right]^{3/2} \quad (5)$$

and where m , R_p , and L_p are as before.

For a typical aspect-ratio $L_p/R_p \approx 2.5$, estimates of $\Delta B/B_{\text{vac}}$ (according to the two models) differ by only 3%, which is insignificant compared to shot-to-shot fluctuations of R_p and uncertainty of the axial hot-plasma scale length.

Line-density profiles. The radius and length of the plasma-current distribution are needed to estimate the field-reversal parameter ($\Delta B/B_{\text{vac}}$) using Eqs. (2) or (5). In this section we present typical beam-attenuation measurements of radius and length of the plasma line-density distribution. In the next section we infer the radius and length from the small magnetic-probe measurements.

Figure 8 shows typical line-density profile data obtained by beam attenuation. The radial line-density data are fit to a Gaussian profile shape $F_0 \exp[-(x - x_0)^2/R_p^2]$ with the peak line density (F_0), plasma center (x_0), and radial scale length (R_p) as free parameters. Density is related to line density by Abel inversion. Since the Abel inversion of a Gaussian function is again Gaussian with the same

e-folding width, the radius (R_p) that we calculate by a reasonable Gaussian fit to line density yields the density radius. The axial line-density profile is more difficult to interpret because it consists of two components—a hot-ion component centered at axial distance, $z = 0$ and a cold-streaming component. We have also observed axial density profiles similar to Fig. 8(b) in computational work simulating the cold-streaming plasma.²³ Often the kink at the $z = 10$ -cm probe position in Fig. 8(b) is not observed, and the axial line-density data decrease smoothly from $z = 0$ to 25 cm. If the sides of the peak centered at $z = 0$ are simply extrapolated to zero, an axial e-folding length $L_p \approx 13$ cm is inferred. This length is somewhat shorter than that inferred from magnetic-loop probe data discussed below. Ad-

Fig. 8. Typical line-density profile data obtained from beam attenuation. (a) The radial line density data are fit to Gaussian profiles. Data shown have a 6.5-cm e-folding scale length. (b) The axial line density data does not appear Gaussian due to its two-component nature: a hot-ion component centered at $z = 0$ and a cold-streaming component flowing in from the ends. Square blocks indicate corrections to the data for vacuum-field-line fanning.

ditional uncertainty arises from the effects of field-line fanning due to the minimum-B vacuum field strength. The line-density measurements from $z > 0$ in Fig. 8(b) are in the plane of the fanning field lines and, therefore, indicate larger line densities than appropriate for an equivalent-cylinder model of the plasma. The correction to be applied to the data is uncertain because of the finite- β (plasma pressure/magnetic pressure) distortion of flux tubes. An upper limit, calculated for the vacuum-field lines, is indicated by the x's on Fig. 8(b).

Small magnetic-loop data. A second estimate of the scale lengths appropriate for estimating the field-reversal parameter ($\Delta B/B_{vac}$) came from three small magnetic-loop probes at $r = 25$ cm and axial distance, $z = 0, 8.6$, and 21.8 cm. Data from these probes were only available for vacuum field strength (B_{vac}) = 4.35 kG and injected-beam current (I_{beam}) = 400 A (Fig. 9). We plotted the change in the axial component of magnetic-field strength at the probe vs axial-probe position. The data were with the rigid-rotor model, with the central line density and total magnetic moment constrained to the observed values, $1.3 \times 10^{15} \text{ cm}^{-2}$ and $14 \times 10^6 \text{ A} \cdot \text{cm}^2$, respectively. The radius and length were free parameters. The current distribution for this model was given by the formula

$$j(r, z) = en(0) \Omega r \exp\left(-\frac{r^2}{R_p^2}\right) \exp\left(-\frac{z^2}{L_p^2}\right) \quad (6)$$

Fig. 9. Plasma magnetic-field strength measured by three small magnetic-loop probes at $r = 25$ cm are plotted against the axial position of the three probes. Plasma scale lengths of $R_p = 6.8$ cm and $L_p = 38$ cm are derived from a best fit to the data from a rigid-rotor model of the diamagnetic currents.

The solid curve in Fig. 9 was the best fit obtained for radial scale length (R_p) = 6.8 cm and axial scale length (L_p) = 18 cm, giving a rotation frequency $\Omega/\omega_{ci} = 0.35$. Changes of radius and length ($\Delta R_p = \pm 1$ cm and $\Delta L_p = \pm 2$ cm) caused the fitted curve to fall outside the error bars of the data points. The radius determined this way agreed well with the radial line density. This gave us confidence that the radial line-density profiles provided an adequate measure of plasma-current distribution. The axial scale length agreed numerically with the e-folding axial halfwidth of the injected beam-current profile (Fig. 4). For all of the estimates of $\Delta B/B_{vac}$ discussed below, the cylinder formula discussed above [Eq. (2)] was used where R_p was taken from the line-density profile and $L_p = 16$ cm, about halfway between the value determined by this fit to the loop-probe data and that determined by the central peak in the axial line-density profile in Fig. 8(b).

Numerical estimates of field-reversal parameter. Figure 10 has estimates of field-reversal parameter ($\Delta B/B_{vac}$ vs injected-beam current (I_{beam}), for vacuum field strength (B_{vac}) = 4.35 kG. $\Delta B/B_{vac}$ increases approximately linearly with I_{beam} , reaching an average value $\Delta B/B_{vac} = 0.9 \pm 0.2$ at $I_{beam} = 400$ A. Changes in scale lengths ($\Delta R_p = \pm 1$ cm and $\Delta L_p = \pm 2$ cm) correspond to changes in $\Delta B/B_{vac}$ by ± 30 and $\pm 10\%$, respectively. The data at $B_{vac} = 6.7$ kG show a similar approximately linear increase of $\Delta B/B_{vac}$ with I_{beam} , reaching an average value $\Delta B/B_{vac} = 0.6 \pm 0.1$ at $I_{beam} = 500$ A. For the $B_{vac} = 6.7$ kG case we also took data with head-on beam injection [Fig. 3(b)]; the data appear as open triangles in Fig. 10.

Compared with tangential-beam injection, the field-reversal parameter was reduced by a factor of 2.4, reaching $\Delta B/B_{vac} = 0.25 \pm 0.1$ at $I_{beam} = 500$ A. For constant dipole moment, the reduction factor would be expected to be 3.5 since R_p increased from 6.8 to 11.5 cm in going from tangential to head-on injection. The total magnetic dipole moment increased from 14×10^6 to $20 \times 10^6 \text{ A} \cdot \text{cm}^2$, however, accounting for the factor 2.4.

Ion Confinement. Electron temperature (T_e) is plotted vs neutral-beam current (I_{beam}) in Fig. 11. For the vacuum-field strength (B_{vac}) = 6.7-kG data, T_e increased approximately linearly with I_{beam} . T_e also increased with increasing I_{beam} for $B_{vac} = 4.35$ kG there was considerably more scatter in the data points. Raising B_{vac} from 4.35 to 6.7 kG caused T_e to increase roughly a factor of two, implying a dependence of T_e on total field strength or vacuum mirror ratio (which increased from $R = 1.8$ to 2.0).

The scaling of T_e with I_{beam} agreed with an

Fig. 10. Estimated field-reversal parameter $\zeta = \Delta B/B_{vac}$ vs injected neutral-beam current, I_{beam} . $\Delta B/B_{vac}$ can be inferred from the total plasma dipole moment, m , the plasma radius, R_p , and the plasma axial length, L_p , from the expression $\zeta = \mu_0 / 2\pi B_{vac} m / R_p^3 \sqrt{1 + L_p^2 / R_p^2}$. ζ increases approximately linearly with I_{beam} .

electron-power balance that equated the flow of energy from ions to electrons with the power carried out by electrons produced by ionization in the gas box:

$$\int \frac{n W_i}{T_e} d^3x = \eta T_e I_{gas} \quad (7)$$

where $n\tau_{ie} = 4.4 \times 10^7 T_e^{3/2}$ for deuterium plasmas, T_e is in eV, I_{gas} is the neutral-atom current fed into the gas box, and η is a proportionality constant describing the multiple of T_e each electron carried to the wall. The equation predicts $T_e \sim n^{4/5} W_i^{2/5}$ or $T_e \sim I_{beam}^{4/5}$ for $n \sim I_{beam}$ as in Fig. 5; W_i is independent of I_{beam} (Fig. 12). The $4/5$ scaling of T_e was consistent with the data in Fig. 11. We obtained the T_e data displayed in Fig. 11 at $r = 0$ cm. Radial scans of T_e in 2-cm intervals from $r = -2$ to $+6$ cm at $I_{beam} \approx 400$ A for the $B_{vac} = 4.35$ -kG data and $I_{beam} \approx 500$ A for the $B_{vac} = 6.7$ -kG data, revealed that the T_e profile was essentially flat over this spatial range.

Mean-ion-energy confinement parameter. The mean-ion-energy confinement time was the total plasma-ion energy divided by the trapped neutral-beam power:

$$\tau_{E_i} = \frac{\int n_i(x) W_i d^3x}{P_{trapped\ beam}} = \frac{\pi \sqrt{\pi} R_p^2 l_p n_i(0) W_i}{P_{trapped\ beam}} \quad (8)$$

where we assumed Gaussian shapes for the plasma-density profile $n_i(x) = n_i(0) \exp(-x^2/R_p^2) \exp(-x^2/L_p^2)$ and W_i independent of x . Multiplying τ_{E_i} by the mean ion density ($\langle n_i \rangle = \int n_i^2 d^3x / \int n_i d^3x = n_i(0)/2\sqrt{2}$ defined the mean-ion-energy confinement parameter ($\langle n\tau_{E_i} \rangle$):

$$\langle n\tau_{E_i} \rangle = \frac{1}{2} \sqrt{\frac{\pi}{2}} \frac{(\int ndl)^2 l_p W_i}{P_{trapped\ beam}} \quad (9)$$

where $\int ndl = \sqrt{\pi} R_p n(0)$ is the line density measured through the center of the plasma. The trapped beam power contained contributions from

Fig. 11. Measurements of electron temperature, T_e , vs incident neutral-beam current, I_B , show T_e increasing approximately linearly with I_B . For $B_{vac} = 4.35$ kG, the increase in scatter among the data points may be due to poorer vacuum conditions or wall effect or both.

ionization of the neutral beam and from charge-exchange replacement of a plasma ion by a beam-injected neutral particle:

$$P_{\text{trapped beam}} = f_{\text{ioniz}} I_{\text{beam}} W_{\text{beam}} + (f_{\text{abs}} - f_{\text{ioniz}}) I_{\text{beam}} (W_{\text{beam}} - W_p). \quad (10)$$

The parameters f_{abs} and f_{ioniz} are the fractions of incident neutral-beam current (I_{beam}) absorbed by the plasma and trapped by ionization, respectively. The difference $f_{\text{abs}} - f_{\text{ioniz}}$ is the fraction of the incident-beam current reradiated from the plasma as charge-exchange neutrals with mean energy W_p . We calculated the fractions f_{abs} and f_{ioniz} by integrating beamlets over the spatial distribution of the injected-current profiles (Fig. 4) for a specified center-plasma density $n(0)$ and Gaussian scale lengths R_p and L_p . Our calculation included ionization after multiple charge-exchange collisions. At the highest electron temperature ($T_e \approx 130$ eV ($I_{\text{beam}} W_{\text{beam}} = 7$ MW)) we estimated that $f_{\text{abs}} = 0.61$ of the beam current was absorbed by the plasma and $f_{\text{ioniz}} = 0.23$ of the beam was trapped by ionization. The energy content of the plasma ions for these shots was $W_{\text{plasma ions}} = \int n W_p d^3x = 1100$ J.

In Fig. 13 we plot $\langle nr \rangle_{F_1}$ calculated according to Eq. (9) for the $B_{vac} = 4.35$ -kG data (open triangles) and $B_{vac} = 6.7$ -kG data (closed circles). If classical drag of ions on the cooler electrons is the dominant ion loss, then $\langle nr \rangle_{F_1}$ would be expected to follow Spitzer's relation $\langle nr \rangle_{F_1} = 4.4 \times 10^7 (T_e)^{3/2}$, for deuterium with T_e in eV, plotted as the dashed line in Fig. 13. Comparing the $B_{vac} = 4.35$ -kG data at low T_e with the $B_{vac} = 6.7$ -kG data at higher T_e we note a general trend of $\langle nr \rangle_{F_1}$ improving as T_e increases. Above $T_e \approx 80$ eV, however, $\langle nr \rangle_{F_1}$ appears to flatten as T_e increases. One may expect, therefore, that the field-reversal parameter at the highest T_e points (and, therefore, highest I_{beam}) for $B_{vac} = 6.7$ -kG will fall below predictions that assume electron drag is the dominant ion-loss mechanism (see the upcoming discussion that compares SUPERLAYER calculations with experimental results). Even below $T_e \approx 80$ eV, however, the detailed agreement with the Spitzer result in both absolute magnitude and power-law dependence is not satisfactory. The $B_{vac} = 4.35$ -kG

Fig. 12. Measurements of the mean ion energy, W_p , vs incident neutral-beam current show W_p to be independent of I_B .

Fig. 13. Experimentally determined values of the volume average ion energy containment, $n\tau_E = 1/2 \int_0^R \langle n\tau \rangle r dr / \int_0^R n_r r dr$, are plotted vs. measured values of the electron temperature, T_e , for 2 different values of the vacuum magnetic field. The flattening of $\langle n\tau \rangle$ above $T_e \approx 80$ eV occurs simultaneously with an increase of the fluctuations near the ion-cyclotron frequency indicated by open circles.

$\langle n\tau \rangle_{T_e}$ data all fall above the Spitzer result, which is not understood.

A clue possibly explaining the flattening of $\langle n\tau \rangle_{T_e}$ above $T_e \approx 80$ eV is provided by the amplitude of ion-cyclotron oscillations detected by phase modulation of a 2-mm microwave beam shown in Fig. 13 (indicated by open circles). Spectral analysis of these fluctuations shows that they are centered in a narrow band at the fundamental of the ion-cyclotron frequency. They are, therefore, similar to the fluctuations previously measured in detail. Also, they have a deleterious effect on ion confinement and a wave-number consistent with the drift-cyclotron loss-cone mode.²⁴

Evidence that there are ion losses in addition to electron drag may also be inferred from the scaling of plasma line density (Fig. 5) and T_e (Fig. 11) with I_{beam} . A simple rate equation for the ion-power

balance is

$$\begin{aligned} \frac{d}{dt} \int d^3x n W_i &= \int dxdz \frac{J_{beam}}{c} W_{beam} [1 - e^{-\sigma_1 f n dy}] f_{ioniz} \\ &+ \int dxdz \frac{J_{beam}}{c} [W_{beam} - W_i] [1 - e^{-\sigma_1 f n dy}] \\ &+ (1 - f_{ioniz}) - \int d^3x \frac{n^2 W_i}{\langle n\tau \rangle_{T_e}} \end{aligned} \quad (11)$$

J_{beam} is the injected neutral-current density, normalized so that $I_{beam} = \int dxdz J_{beam}$; f_{ioniz} is the fraction of absorbed beam particles trapped by

ionization. In the thin-plasma limit $\sigma_T \text{Indy} < 1$, Eq. (10) predicts in steady state,

$$I_{\text{beam}} n(0) \sim \frac{n^2(0)}{(\pi r)_{E_i}} \quad (12)$$

and in the thick plasma limit $\sigma_T \text{Indy} \gg 1$,

$$I_{\text{beam}} \sim \frac{n^2(0)}{(\pi r)_{E_i}} \quad (13)$$

If $(\pi r)_{E_i} = 4.4 \times 10^7 T_e^{3/2}$, appropriate for electron-drag-dominated confinement, then in the thin plasma, $n(0) \sim I_{\text{beam}} T_e^{3/2} \sim T_e^{5/2}$; whereas in the thick plasma limit, $n(0) \sim [I_{\text{beam}} T_e^{3/2}]^{1/2} \sim I_{\text{beam}}^{1/2}$. We have assumed $T_e \sim I_b$ (as in Fig. 11). Both limits predict $n(0)$; therefore, $\text{Indy} = \sqrt{\pi} R_p n(0)$, which increases faster than linearly with I_{beam} in contrast with the nearly linear increase in Fig. 5.

Comparison of Experimental Results with SUPERLAYER-Code Simulation. Our most detailed attempt to theoretically describe the 2XIIB experimental results was simulations by the SUPERLAYER code.^{18,23} This code computed the self-consistent magnetic field from ion orbits in their own self field plus an applied axisymmetric mirror field. The ion orbits were followed in five phase-space dimensions—three velocity coordinates and radial and axial spatial coordinates. The simulated plasma built up by neutral-beam trapping on a cold target. We chose the geometry, energy distribution, and ionization and charge-exchange cross sections to accurately model the 2XIIB neutral-beam injectors. Electrons were treated as a charge-neutralizing background with a specified temperature (T_e). The effect of electrons on the ions was included as Spitzer velocity drag in the ion equation of motion.

In the present SUPERLAYER version the electrons do not carry current, so electron cancellation on closed field lines is not assessed. Line tying is believed to prevent electron return-current cancellation on open field lines, so the code calculations are thought to be reliable in this respect up to the condition $\Delta B/B_{\text{vac}} = 0$, which includes the range of 2XIIB data.

Ion-cyclotron oscillations due to the drift-cyclotron loss-cone modes are treated by a Monte Carlo method²⁶ that includes diffusion due to a specified constant-wave amplitude in the particle motion. This calculation is not done self-consistently with the wave amplitude and growth rate dependent on the shape of the velocity distribution and radial density gradient as with the

quasilinear codes.²⁷ Including the ion-cyclotron oscillations, this way does not have a large effect in altering the ion-energy confinement, but it does change the ion-energy distribution compared with a purely electron-drag-dominated situation. The amplitude of wave oscillation is empirically adjusted until the mean ion energy of the simulation is close to the experimental result. For the code calculations to be practical, it is necessary that all time scales—beam-trapping rates, electron-drag rate, wave-diffusion time—be accelerated by a constant multiplicative factor of the order of 100 compared with the ion-cyclotron motion. With this acceleration factor, the ions execute several axial bounces in a confinement time. For the simulations presented here, orbits of approximately 2×10^4 "super" particles are followed for 40 ion-cyclotron orbits with 30 times steps per orbit. This length of time is sufficient for the simulation to reach a steady state. A typical code run takes 30 min to execute on a CDC-7600 computer.

The code calculations that we will present include predictions of the field-reversal parameter (ζ) = $\Delta B/B_{\text{vac}}$ vs injected-beam current (I_{beam}) $T_e^{3/2}$ (i.e., the ratio for the ion-trapping rate to loss rate), a point comparison of simulation and plasma parameters at $\zeta \approx 1$ for the $B_{\text{vac}} = 4.35$ -kG data, and a comparison of charge-exchange-analyzer energy spectra and spatial scan of charge-exchange flux and mean ion energy. The latter are important because they contain detailed information on the ion orbits that generate the field-reversing current.

The SUPERLAYER prediction of $\zeta = \Delta B/B_{\text{vac}}$ vs $I_{\text{beam}} T_e^{3/2}$ is shown in Fig. 14 together with the experimental data for $B_{\text{vac}} = 4.35$ and 6.7 kG. The experimental data at $B_{\text{vac}} = 4.35$ kG reasonably agree with the scaling and absolute magnitude of ζ achieved. The high-field $B_{\text{vac}} = 6.7$ -kG data disagree, falling about a factor of two below the code prediction. The difference between the two cases is likely due to dominance of electron drag for the low-field data (which is properly treated in the SUPERLAYER calculations) and the increasing importance of wave diffusion for the higher field, higher electron temperature data (which is not treated self-consistently in the SUPERLAYER calculations).

Table 2 compares simulation and plasma parameters for the $B_{\text{vac}} = 4.35$ -kG case with $I_{\text{beam}} = 400$ A and $\zeta \approx 1$. Density ($\bar{n}$), ion energy ($\bar{E}_i$), and ζ reasonably agree. The plasma shapes of the code results and experimental data differ. The code tends to predict shapes larger in radius and considerably shorter in axial length than those for the experiment.

Fig. 14. Comparison of 2X11B field-reversal parameter $\Delta B/B$ with SUPERLAYER code predictions shows reasonably good agreement at the lower vacuum magnetic field data. (a) Electron drag dominates the energy confinement but in the higher-field data. (b) The agreement breaks down possibly due to the increasing importance of wave diffusion on energy confinement.

Conclusions. We have presented results of experiments directed toward achieving the largest field reversal possible in the 2X11B mirror machine (using our existing set of neutral-beam injectors and the already demonstrated streaming-plasma gun/gas-feed methods of stabilizing ion-cyclotron fluctuations). The experiments have mainly been done at two values of vacuum magnetic-field strength (B_{vac}): 4.35 and 6.7 kG. For both sets of data, the plasma line density and peak plasma beta (β) increased approximately linearly with injected-beam current (I_{beam}) while the plasma radius (R_p)

Table 2. Comparison of 2X11B and SUPERLAYER plasma parameters, where $B_{vac} = 4.35$ kG, $I_{beam} = 400$ A (tangential injection), and $T_e = 50$ eV.

Parameter	2X11B experiment (4/14/77)	SUPERLAYER calculations (RF-17)
E_i (keV)	10.0	10.8
R_p (cm)	6.5	10.0
L_p (cm)	16.0	4.9
$\hat{n} = \frac{fndI}{\sqrt{\pi}R_p} (\text{cm}^{-3})$	1.0×10^{14}	0.95×10^{14}
$\xi = \frac{\Delta B}{B_{vac}}$	0.9	1.1

remained constant, indicating that a β limit had not been reached up to the highest values of I_{beam} .

The best field-reversal result was obtained at the lower field setting $B_{vac} = 4.35$ kG, achieving $\hat{\beta} = 8\pi n^{(i)} \bar{E}_i / B_{vac}^2 = 2.2$ and an estimated field-reversal parameter (ξ) = $\Delta B/B_{vac} = 0.9$ at 400 A equivalent injected-beam current. For the $B_{vac} = 6.7$ -kG experiment, the corresponding parameters were $\hat{\beta} = 1.2$ and $\xi = 0.6$ at $I_{beam} = 500$ A. Electron temperature (T_e) increased approximately linearly with I_{beam} , reaching $T_e = 130$ eV at $I_{beam} = 500$ A; since $\xi < 1$, it was not possible to observe the large increase in T_e expected if internal closed-field lines had been formed.

For the $B_{vac} = 6.7$ -kG data, the ion-energy confinement parameter ($\langle n\tau \rangle_{ij}$) reached $2.5 \times 10^{10} \text{ cm}^{-3} \cdot \text{s}$ at $T_e = 80$ eV; it no longer continued to improve as T_e increased. An increasing amplitude of ion-cyclotron oscillations suggested that there were ion losses (in addition to electron drag) due to the drift-cyclotron loss-cone (DCLC) mode. This caused the ξ achieved to be less than that if ion loss were dominated by electron drag alone.

Gross comparisons of the SUPERLAYER simulation code with the field-reversal parameters achieved experimentally showed that the $B_{vac} = 4.35$ -kG data agreed with the simulation prediction, while the $B_{vac} = 6.7$ -kG data fell a factor of two below the prediction. It was not possible to assess the losses due to the DCLC mode with the present version of the SUPERLAYER code. Detailed comparison of experiment and code results indicated disagreement of plasma shape, the ratio of plasma radius to plasma length being $R_p/L_p \approx 2$ in the simulation and $R_p/L_p \approx 0.4$ in the experiment.

Additional experiments demonstrated that the plasma radius and degree of field reversal achieved could be controlled by precise aiming of the neutral-beam injectors. The results summarized above were obtained with the beams aimed tangentially so that trapped ions tended to encircle the axis. Aiming the beams directly at the axis approximately doubled the plasma radius and reduced the estimated ξ a factor of three.

The experimental data suggest that an increased ξ could be achieved by improved stabilization of ion-cyclotron oscillations. In addition to modification of the streaming-plasma gun/gas-feed stabilization method reported here, we may consider electron-beam stabilization¹⁹ or field reversal in a mirror end cell of the Tandem Mirror Experiment,²⁰ with the end cell stabilized by the Maxwellian solenoidal plasma. For future experiments, there is also the possibility of creating a field-reversed target by one of the demonstrated fast-pulsed methods^{11,13-15}

and then using neutral-beam injection to heat the target.

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Thomson-Scattering Measurements

Using a Thomson-scattering system, we measured the dependence of electron temperature (T_e) on various machine parameters for two modes of plasma stabilization: gas box and stream gun. We found that 140-eV electron temperatures at plasma center can be routinely generated; on occasional shots, T_e reached 180 eV. This general increase in electron temperature was attributed to the following: more beam power, improved stream-gun stabilization, and better vacuum conditions. The better vacuum conditions were achieved by using the newly installed liquid-nitrogen-cooled liners.

Improved stream-gun stabilization is associated with the use of stream guns that map into the edges of the plasma. For stream-gun stabilization, T_e can be changed a factor of two by using different stream guns. With gas-box stabilization, the changes due to different stream guns are not as severe. This stream-gun effect is not due to changes of the electron density as measured by Thomson scattering. The

Fig. 1. Measurements of electron temperature, T_e , by Thomson scattering show a linear dependence of T_e on the incident neutral-beam current, I_{beam} .

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Fig. 2. T_e measurements vs the amount of gas-box drawing pressure show no dependence on gas current.

dependence of T_e on beam current (I_{beam}) is seen in Fig. 1. Electron density shows an almost linear dependence on I_{beam} . With the neutral beams aimed tangentially (plasma radius ~ 7 cm), measurements of T_e at radial positions $R = 0$ to 6 cm show it to be nearly independent of R , but slightly lower for $R \geq 4$ cm. With the beams aimed head-on (plasma radius ~ 12 cm), the dependence of T_e on R is very flat out to 6 cm.

For gas-box stabilization the relation of T_e to the gas-flow rate is shown in Fig. 2. Here, T_e is normalized to I_{beam} and plotted against the gas-box driving pressure (proportional to the gas-flow rate). This plot, which ranges from no gas to $\sim 10^{-4}$ A equivalent, shows that T_e is independent of this current. Measurements of electron density also show no dependence on this gas current.

In another series of experiments we changed the gas species while holding the gas-driving pressure constant. For most of the gases used—deuterium, nitrogen, neon, and helium— T_e did not change. However, when we used argon, T_e was reduced by a factor of three. Electron density was also lowered by a similar factor.

When the solenoidal and quadrupole-mirror magnetic fields were independently varied, both the central magnetic field (B_z) and the vacuum mirror

ratio (R_{vac}) could be varied. Unfortunately, in the present experiments, the quadrupole contribution and mirror ratio could not be varied independently; thus their individual effects could not be determined. Figure 3 shows the dependence of T_e on

Fig. 3. T_e measurements show a dependence on the vacuum mirror ratio, R_{vac} . The central magnetic field varied between 4.35 and 8.80 kG.

$R_{vac} = 1$. In this experiment, B_z was also changing. However, another experiment in which B_z was varied while R_{vac} was held nearly constant indicated that over this range of B_z , T_e strongly depended on $R_{vac} = 1$.

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Plasma-Diamagnetism Measurements

We have integrated data from the diamagnetic loop [a single-turn wire around the pyroceram high-vacuum chamber (Fig. 1)] into the computer data-acquisition system of 2XIB. Where in the past it was necessary to compare Polaroid film records to quantify the measurement of plasma diamagnetism, a computer printout is now available after each data shot. The data is presented in its final form, with all necessary compensation being done by the computer. The format appears in Fig. 2.

The magnetic dipole moment of the plasma (m) associated with the measured excluded magnetic flux ($\Delta\phi$) is given by

$$m (10^6 \text{ A} \cdot \text{cm}^2) = 40 \text{ V(mV)}, \quad (1)$$

where $V = \Delta\phi/RC$ (integration time) is the voltage signal displayed as a function of time (Fig. 2). For example, at time 6 ms a value of $V = 0.4 \text{ mV}$ is equivalent to a dipole moment, $m \approx 1.6 \times 10^6 \text{ A} \cdot \text{cm}^2$. For typical plasma radii of about 6.5 cm determined under the field-reversal experimental conditions, this measurement of m implies plasma circulating currents in excess of 10^5 A ($m = I\pi r^2$). The offset from zero after 10 ms displayed in Fig. 2 is due to the variation in shot-to-shot reproducibility of the vacuum magnetic field.

Fig. 1. The diamagnetic loop and its geometrical relationship to the yin-yang coil set and plasma.

Fig. 2. Measurement of the bulk magnetic dipole moment, m , of the plasma as a function of time, where $m (10^6 \text{ A} \cdot \text{cm}^2) = 40 \cdot \text{Voltage Signal, V(mV)}$.

The diamagnetic loop directly measures the total magnetic dipole moment of the plasma. Because of the lack of a direct measurement of the total magnetic field at the plasma center, we used the following model.

Assume that the dipole moment (m) determined by the diamagnetic loop can be approximated by circulating currents at a radius $r = a$ and as extended over a total length ($2l$) in the z direction. The plasma's contribution to the magnetic field at $r = 0$ is given by

$$\Delta B = \frac{\mu_0 m}{2\pi a^3} \frac{1}{\sqrt{1 + l^2/a^2}} \quad (2)$$

At vacuum magnetic fields $B_0 = 6.7$ and 4.35 kG values of ΔB as high as 3.8 kG have been inferred from Eq. (2). In the latter case, the vacuum field was reduced to 13% of its initial value. Although the 2XIB vacuum magnetic field was not reversed, the field-reversal parameter ($\Delta B/B_0$) was increased for $B_0 = 6.7 \text{ kG}$ from a high of 0.3 last fiscal year to a high of 0.7 this fiscal year. We obtained the highest field reversal parameter, $\Delta B/B_0 = 0.9$, at $B_0 = 4.35 \text{ kG}$. A value of $\Delta B/B_0 = 1.0$ marks the onset of field reversal, where the field at $r = 0$ is reduced to zero.

We deduced plasma-current distributions, other than the cylindrically shaped ones already discussed, from simultaneous measurements of the magnetic dipole moment, plasma line density, and three-point measurements of the plasma magnetic field at $r = 25 \text{ cm}$ and at various values along the length of the plasma. The magnetic probe used for these three-point measurements is discussed in detail in the new diagnostics section. Current distributions consistent with these measurements were then modeled and numerically solved for the magnetic field at $r = 0$ by means of a 2-D-axis symmetric code. All the various current distributions,

including the simple cylindrical model, gave the same value of $\Delta B/B_0$ within experimental accuracy.

Author

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Power-Balance Measurements

We increased neutral-beam current to 500 A and injected-beam power to 7 MW. Neutral-beam power was measured by a segmented copper calorimeter. The neutral-beam output contained full-, half-, and third-energy components; consequently, the mean neutral-particle energy was ~ 0.7 of the extraction voltage. From the neutral-beam power and extraction voltage, we determined the neutral-beam current (atom equivalent).

To determine what fraction of the beam power was deposited in the plasma by ionization and charge exchange, we used a small computer code developed by W. Turner. This code took into account multiple ionization events; i.e., it allowed for ionization of charge-exchange products.

Using this code we determined the particle and power balance as shown in Fig. 1. This figure is appropriate for line densities of $1.5 \times 10^{15} \text{ cm}^{-2}$ (as measured on September 12, 1977). In these experiments 125 A was trapped in the plasma. In comparison, the gas feed was 650 A atom equivalent, of which 400 A was required, by quasilinear theory, for stabilization.

Author

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Neutron Measurements

We measured deuterium-deuterium (D-D) neutron emission 3 m from the stabilized 2X11B plasma center, using a lead-shielded plastic scintillation detector (polystyrene plus 2.5% p-terphenyl and 0.03% tetraphenylbutadiene). Integrated neutron emission was measured using a calibrated silver-activation postpulse counting technique that typically gave 3×10^9 neutrons during the 10-ms plasma pulse. Both detectors were simultaneously

Fig. 1. Ion particle balance (a) and ion power balance (b) for a typical field-reversal experimental data shot at a line density of $1.5 \times 10^{15} \text{ particles/cm}^2$.

calibrated with a californium-252 neutron source that had a spontaneous fission neutron spectrum centered on the average energy of 2.35 MeV. The californium-252 neutron average energy was close to the average energy of the 2.45-MeV neutrons from the D-D fusion reactions. We added an unshielded scintillation detector, operating in a counting mode, 8-m from the plasma center and calibrated it by an independent technique. Intercomparison of the results from these three neutron detectors indicated that no extraneous components existed in the reported data, as illustrated by the linearity (Fig. 1) between the silver-activation detector signals and the 8-m scintillation detector.

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Fig. 1. Comparison of data from 8-m scintillation and activated-silver neutron detectors.

Zeeman-Effect Magnetic-Field Diagnostic

We pursued development of a new field-reversed diagnostic that would

- be nonperturbing
- provide a "point" measurement of both the magnetic field strength as well as its direction,
- and have a measurement accuracy expected to be at least 1 kG (although optimistic estimates approached 100 G).

The system will measure the polarization of the wings of a spectral line induced by the unresolved Zeeman splitting of the line. The measurement will be made by exciting fluorescence in the line by two tunable-dye laser beams. We selected the effective wavelengths of these to simultaneously pump opposite wings of the line.

For the first experiments, we will choose an excited state line in helium-iodide. The line width will

be kept narrow by injecting helium in a neutral beam (20 keV), with the laser beams roughly normal to the helium beam but parallel to the magnetic field. In practice the two laser beams actually will have the same wavelength, but will impinge on the neutral beam with a small angle between them. The helium forward velocity will then Doppler shift the effective wavelengths relative to each other. The two laser beams will have opposite senses of circular polarization, senses quickly interchanged halfway through the laser pulse. The resulting change in the fluorescence intensity (monitored through the Thomson-scattering lens system) will then be a direct measure of field strength and direction. The sampled volume will be defined by the intersection of the fluorescence monitor field-of-view and the laser beams. Initial measurements will use helium in one of the Lawrence Berkeley Laboratory 50-A sources; for more precise results, however, J. Osher has developed a well-collimated SARA source to provide an ~ 1 -eV linewidth helium beam.

Author

J. F. Clauser

Faraday Rotation (Interferometer Diagnostic)

We assembled a system that measures magnetic field and plasma density by using submillimeter radiation at $337 \mu\text{m}$ (hydrogen cyanide, gas-discharge laser). Magnetic fields will be determined by measuring the Faraday rotation of the plane of polarization of a linearly polarized probing beam. Measurements of plasma line density will be determined from the phase shift of the same probing beam.

The rotation of the plane of polarization is given by

$$\Delta\psi = 2.63 \times 10^{-14} \lambda^2 \int n \bar{B} \cdot d\vec{r}, \quad (1)$$

and the plasma-fringe shift is given by

$$N_f = 4.38 \times 10^{-14} \lambda \int n d\vec{r}, \quad (2)$$

where the units are cm and kG. The density-weighted, line average of the magnetic field is given by

$$\langle B \rangle = \int n \bar{B} \cdot d\vec{r} / \int n d\vec{r}. \quad (3)$$

Figure 1 shows the path of the probing beam. We have chosen the 45° path to avoid cold, stabilizing plasma, which is exterior to the hot-plasma volume.

Fig. 1. Path of the 337- μ m beam in the 2X11B Experiment.

A corner-cube retroreflector is used so the return beam can retrace its original path, thus minimizing the effects of plasma refraction. Since the sub-millimetre beam passes through the plasma twice, the rotation and phase shift are doubled.

Figure 2 shows a layout of the optics used for the measurement. The laser is remotely located from the 2X11B machine and radiation is propagated to the optics table with a pyrex glass waveguide. The beam is split by beam-splitter S_1 ; the reflected beam (probing beam) passes into the machine and back

out to detectors D_2 and D_3 . Of the portion of the beam transmitted by S_1 a fraction is focused on detector D_1 (reference detector). The remainder is reflected from a rotating grating and is Doppler shifted at 125 kHz. The Doppler-shifted beam is then focused on all three detectors to obtain a beat frequency of 125 kHz.

Detector D_1 produces a constant frequency reference that is compared with the time-changing frequency (due to the time-varying plasma density) of detector D_2 to determine the plasma line density

Fig. 2. Layout of the optics for the Faraday-rotation interferometer.

Fig. 3. Differential detector arrangement used to measure the direction and magnitude of rotation of the plane of polarization.

as a function of time.

Detectors D_2 and D_3 are used in a differential detector arrangement (Fig. 3). The direction of rotation of the plane of polarization is given by the sign of the differential signal.

Fig. 4. The rotation of the plane of polarization, ψ , the plasma fringe shifts, N_f , and the line average of the magnetic field, B_1 , are plotted against the field-reversal parameter, $\Delta B/B$. The data was generated from a rigid rotor model of the diamagnetic plasma currents for a 45° path angle, $B_{vac} = 4.35$ kG, $R_p = 7$ cm and $L_p = 18$ cm.

is normalized to eliminate amplitude changes (due to plasma refraction) in the returning probing beam.

We calculated estimates of the expected rotation and plasma-fringe shift with a computer code that solves Ampere's Law for the magnetic field for a given spatial-current distribution. The calculated result for a Gaussian-profile rigid rotor with radial and axial scale lengths $a = 7$ cm and $l = 18$ cm, respectively, is shown in Fig. 4. The rotation is seen to reach a maximum at the field-reversal parameter $(\Delta B/B) \approx -0.75$; negative rotation occurs for $\Delta B/B = -1.35$ (35% field reversal).

Measurements with this diagnostic will be made during our continuing experiments to reach the field-reversed state in 2X11B.

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New Diagnostics: Magnetic probe

The magnetic probe is an axial array of 100-turn, 1-cm diam by 1-cm length wire loops used to measure the plasma's self-magnetic field at a fixed radial position (r) but at several axial positions in z . Figure 1 in the plasma-diamagnetism measurements section shows the position of the 100-turn loops in relation to the single-turn diamagnetic loop. The small loops are at $r = 25$ cm and $z = 0, 8.6$, and 21.8 cm. Figure 1 of this section provides a photograph of the loops.

Fig. 1. Magnetic probe loops.

Figure 2 displays magnetic-probe data for the $z = 0$ position. In Fig. 2(a) the integrated electromotive force signal (V_0) due to the vacuum magnetic field (B_0) is displayed as a function of time with $V_0 = B_0 \Delta n / RC$, where $\Delta \approx \pi l \text{ cm}^2/4$, $n = 100$, and RC is the integration time. Because the plasma signal is

expected to be only a few parts out of a hundred of the background vacuum-field signal, the vacuum magnetic field is compensated against by monitoring the external currents supplied to the yin-yang coils. Figures 2(b) and 2(c) are the result of a compensated data shot without and with plasma being present, respectively. The difference is shown in Fig. 2(d), where $V_p = B_p \Delta n / RC$, with the plasma's self-magnetic field (B_p) being determined by $B_p/B_0 = V_p/V_0$. For a pulsed magnetic-field level of 2.35 kG (total vacuum field is $4.35 \text{ kG} = 2.35 \text{ kG} + 2 \text{ kG}$ dc guide field), the measurement shown in Fig. 2 indicates a plasma self-magnetic field of $B_p \approx 70 \text{ G}$.

The magnetic probe, by defining the spatial gradient of the plasma's axial magnetic field, allows current distributions within the plasma to be modeled. These distributions are consistent with the measured magnetic dipole moment.

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Fig. 2. Voltage, V_0 , due to the vacuum magnetic field, B_0 , as seen by the uncompensated magnetic probe, $B_p = V_0 RC / \Delta n$. (b) and (c) Data shots without plasma (b) and with plasma (c), where the influence of B_0 on the total magnetic probe signal has been compensated by monitoring the yin-yang coil currents. (d) Voltage, V_p , due to the plasma's magnetic field, B_p , as seen by the compensated magnetic probe, $B_p = V_p RC / \Delta n$.

Reaction-Ion Analyzer Diagnostic

We emphasized solid-state detectors and particle-counting techniques to investigate ions produced from fusion reactions in mirror configurations. These ions leave the plasma region with energies in the MeV range. Preliminary testing of this diagnostic was carried out on 2X11B, with applications to the Tandem Mirror Experiment and the Mirror Fusion Test Facility considered. The ions produced in deuterium-deuterium (D-D) fusion reactions are 3.02-MeV protons, 1.01-MeV tritons, and 0.82-MeV helium-3. To date, we have detected the protons.

We used silicon surface-barrier, semiconductor detectors to readily record energetic-reaction ions. These compact detectors can function in an environment that includes high magnetic field, good vacuum, and low temperature. They produce an output voltage proportional to the energy deposited in the detector by the incident particle. They also provide the possibility of good energy resolution.

Several plasma characteristics might be examined when detecting ions from fusion reactions. First, this diagnostic may provide a measure of the reaction rate—an independent check of neutron results without such disadvantages of neutron measurements as poor spatial and energy resolution. Good spatial resolution of the reaction rate may be practical because ion paths in magnetic fields are calculable. Radial resolution may be possible from reaction ions leaving the plasma along magnetic-field lines. Axial resolution may be possible from these large gyroradius ions being displaced outward near the midplane to regions where detectors can be placed.

Because reaction rate depends on both density and plasma-ion temperature, either of these parameters can in principle be estimated by assuming or measuring the other. Possibly both density and ion temperature can be simultaneously measured because the energy spread of the final MeV ions is related to the temperature of the initially reacting plasma ions. (This energy spread arises from the range of angles possible between the velocity of the final MeV ion and the center-of-mass velocity of the interaction.)

Another conceivable use of reaction ions is for well-collimated detectors to detect in coincidence near the midplane the proton and triton from the same D-D reaction. The ion paths and region of origin may then be well enough defined to give information on the average magnetic field encountered by the detected particles. By comparing the trajectories with those in a low-beta (plasma pressure/magnetic pressure) situation, information

might be obtained on the depressed magnetic field in the high-beta plasma region. We may also get information on field reversal.

In the initial experimentation with this diagnostic on 2X11B, we positioned a surface-barrier detector 3.2 m from the plasma center along magnetic-field lines, outside the mirror region.* Thin (1.0- to 8.5- μm) aluminum foils were placed before the detector to shield against unwanted radiations from the plasma region. When we decreased the aluminum-foil thickness to the 1.0-to-2.0- μm range, the output signal of the preamplifier that immediately follows the detector saturated during the time the plasma existed. Our tentative conclusion was that this large signal was caused by photons incident on the detector, with frequencies in the ultraviolet or x-ray region or both. This flux was eliminated with an 8.5- μm aluminum foil; there was no concomitant observation of 3-MeV protons. Experimentation continued with various foil materials and thicknesses, and with appropriate collimation, to optimize the reaction-ion signals.

This diagnostic has already been attached to the 2X11B machine for hundreds of plasma pulses. No apparent damage has been noted to the detector, thin foil, or preamplifier during this period, even though the diagnostic apparatus receives a sharp mechanical shock during each pulse and the environment (e.g., electrical, thermal, and radiation) with or without the plasma present can be harsh.

Author

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Improvements to Thomson-Scattering System

We made several modifications in the Thomson-scattering system (previously described in UCRL-50002-76).¹ Aimed at reducing systematic errors and making the whole system more reliable, these modifications included the following:

Ruby Laser. We installed a beam expander that followed the oscillator and provided more uniform illumination of the amplifier rod. The lamp and Q-switch timing were also revised; several minor modifications were made in the power supplies and capacitor banks. As a result, the ruby laser became a highly reliable unit. We built and installed a new support structure for the laser and the machine input-optics arm. This provided increased stability and ease of optical alignment.

* For a discussion of preliminary testing of this diagnostic on a beam test stand, see *Magnetic Fusion Energy Annual Report, July 1975 through September 1976*, Lawrence Livermore Laboratory, UCRL-50002-76 (1976), p. 36.

Viewing System. The viewing optical system was aligned to make measurements at plasma radial positions of $R = -2, 0, +2, +4$, and $+6$ cm. A moveable mirror system allowed the polychromator to look at any of the above positions. Interference filter sets looked at the $R = +2$ and $+6$ positions. To improve measurement accuracy, we increased these filter sets from four to six filters each. A quartz beam splitter, for the calibration light source, replaced a previous one that had poor transmission and reflection characteristics over the wavelengths used.

Data Analysis. In general, the computer data analysis proved useful. The original integrators, however, were not reliable and gave random errors. We replaced these and added a microprocessor for temporary data storage. This system also allowed for more efficient use of the main computer. Comparisons made between computer and hand-reduced data then showed comparable results, indications that the system was reliable and accurate. Mainly, the laborious process of manual data reduction was eliminated. Thus the volume of data that could be analyzed in a reasonable time was greatly increased.

Reference

1. *Magnetic Fusion Energy Annual Report, July 1975 through September 1976*, Lawrence Livermore Laboratory, UCRL-50002-76 (1976).

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Langmuir-Probe Measurements

Electron Temperature. We used Langmuir probes in the end tanks, both east and west, to evaluate the parameters of the external plasma, the electron temperature (T_{ep}), and the ion flux across the fan. Added information about the ion temperature and the local ambipolar potential could be obtained at least qualitatively. These measurements were performed in a time scale of about $20 \mu s$. One set of three probes spaced vertically across the west horizontal fan was usually located at $(Z) = -220$ cm from the 2X11B center, but could be positioned between $Z = -185$ and -275 cm. A single probe was used in the east tank at $Z = +160$ cm from the center.

There are two different series of measurements that depend on the plasma-stabilization method:

- **Gas-Feed Stabilization.** The gas box was first located outside the west mirror at 90 cm (slit aperture, 1.4 cm). We subsequently moved it to the mirror throat (slit aperture, 2.4 cm). For gas-box

operation at a constant gas pressure (25 Torr), the electron temperature in the external region ($Z = -220$ cm west) was clamped at a low value: $T_{ep} \sim 30$ eV. This value only weakly depended on $T_e(0)$, the electron temperature at the 2X11B center. The latter scaled approximately with neutral-beam current.

- **Edge Stream-Gun Stabilization.** We obtained similar, but less consistent, results with edge stream-gun stabilization. For most shots we found $T_{ep} \approx 30$ eV in the east-fan region while $T_e(0)$ varied up to ≈ 90 eV with beam current. On the other hand, depending on stream-gun configuration, we found occasional shots for which $T_{ep} \approx T_e(0)$. These results appear in Figs. 1 and 2.

Although in most cases T_{ep} is independent of $T_e(0)$, we find, for gas-box operation, that it strongly depends on gas pressure (P_{gas}). Figure 3 shows this variation as a function of P_{gas} and beam current. In contrast, $T_e(0)$ is virtually independent of P_{gas} over an even wider range (0 to 1000 Torr). The variation of T_{ep} vs P_{gas} can be interpreted qualitatively in terms of equipartition between mirror-confined hot electron losses (140 eV) and both cold electrons coming from the walls and gas ionization. Gas feed, for reasons not yet understood, evidently cools only the electrons in the external plasma regions.

No quantitative energy balance has yet been made; nonetheless the following phenomena seem quite clear. The behavior of the external electron temperature is markedly different from that of $T_e(0)$. It is not possible to fit these values of electron temperature with a collisional electron-energy transport model along the field lines, even when the heat-conduction equation includes the thermoelec-

Fig. 1. The electron temperature, T_{ep} , at 220 cm west of the center, is weakly dependent of the central electron temperature, $T_e(0)$.

Fig. 2. Same plot as Fig. 1. The electron temperature T_e is measured at 160 cm east of the center.

tric term caused by the ambipolar potential (~ 50 V at the probe location, and probably a few hundred volts at the center). This model makes two quantitatively precise predictions in sharp disagreement with our observations: (a) $T_{ep}/T_e(0) \cong 0.67$ and (b) for hot plasma length, density, and average energy, $T_e(0) \leq 65$ eV. The electron heat-conduction model may still hold in the external region where the electron-electron mean-free-path $\lambda_{ee} \sim 1$ m, but obviously it is not valid all the way to the center where $T_e(0) \sim 140$ eV. One is thus led to ask what is the insulation mechanism between the 140-eV central electrons and the 30-eV electrons in the external regions? With the gas box located at 90-cm west,

Fig. 3. The electron temperature, T_{ep} , at 220 cm west of the center, varies inversely with the gas pressure at a constant neutral-beam current, I_b , of about 500 A. The variation of T_{ep} with the neutral-beam current is shown at a given gas pressure of 25 Torr.

measurements made as far in as 10 cm outside the mirror throat still indicate a low T_e value. One can expect a sharp variation of T_e near the mirror throat. We plan further measurements with an array of probes along the axis.

Stream transmission. From the ion-saturation current (I_{sat}) collected by Langmuir probes (described in the electron temperature section), one can deduce interesting features about stream transmission through the hot plasma. In gas-box operation we find that the gas box alone seems dominantly responsible for the flux of ions measured at the probe position; i.e., no other cold-plasma sources are relevant.

For a constant gas current (P_{gas} 25 Torr), the variation of I_{sat} vs $T_e(0)$, the central electron temperature, shows a flat portion below 80 eV and then a roughly linear increase between 80 and 140 eV. This kink at 80 eV is apparently correlated with a corresponding kink observed for the same conditions at the rf-fluctuation level vs $T_e(0)$, (Fig. 4). The following explanation seems consistent with these observations.

At low $T_e(0)$ a certain amount of cold ions from the gas box can penetrate the central plasma, fill the ambipolar hole of the ion-distribution function, and thus achieve stability. However, as $T_e(0)$ increases, so does the ambipolar barrier. More cold ions then get reflected. The stabilization deteriorates and the fluctuation level increases. The transition between these two effects occurs near 80 eV. At a constant beam current of about 500 A, I_{sat} is proportional to

Fig. 4. The ion-saturation current, I_{sat} , collected by the west probe at 220 cm from the center (25 Torr) increases with the central electron temperature, $T_e(0)$, above 80 eV. Cold ions from the gas get reflected above 80 eV, and the central plasma gets destabilized as shown by the increase of the rf fluctuation level ϕ_{rf} above 80 eV.

P_{gas} ; but near $P_{\text{gas}} \approx 25$ Torr a net decrease of slope occurs, witnessing an increase of transmitted cold ions across the hot plasma with increased gas pressure. Operation at higher gas pressure evidently will not exclude gas for $T_e \lesssim 80$ eV. By using the probe array perpendicular to the west fan at $Z = -220$ cm we have crudely evaluated the I_{sat} profile (Fig. 5) and thus estimated the total current of cold ions flowing through the fan. One can then plot I_{sat} vs P_{gas} as this total current vs the total cold-gas current injected. This is shown in Fig. 6. Below 25 Torr (650 A) the slope is about unity. Nearly all the cold ions are reflected; thus they do not participate in the stabilization mechanism. Further confirmation of this hypothesis is that we observed poor stabilization at low gas pressure (10 Torr). Above 25 Torr the slope is about 0.2, indicating that 80% of the increase of cold-ion current above 650 A is transmitted. With the gas box positioned outside the mirror throat, measurements have also been made simultaneously using both the east and west probes. These data show the same behavior: negligible transmission for low-gas pressure but increasing transmission at a certain threshold pressure, with the transition depending on $T_e(0)$.

A possible explanation of these observations lies in the fact that a reservoir of cold-ion density has to

be filled between the gas box and the central hot plasma to raise the ambipolar potential locally. Once the reservoir density is sufficiently high, the cold ions can penetrate the central barrier. However, a more precise quantitative evaluation of the transmitted and reflected cold-ion fluxes will require many different measurements (profiles across and through the fan) or various assumptions concerning the density profile or both. Nonetheless, we do have some good experimental evidence of cold-ion exclusion.

In the edge-stream stabilization operation, the variation of I_{sat} given by the east probe is nearly linear vs $T_e(0)$. The absolute magnitude of I_{sat} is higher, by almost an order of magnitude, than that for the gas-box operation. The interpretation is more difficult because of the numerous streaming guns used on both the east and west sides. Also the data strongly depend on the stream-gun configuration.

Authors

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Fig. 5. The ion-saturation current profile, being characterized by the ratio of the ion-saturation currents collected by two probes located at 2 cm from each other across the west fan, is getting more and more peaked as the gas pressure increases.

Fig. 6. The cold-ion current through the west fan (magnitude and profile being evaluated by Langmuir probes) is found to increase linearly with the gas pressure up to about 25 Torr. All the cold ions from the gas are reflected by the central plasma. Above 25 Torr, the cold ions start penetrating the central barrier, as shown by the change in slope at a given neutral-beam current $I_b \approx 500$ A. Similar curves could be drawn at lower beam currents.

Neutral Beams

The amount of neutral-beam current delivered to the center of the machine was doubled from 250 to 500 A. This increase is seen in Fig. 1, where neutral-beam current (I_B) is plotted chronologically. The spaces in the plot represent shutdown periods of the experiment. Beam currents greater than 250 A were achieved before October 1977 but only for a limited number of data shots. The value of I_B plotted in Fig. 1 is not a "best shot" value but is an average value that could be obtained with greater than 50% reliability.

The 100-A improvement during the first quarter of FY 1977 can be mainly attributed to two factors:

- Improved operating beam optics through the aid of a computer program that reduced the calorimetric data.
- Staggering of the firing times for the 12 beams. This reduced the amount of interference due to current from opposing beams on the machine striking each other's grids.

During a 6-week shutdown from January 15 to March 1, we optimized each beam-associated power supply and, in some cases, replaced the beam module. This improved the average deliverable current per source from 25 to 30 A.

We installed longer neutralizer sections on the beams during the shutdown from April through July. This allowed the arc chambers of the beam modules to be run at a more optimum value of gas density for better beam optics without sacrificing the overall neutral particle to the ion-atom ratio of the extracted current. At the same time, each beam received its own gas-pressure control to the arc

chamber. All beams were then pretested during a burn-in cycle of about 800 shots each on the 2XIB test stand before installation. The final result was an average current injected into the center of the machine of 45 A per beam, giving a total of 500 A for all 12 sources.

Author

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40-keV Neutral-Beam Extractors

During FY 1977, development of 40-keV extractors made sufficient progress to meet the neutral-beam requirements of 2XIB and the Tandem Mirror Experiment (TMX). At the beginning of the year, we removed the 40-keV extractors that had been tried on 2XIB. They were replaced by 20-keV units because beam current was inadequate at the reduced energy required for operation. The 2XIB neutral-beam test stand was not operational from October 1976 to January 1977 during remodeling of that facility. We then tested several extractors on the 2XIB test stand, but 40-keV operation was not possible due to power supply problems.

One extractor, modified by the Lawrence Berkeley Laboratory (LBL) neutral-beam group, operated successfully at 40 keV on their test stand in December 1976. Several of our extractor modifications were operated at the LBL test stand; one that had been modified like the successful LBL unit was operated at 40 keV for a short run during May. We tried many more modifications but failed after 100 or fewer shots at 40 keV.

The defect that caused failure in nearly all cases was distortion of entrance-grid wires—evidently due to overheating. The damaged wires were always located near the end of the array. We used lateral offset of the entrance-grid wires to steer the outer beamlets toward the center of the target plasma. Non-optimum operation caused the beamlets to graze the nearly suppressor and exit grids. Secondary electrons then struck the entrance wires, causing abnormal heating. To avoid this problem, we assembled an extractor without offset. The wires were bowed, as usual, for vertical focus. This unit was operated at 40 keV for over 1000 shots without damage. The beam was equivalent to 50 A of neutral-atom current in a $10 \times 33 \text{ cm}^2$ area located 3.2 m from the first grid. As TMX performance was predicted assuming 40 A of neutral atoms in $10 \times 33 \text{ cm}^2$ at 3.2 m, the zero-offset module was adequate for TMX.

Steering of the outer beamlets toward the center is necessary to concentrate the beam on the target

Fig. 1. The improvement in the incident neutral-beam current on the plasma, I_B , is plotted chronologically for FY 1977.

plasma. To obtain horizontal focus without offset, we began constructing a newly designed extractor. There were many changes, including horizontal curvature of the grids to point each beamlet at a common point at the plasma center. The wires were still bowed for vertical focus. Our test of the straight, zero-offset grid also tested feasibility of the curved-grid design. The new extractor design has grid wires that are 4/3 the size of the old ones. This increase lowers the spatial tolerance of wire placement and makes a more rugged, more easily fabricated assembly.

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80-keV Source Design for Mirror Fusion Test Facility

The Mirror Fusion Test Facility requires 48 neutral beams: 24 sustaining beams (80-keV, 80-A, 0.5-s) and 24 startup beams (20-keV, 80-A, 10-ms). Constraints must be placed on the cross-sectional area of each module to locate every 80-keV sustaining beam within the solid angle that hits the plasma but misses the magnet at entrance and exit.

Integration of the arc chamber/extractor with the isolation valve and magnetic shield produces the more compact design shown in Fig. 1. Compactness is achieved by immersing the arc chamber/extractor in a high vacuum, where high voltage can be held over smaller distances by redesigning grid-support structures and by bringing services (water, deuterium, power) in only at the backplate to allow close packing of sources.

Reliability is increased by reducing the electric fields everywhere else below those present between grids. Design innovations also increase reliability. The latter includes techniques to reduce stray magnetic fields and uniformly disperse gas, all metal-ceramic construction, and a 60-kV shield enclosing all 80-kV electrodes. Easy maintenance is obtained by a compact isolation valve and by modular construction. Curving both the grid wires and their holders provides focusing in two planes.

The source module and the details of the arc chamber and extractor appear in Figs. 1 and 2, respectively. The design is being completed, and the arc chamber and extractor will be constructed during FY 1978. Initial testing will be at Lawrence Berkeley Laboratory, to be followed by testing with the 80-keV model power supply on the High-

Fig. 1. Compact neutral-beam module integrates the arc chamber and extractor with the isolation valve and magnetic shield. The outer magnetic shield forms the vacuum wall around the arc chamber, extractor, and cylindrical isolation valve. The arc chamber is mounted off the grounded backplate by two triaxial feedthroughs. The extractor is supported by a grounded frame from an angular backplate. We mounted the isolation valve on the neutralizer tube, which is cantilevered from the exit end.

Fig. 2. The arc chamber and extractor, designed to occupy a minimum cross-sectional area, will be constructed during FY 1978.

Voltage Test Stand at Lawrence Livermore Laboratory.

Author

A. W. Molvik

Computer Control

The computer-control system for the 12 neutral beams became fully operational on a regular basis. During normal operation, this system monitors the

operation of each beam on each shot, automatically adjusting the beam controls to maintain a predetermined operating level. The system continuously adapts to the changing individual characteristics of the sources by adjusting the control equations to maintain constant output current and focus.

The computer system provides automatic conditioning for all 12 sources simultaneously. In this "break in" process, the sources are carefully advanced from 5 to 20 kV. Each source is treated individually and allowed to progress at its own rate.

Data collected from a retractable calorimeter is also processed, providing numerical and graphical output to the operator for energy calibration, focus adjustment, and aiming adjustment.

Author

G. G. Pollock

Data Acquisition and Processing

We had three main developments in the data acquisition and processing system:

- Full implementation of the Real-Time Executive Batch-Spool Monitor (RTE/BSM) system.
- Development of efficient processing codes.
- Installation of digital acquisition and control hardware on individual diagnostic systems.

This computer system is presently operating at capacity and the demands on it are constantly growing. Thus we are in the process of procuring an improved system that should satisfy experimental requirements through the TMX operating period.

The RTE/BSM operating system, which was coming on line at the end of the last reporting period, was upgraded and developed to its practical limit. The experimental data base grew to ~185K data words per shot from 22 to 26 diagnostics. There are ~70 channels of data. About 100K of this is processed between shots and retrieved to the physics staff as hardcopy. An interruptible batch-processing job runs in background with a couple of the diagnostic codes that cannot finish between shots. Offline, the system will support about four users doing programming, data retrieval, processing, or miscellaneous calculations.

We enhanced our ability to quickly process a large quantity of data between shots by developing codes that use table-lookup and integer-calculation techniques. This replaced a large amount of floating-point calculations for what is primarily data conversion to physical quantities. Once the necessary tables are initially generated, the raw input data can—with a few integer manipulations—be mapped directly onto a graphic screen. These techniques were particularly effective on our large-data-base diagnostics. For example, we reduced processing time for the 15-channel neutral analyzer from 30 to 8 s. The other class of problems that required data analysis tended to have a small amount of data (as in the case of the Thomson-scattering measurement) or had to run in background.

Multichannel transient recorder systems were installed on these diagnostic systems: neutral analyzer, beam-attenuation probes, and magnetic

loop probes. They handle 48 channels of data and are a distinct improvement over the analog-disc system. In addition we developed dedicated miniprocessor (LSI-11) systems for control and data acquisition and for the Thomson-scattering and hydrogen cyanide (HCN)-laser diagnostics. These devices communicate with the Hewlett-Packard equipment, using a standard CAMAC (computer-automated measurement and control) protocol. An effort is under way to establish a CAMAC input/output standard on the whole diagnostic system. We continued replacement of analog-disc recording with modular transient-recorder systems.

Delivery began on an improved central processor (21MX-E) and storage system. This machine will be the main executive for a distributed system consisting of the present diagnostics computer, the neutral-beam system, and the getter/vacuum controller. Most of the present data processing load will also be shifted to this machine. A 50M byte disc pack will allow ~2 days of data to be stored for quick access. An improved data management system is being developed to enhance our ability to retrieve, process, and compare experimental results.

Authors

W. F. Cummins

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Streaming-Plasma 1-kV Ion-Source Development

Recent theory and experiment indicate that a warm plasma is required to stabilize the hot plasma in 2X11B against the drift-cyclotron loss-cone instability. The streaming current needed to furnish the predicted minimum warm-ion density for stabilization is

$$I_s \gtrsim 7.4 \times 10^{-10} \frac{T_e^{3/2} (\text{keV}) n (\text{cm}^{-3})}{E_i (\text{keV})} \text{ amperes, (1)}$$

where I_s is streaming current, T_e is electron temperature, n is plasma density, and E_i is ion energy.

Present 2X11B experiments with either titanium-washer stack guns or an end-fan box show stabilization as expected for I_s up to ~200 A. There are, however, some undesirable features. We thus will describe our work on a low-voltage ion source as a more optimum source of streaming plasma, with the advantages and disadvantages of the several approaches listed in Table I.

In each case we assume that the resultant warm-ion stream would be guided along end magnetic-field lines into the central hot-ion confinement volume. Thus a new type of ion source is indicated

Table 1. Comparison of approaches to a streaming-plasma source.

	Titanium-washer stack	Gas box	Low-voltage ion source
Ion-injection efficiency	~ 0 ; $E_i < \phi$; ok above ~ 0 ; $V_i > V \sqrt{\frac{B_{\text{gun}}}{B_{\text{mirror}}}}$	~ 0 ; $E_i < \phi$; severe limitation, requires turbulence	very high; $E_i \geq \phi$ very high; $\bar{\phi}$ good enough so that $V_i \sim V \sqrt{\frac{B_{\text{sources}}}{B_{\text{in}}}}$
Gas efficiency neglecting ionization from end losses	$\sim 10\%$ (?)	Low	Moderate: ~ 40 to 70%
Impurity	Poor titanium a problem	Good-very low	Good-very low
Simplicity	Moderate	Good	Poor-fairly complex
Streaming current (I_s)	~ 15 A @ source	Unlimited	~ 50 -A modules
Long-pulse capability	Difficult, requires research and development	Good	Moderate length ok; long pulse poor without research and development
Cost (\$)	Moderate	Relatively cheap	Relatively expensive
Heat flux a problem	Yes	Minor	Yes

with plasma formation and ion extraction occurring in the fringe magnetic field (B_z) to avoid the necessity of a non-adiabatic transition for the ions onto the field lines. The initial, fringe field (B_z) also allows compression of the plasma stream by B_0/B_z ; thus it allows use of a large-area ion source at only ~ 150 mA/cm² to achieve the needed midplane density of $\lesssim 1$ A/cm² at a central field (B_0) (i.e., field ratios $\lesssim 6:1$).

Low-Voltage-Source Construction. The presence of a substantial axial magnetic field and the desire for high gas efficiency suggested the use of a penning discharge as a plasma source. To insure plasma uniformity over the type of large area needed, we chose a large-area oxide-coated cathode. We borrowed a suitable 18-cm diam unit from the old Astron electron linear accelerator. To achieve discharge uniformity with short Debye lengths, we chose a coarse tungsten-mesh anode. The resultant penning geometry was tested on the Bicentennial-Tank Test Stand and found to yield a relatively low rf noise and fairly uniform plasma, providing the cathode temperature was maintained over $\sim 1000^\circ\text{C}$. The observed density gradient (measured by Langmuir probes) was consistent with that expected for gas injection from a single gas feed. We then incorporated this type of arc in a small (10×15 cm extraction area) "prototype" low-voltage ion-source test unit (Fig. 1). The extraction-grid details are shown in Figs. 2 and 3.

Initial tests resulted in the data shown in Fig. 4, with drain currents of positive-hydrogen ions extracted to ~ 20 A total at 1.2 kV, but with a distinct gas-pressure-(and delay-)sensitive drop to ~ 12 A

before leveling off. We continued work to even out and optimize the gas-feed distribution. Also, after ~ 500 pulses, the tantalum wire worked loose and sagged. So we began a study of a molybdenum wire-wound extractor system.

Table 2 summarizes typical data obtained on the Bicentennial-Tank Test Stand. Diagnostics included a large-area calorimetric and electrical signal target, a 45-element Faraday Cup array for spatial resolution, and a gridded detector to evaluate ion composition.

Results are very encouraging (though more research and development is indicated). Plans are under way to install the small prototype test unit on 2X11B to evaluate its effectiveness for a streaming source (~ 10 A level) and to determine if plasma end losses will reveal any adverse voltage-holding problems. If these tests meet expectations, larger 50-A modules will be fabricated for use with either the Tandem Mirror Experiment or the Mirror Fusion Test Facility.

Authors

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Fig. 1. The 1-kV source within a vacuum test stand.

58 Fig. 2. Detail of extractor winding: 0.018 tantalum wire/0.040-in. spacing; accel and decel grids identical; grid area used, 10×15 cm.

Fig. 3. Detail of extractor assembly: insulators made of synthane (voltage feedthrough for decel not shown).

Fig. 4. Current and voltage characteristics of the 1-kV source as a function of time (2 ns/div).

Table 2. Performance of streaming-ion source (10-ms pulses; magnetic field, $B \sim 1$ kG; hydrogen gas).

Property	Value
Drain current, I_{drain} (A)	~ 20 (peak); ~ 12 (flat) for $V = 1.5$ kv
Arc current, I_{arc} (A)	~ 150 at 75 V required for drain current of ~ 12 A (implies ~ 1 kW/A extracted, de-cathode power relatively small)
Calorimetric current, I_{cal} (A)	~ 0.6 drain current on 10-x-40-cm collector located 60 cm from ion source
Electrical current density, (mA/cm^2)	~ 100 over $\sim 10 \times 15$ -cm area (45-element Faraday Cup array) at 60 cm from ion source; mean magnetic field strength, $B \sim \text{uniform } 1$ kG
Ion energy, E_i	$\sim V$ for main component
Plasma gas density, n_{gas}	Preliminary measurement $\sim 50\%$

Radially Dependent Fokker-Planck Code

We developed a radially dependent buildup code that describes the trapping and loss processes of mirror-contained plasmas sustained by neutral-atom injection. During the past year, we modified the numerical procedure for solving the buildup equations. The new formulation eliminated the matrix inversion procedure for obtaining the guiding-center distribution function from the real-distribution function. It increased the computational accuracy and efficiency of the code. In addition, we added an optional feature that allows electron distribution to be calculated by the Fokker-Planck equation or by assumed Maxwellian, with loss terms calculated by Pastukhov formulas.

The Fokker-Planck equation for the guiding-center distribution function of each species is solved as a function of radius and time. The code also solves for the self-consistent radial dependence of various neutral species. It takes into account gas sources such as diffuse and direct streaming of gas from beam sources, outgassing from the walls of the vacuum chamber, and wall reflux of neutrals following bombardment by various ion and neutral species.

The Fokker-Planck equation for the guiding-center density is

$$\begin{aligned} \frac{\partial D_m^a(R,t)}{\partial t} = & -K_1^a(R,t) D_m^a(R,t) + K_2^a(R,t) \\ & + \frac{1}{x^2} \frac{\partial}{\partial x} \left[A D_m^a(R,t) + B \frac{\partial D_m^a(R,t)}{\partial x} \right] \\ & - \frac{C}{x^2} D_m^a(R,t), \quad (1) \end{aligned}$$

where the first term on the right side of the equation corresponds to charge-exchange loss of the guiding-center density (D_m^a) as a result of collisions with neutral beams and background gas; K_2^a is the collisional trapping term. The remaining terms are the usual one for Fokker-Planck, where the coefficients A, B, and C are obtained by averaging the local coefficients over the guiding-center orbits.

The real-distribution function is then obtained from the guiding-center density by the transformation

$$f_m^a(r,t) = \frac{2}{\pi} \int_{r-\rho}^{r+\rho} \frac{D_m^a(R) R dR}{\sqrt{4R^2 r^2 - (R^2 + r^2 - \rho^2)^2}}, \quad (2)$$

and the density of specie α is calculated by

$$n^a(R,t) = K_a \int f(R,t) x^2 dx. \quad (3)$$

The plasma potential, $\phi(r,t)$, is computed at each time step of the calculation by requiring charge neutrality. For a velocity grid of 100 points and a radial grid of 20 points, the radial Fokker-Planck code requires ~2 min per 100 time steps on a CDC-7600 computer for a run containing electrons and one ion species.

The Radial Fokker-Planck (RFP) code was compared with a similar buildup code (BUC) by using rate equations. Common input parameters of both codes were identical. This is not possible for all parameters since some parameters such as energies, cross sections, and end-loss parameters (ηr), which are inputs for the BUC of Moir and Stallard, are calculated self-consistently from the distribution function for the RFP code.

For a 31-keV neutral beam, the BUC code required a current of 3.4 A to maintain a plasma of ~9-cm radius at an equilibrium density of 3×10^{13} ions/cm³ at the center. A corresponding current of 1.4 A was required for the RFP code. In both cases the molecular gas density external to the plasma was 1×10^{10} particle/cm³; both the thermal-atom density and the Franck-Condon density were set equal to zero for this comparison.

An important feature of the RFP code is its ability to calculate kinetic parameters such as electron temperature. Figure 1 shows the effect of Franck-Condon neutral particles on electron tem-

Fig. 1. Comparison of electron temperature as a function of radius with and without the presence of Franck-Condon neutral particles.

perature as a function of radius. It gives curves for two limiting cases corresponding to zero Franck-Condon density and a Franck-Condon density at the surface equal to the molecular gas density times the ratio, V_0/V_{fc} , which is the thermal velocity divided by the Franck-Condon velocity. We expect to make a detailed comparison of code parameters with the 2XIIB parameters during the next few months.

Author

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Major Contributors

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rf-Heated Gas Box

The idea of using rf for improving gas-box efficiency has been suggested by D. E. Baldwin and T. K. Fowler. The scheme is to give rf perpendicular energy at the mirror throat to the ions coming from the gas box. As this perpendicular energy is then converted into parallel energy at the midplane magnetic field, these ions can then more easily climb the ambipolar barrier. We have analyzed the associated problems of rf-wave launching and field penetration for 2XIIB plasma conditions. In the gas box the following plasma parameters can be considered: plasma density, $10^{13} < n < 10^{14} \text{ cm}^{-3}$; electron temperature, $T_e \sim 100 \text{ eV}$; ion temperature, $T_i \sim 0$; ion-cyclotron frequency, $f_{ci} = 10 \text{ MHz}$; and a plasma thickness (west horizontal fan) of $\sim 2 \text{ cm}$.

The Japanese experiments in cusps in Nagoya show that rf coupling is nearly independent of plasma density when one uses antennas carrying rf currents parallel to the magnetic field. This is interpreted as the excitation of electrostatic waves. In 2XIIB the conditions for such an excitation, $\omega/k_{\perp} v_{te} \ll 1$, $k_{\parallel} v_{ci} \geq 1$ will be perhaps only marginally fulfilled, and the coupling to an E_z electrostatic field will be poor. Thus we must use in an rf gas box experiment either the electromagnetic ion-cyclotron wave (slow mode, $\omega < \omega_{ci}$) or the magneto-acoustic wave (fast mode, $\omega > \omega_{ci}$).

We have calculated the fields inside the plasma by using the following approximations. A cold-plasma slab is used to simulate the horizontal fan. The plasma density is assumed to be uniform. One excites rf fields by rf sheet currents (I_y) perpendicular to the magnetic field in the horizontal plane. The displacement current is neglected ($\omega \ll \text{kc}$). The electric field (E_z) can also be neglected. (In vacuum, the excitation does not facilitate the E_z field, and in the plasma the dielectric tensor element K_{zz} is high).

From these calculations we find that the excitation by antisymmetrical currents (currents on top

and bottom of the gas box flowing in opposite direction) is poor and that symmetrical excitation has to be used. The distance between the sheet currents and the plasma must be as short as possible. Better penetration is obtained while minimizing the wave number (k_y) along the excitation current and maximizing the wave number (k_z) along the magnetic field. Fast-wave excitation ($\omega \sim 2\omega_{ci}$) works well, but heating will affect only the tail of the ion-distribution function—not what is desired. Finally, ion-cyclotron wave excitation ($\omega < \omega_{ci}$) appears to be the best solution. The rf penetration can be made very good at high density ($\sim 10^{14} \text{ cm}^{-3}$). A maximum absorption volume will be obtained at large k_z , since the resonant-heating condition, $\omega - \omega_{ci} - k_z v_{ti} = 0$, will be broadened. Experimentally, it seems possible to design the requisite coil. The rf power will be transmitted to the cold ions with a maximum coupling efficiency of 50% while the remainder of the power may, at least partially, be absorbed by the electrons through Landau damping.

Author

G. M. Melin

Electrical Engineering Support

Following successful installation and operation of the "flat top" power supply at the end of last year, we worked on maintenance and improvement of existing systems. A major maintenance item was repair of the flat-top system. This happened when a planned nonstandard flat-top operating sequence resulted in failure of a large number of semiconductor diodes.

We made improvements and additions to the stream-gun supplies and continued our improvements in neutral-beam power-supply operation. Stream-gun capabilities were increased by the construction and installation of added pulse-forming networks. We increased operating pulse length from 5 to 10 ms and also increased the number and versatility of the supplies so that up to four of the 2-in guns and four of the 1/2-in guns could be pulsed for 10 ms or less.

Neutral-beam power supplies progressed through a sequence of gradual improvements that permitted even higher levels of reliable source operation. We developed a new accel voltage regulator that will provide improved regulation and switching performance along with a high degree of noise immunity. The new regulator assembly will replace the existing hot-deck assembly and control amplifier.

Author

G. G. North

Mechanical Engineering Support

Our continued improvements to the 2XIIB vacuum system included the following:

- Liquid-nitrogen (LN)-cooled liners were added.
- Smooth vacuum-chamber walls were incorporated in the 2XIIB machine.

We fabricated LN-cooled liners and installed them in the two source tanks. Each assembly comprised five liners: bottoms, aperture, re-entrant tank, cylinder, and cover (Fig. 1). The liners were made of corrosion-resisting steel, 316 or 316L. The total cost of the LN-liner system (including engineering, procurement, and installation) was \$520 000.

Smooth vacuum-chamber walls describe a type of surface treatment applied to non-metallic walls (Pyrocera[®]) exposed to the plasma. The treatment intended to minimize the wall background-gas fluxes, which affect plasma parameters, by reducing

wall-surface crevices containing gases not released during gettering. We obtained a smooth wall surface on the Pyrocera[®] walls by (a) vacuum depositing a thin layer of chromium as a substrate and then (b) placing a layer of gettered titanium on the chromium before installation in the 2XIIB machine.

Calculated results of the effects of the LN-liner installation indicated that thermal gas load on the 2XIIB plasma would be reduced by up to two orders of magnitude. Observations under actual operating conditions showed the pressure rise in the machine to be small. This indicated that background gases stayed on the pumping surfaces as predicted. Also, the installation reduced recovery time to reach base-machine pressure following an experimental shot.

Author

D. F. Hillyer, Jr.

Fig. 1. 2XIIB source tank, liquid-nitrogen liners, and supply system.

Mirror Fusion Test Facility

Introduction

Lawrence Livermore Laboratory (LL) proposed the Mirror Fusion Test Facility (MFTF) to the Department of Energy (DOE) in March 1976¹ as the MX (Mirror Experiment). A review of the proposal was conducted by the Energy Research and Development Administration's Division of Controlled Thermonuclear Research, now the Division of Magnetic Fusion Energy. The review, held at LLL in May 1976, confirmed the scientific and technological value of larger experiments on the scale of MFTF. The review committee recommended proceeding with the proposed project.²

DOE included MFTF in its FY 1978 budget, and LLL published a report in June 1976³ that summarized the conceptual design. Based on the original concepts, LLL completed further developments and design improvements in the past year. The MFTF Project is organized to move ahead with design and construction when funds become available in October 1977.

Technical Capabilities and Objectives

The facilities provided by the project will build on the succession of experimental and theoretical breakthroughs during the past two years at LLL. Both scientific and technological advances are an essential part of the capabilities now in MFTF conceptual designs and experimental plans for facility operations.

Table 1 presents the main machine parameters.

With these parameters we expect to achieve the initial experimental objectives, or plasma parameters (Table 2).

To estimate ion energy at $T_i = 50$ keV, we estimated that the extracted deuterium-ion currents available at 80 keV contain the same ratios of deuterium components (D^+ , D_2^+ , and D_3^+) as in

Table 1. Machine parameters.

Parameter	Value
Magnet:	
Central magnetic field, B_{central} (T)	2.0
Field length, $L_{\text{mirror-to-mirror}}$ (m)	3.4
Mirror ratio, R_m	2.0
Sustaining beam:	
Energy, E (keV)	80
Current, I (A)	750
Startup beam:	
E (keV)	20
I (A)	1000

Table 2. Plasma parameters.

Plasma parameter	Value
Density, n (cm^{-3})	10^{14}
Ion energy, T_i (keV)	50
Confinement, $n\tau$ ($\text{cm}^{-3}\cdot\text{s}$)	10^{12}

present 20-keV sources on the 2XIIB Experiment. At $T_i = 50$ keV and mirror ratio $R_m = 2$, the "classical" value of $n\tau$ for deuterons would be $2 \times 10^{12} \text{ cm}^{-3}\cdot\text{s}$.

Our goal of $n\tau = 10^{12} \text{ cm}^{-3}\cdot\text{s}$ reflects the expected supply of cold plasma to maintain stability in face of the drift-cyclotron loss-cone (DCLC) mode microinstabilities that previously limited confinement times to a few hundred microseconds, as overcome in earlier 2XIIB experiments. The density of cold plasma to be supplied, n_{warm} , depends on the size of the plasma, radius R_p , relative to the ion gyroradius, ρ_i , in the magnetic field, or R_p/ρ_i . For MFTF the ratio is 13, which corresponds to an electron temperature, or energy T_e , of ~ 1 keV consistent with n_{warm}/n of 2×10^{-3} to maintain a plasma at $R_p = 30 \text{ cm}$, $h = 750 \text{ A}$ of injected sustaining beams.

With the increased size and strength of the magnetic field and increased neutral-beam/streaming-particle energy and current for startup and sustainment of plasma interactions, a range of new experimental opportunities becomes available. Three types of plasma instabilities will be subject to enhanced investigation:

- The DCLC mode, which occurs for small R_p/ρ_i .
- The convective loss-cone mode, which occurs for large L/ρ_i .
- The Alfvén ion-cyclotron mode.

Research and Development Activities

MFTF research and development (R&D) activities seek the technological base necessary for successful and timely accomplishment of project objectives. These activities generally fall into two categories: development of critical items for MFTF construction and development of techniques and subsystems required to conduct the experimental program. Our scientific and engineering team addressed the following R&D items during FY 1977.

Management Activities. The Project Management Plan was prepared.⁴ In addition, we updated cost and schedule analyses, using a modified LLL computer code, and made manpower loading projections, using project office-generated computer codes.

Stress-Analysis Codes. We developed analytical techniques and computer codes for reliable stress analysis of the magnet structure. Magnetic loading on the coils was calculated with a new computer code that yields the actual pressure distribution. Previous methods were less accurate. We also analyzed the magnet structure (stress and displacement calculations) using an existing 3-D finite element code (SAP-IV). Independent analysis verified the results.

The conclusions of this effort verified the original design concept, and the detailed knowledge gained was incorporated into the magnet design. The net result is high confidence in the structural integrity of the magnet.

Vacuum-Requirements Analyses. We developed analytical techniques and modeling to determine the necessary vacuum requirements for neutral-beam-sustained plasmas. A computer code that solved the self-consistent gas balance for beam-driven plasma was generalized for alternate geometries. It now handles the transient analysis for startup simulation of MFTF. Time-varying pumping capacity was also modeled to simulate startup operations with, for example, titanium-getter pumping. Using the above tools, we optimized the placement of the primary pumps (cryopanels) for the most cost-effective operations.

Fokker-Planck Code Development. A radially dependent Fokker-Planck code was developed. This code allows us to include energy effects during plasma buildup.

The radial-buildup code was refined to improve its computing time. This allows us to increase the number of radial zones. We can also add energy effects to crosscheck the results of the radially dependent Fokker-Planck code. We used this code to investigate the suggestion that ionized gas on the boundary produces a plasma shield that reduces the loss of hot ions due to charge exchange on background gas.

Because of extended beam time, we evaluated energy partition and its effect on system design, using beam times up to 30 s.

Superconductor Development. Development efforts were applied to optimizing the superconductor, the attached stabilizing copper, and the integrated magnet conductor.⁵⁻⁷ These efforts led to the present conductor design of a wraparound copper stabilizer soldered to a niobium-titanium/copper matrix core [See Fig. 1 in *Superconducting Magnet Development* (Section 2)].

Our ultrasonic testing effort detected poor bonding of the wraparound solder. We then improved our soldering techniques and produced im-

proved test samples of finished magnet conductor.

We performed thermal tests on short lengths of handmade dummy conductor to verify the stabilizer design for effective cooling, independent of the spatial orientation (from horizontal to vertical) of the conductor. Both single-conductor and nine-conductor bundles were tested in liquid helium at about 4 K. The results of the heat-transfer tests supported the design level of heat flux ($0.25 \text{ W} \cdot \text{cm}^{-2}$).

Superconducting-Magnet Coil Design. The precise winding pattern of the coils has been determined.⁸ We designed and tested the inter-turn insulation that separates individual conductors to maintain liquid-helium passage. Conductor splice design, using a cold-weld process, has been proven for the coil.⁹ We are studying acoustic emission-detection techniques for identifying weak splices and have completed analysis of the liquid-helium routing and gas flow during boiloff.

Access for neutral-beam injection has been optimized using a 3-D computer-graphics code, saving months of layout time (Fig. 1).

Fig. 1. Computer-generated views of yin-yang geometry for superconducting magnet. This technique, which enabled us to optimize access for neutral-beam injection, saved months of layout time.

Fig. 2. Large coil-winding machine scheduled for assembly and testing early in FY 1978. We have already received the winder's parts.

Coil Winder. We completed the conceptual design and specifications for the large coil-winding machine early in FY 1977¹¹⁻¹³ (Fig. 2). The task of performing the detailed design and fabrication of this machine was awarded to Teledyne/Readco Division. The coil-winder parts were delivered to LLL; its assembly and testing will be done early in FY 1978. We identified the tooling necessary to wind the coils and itemized the requirements. The critical items are being designed for fabrication.

Magnet Jacket Design. It was desirable to separate the requirements of vacuum integrity and dimensional stability of the magnet winding from the structural requirements (Fig. 3). We accomplished this with a relatively lightweight stainless-steel jacket used both as a winding form and vacuum-tight enclosure for the conductor bundle. The completed winding was then inserted into the more massive structural casing (Fig. 4). The jacket allowed the structural-case procurement schedule to be decoupled from initiation of the coil winding and provided an added vacuum barrier.

We completed a weld development program to provide a step-by-step procedure for welding the segmented jacket around the winding without damaging the composite bundle with excessive temperature.

Neutral-Beam System Design. The physical layout of the neutral-beam injectors within the vacuum vessel was refined for improved beam use and operational flexibility.¹⁴⁻²⁰ The computer-graphics code used to optimize beam access in the magnet

coil was also used to help relocate the injectors. We completed the conceptual design of the isolation valves.

Vacuum-Vessel Design. We reviewed alternate vacuum-vessel configurations to accommodate the new neutral-beam injector layout and to reduce end-loss intensity at the top and bottom domes.

Cryoplant Specifications. After reviewing system consumption, we wrote tentative specifications for the liquid-helium cryoplant.

Fig. 3. Stainless-steel jacket used as winding form for superconducting coil. This lightweight enclosure provides an added vacuum barrier.

Fig. 4. Completed winding inserted in massive structural casing. The inserted jacket allowed us to decouple the structural-case procurement schedule from initiation of the coil winding.

Control and Diagnostic Design. We functionally designed the control and diagnostic system. Control of the overall machine and each system was examined, and functional requirements were listed for each area. The functional requirements serve as input to the detailed design phase. We developed standards for interfacing equipment to computer gear. Also, a standard microcomputer system was specified.²¹

80-kV Power Supply. We formulated a detail plan and a facilities design to support 80-kV power-supply development and testing.²² A working model of an 80-kV power supply was nearly completed.

Project Design Update

Based on our FY 1977 R&D activities, we reviewed and updated the MFTF system requirements and designs. The following system descriptions are based on these updated designs.

Superconducting Magnet. MFTF's yin-yang magnet consists of over 42 km of copper-stabilized superconducting niobium-titanium (Nb-Ti) conductor (Fig. 5). Each of two coils forming the yin-yang configuration produces a separating force of 98 MN at maximum field. The design uses the two 150° coils offset 0.78 m toward each other to give the desired performance with the structural jacket and case to resist forces transmitted through the inter-coil members, which will tie the coils together. The magnet will weight 200 000 kg.

Fig. 5. Superconducting magnet's large coil pair in proven yin-yang configuration. Pool-boiling liquid helium at 4.5 K will cool this 200 000-kg magnet to the superconducting state.

The superconductor core is Nb-Ti in a copper matrix 6.5×6.5 mm, wrapped in a sheath of copper to act as stabilizer for the superconducting mode. The conductor is 13 by 13 mm after assembly. The wraparound stabilizing copper designed to optimize cooling by liquid helium is soldered to the superconductor core to meet the heat-transfer and electrical-performance requirements for the assembled conductor. The conductor winding will be accomplished on the inner jacket; the entire jacket will be assembled to fit in the magnet case. There will be a guard vacuum to prevent helium leakage into the vacuum chamber around the magnet case. Thus, the guard vacuum and double stainless-steel walls of the jacket and case provide high confidence to protect the vacuum environment for effective plasma performance.

The assembled magnet is operated by two separate but coordinate power-supply elements. The coils will operate at up to 4.5 K in pool-boiling liquid helium. The design current is 6300 A, with continuous current-regulated control over the full operating range.

A major requirement for the magnet is to maintain access for beam injection through the side openings of the yin-yang configuration. We used automated computer graphics to optimize the

design and provide beam access consistent with the overall minimum-B field and magnetic mirror parameter during operation.

The magnet parameters appear in Table 3.

Vacuum-Vessel System. The vacuum-vessel system (Fig. 6) will integrate the various MFTF mechanical systems and be the focal point of the experimental facility. This system will maintain the vacuum environment for the plasma, house the superconducting magnet, and provide access and mounting structures for the majority of elements that make up the experimental configuration. The subsystems associated with the vacuum-vessel system are the vacuum tank and its support, cryopumps, thermal absorbers, beamline assembly, titanium-getter system, and personnel platforms.

The vacuum-vessel system will be housed in a pit and be ~18-m high. The vacuum-tank internal diameter is 10.8 m. The vacuum tank weighs 273 000 kg and will support the added weight of attached hardware for plasma operations up to 380 000 kg.

The vacuum-vessel system will:

- House the superconducting magnet within a suitable vacuum environment.
- Establish and maintain a system base pressure of $\sim 1.3 \mu\text{Pa}$ during experimental shots.
- Maintain a pressure in the plasma chamber of $\sim 400 \mu\text{Pa}$ during experimental shots.
- Provide mounting and remote aiming of the 48 neutral beams over a suitable range.
- Provide thermal absorbers, with the necessary cooling water, and other accessories to remove ~ 160 peak MW of energy for 0.5 s every 5 min.

Table 3. Magnet parameters.

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

Fig. 6. Vacuum-vessel system to house superconducting magnet. About 18-m high, this system maintains a vacuum environment for the plasma. Modules for neutral-beam injection rest along its sides; streaming-plasma guns sit on top.

- Provide cryopumps designed to handle $96 \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$ of molecular deuterium gas by condensation pumping on a bare metal surface maintained at $\sim 4 \text{ K}$.
- Provide for periodic degassing of the cryopanel.

● Deposit $\sim 1 \text{ nm}$ of fresh titanium atoms on the magnet-liner surface facing the plasma region shortly before each shot.

External Vacuum System. The vacuum in the plasma chamber must be maintained at $\sim 400 \mu\text{Pa}$ during experimental shots. This will be accomplished by using an external vacuum system to pump down to $133 \mu\text{Pa}$. Then, the liquid-helium cryopumping panels (with radiation shielding by means of liquid-nitrogen-cooled baffles and liquid nitrogen shields in the vacuum vessel) will provide pumping to reach the system base operating pressure of $1.3 \mu\text{Pa}$ (Fig. 7).

The external vacuum system also must pump deuterium and other gases evolving from the cryopanel during regeneration. For regeneration the cryopanel are raised above the $\sim 4.5\text{-K}$ operating point. As the panels warm up, gas evolves and is pumped out by the high-vacuum pumping system.

Fig. 7. Typical pumpdown profile for external vacuum system. The curve shows the sequential steps for bringing the plasma chamber's air down to a desired operating pressure.

During experimental runs the external vacuum system is valved off from the main vessel. Between shots, cryosorbent pumps will be valved into the system to pump deuterium, hydrogen, and helium.

In addition to the external vacuum system and cryopumps, the titanium sublimator system (getters) is activated before each shot to provide a thin layer of atoms on the inner walls, or warm liners, nearest the plasma. The deposited layer thickness (~ 1 nm) will be at least three to five monolayers of titanium atoms.

The sublimators will provide a minimum of 5 monolayers during a 1-min sublimation period with an average of 13 monolayers and a maximum of ~ 18 monolayers. Each unit will consist of six titanium-tantalum alloy wires ~ 3 -mm diam and 2.5-m long. One wire will be activated, with the others used sequentially as each is exhausted. Six wires provide adequate titanium coverage for 600 to 1000 shots for a minimum of 2 to 4 weeks of operation. Retractable wire-support assemblies may be removed through airlocks for routine replacement without taking the vacuum vessel up to air.

The titanium sublimators will be powered by a high-frequency current (10 to 20 kHz). During sublimation, 12 of the 2.5-m wires will be heated. The

power supplies will be controlled to provide a known quantity of evaporated titanium. One local control microcomputer controls the getter system.

Cryogenic System. The cryogenic system will supply the helium refrigeration and liquefaction capacity for cooling the superconducting magnet and cryopanels in the vacuum-vessel system. The cryogenic system will also supply the liquid-nitrogen requirements for cooling thermal shields in the vacuum-vessel system, system cooldown, and heat-exchanger loads in the helium liquifier. The system will function in five distinct modes: cooldown, steady-state operation, warmup, standby, and emergency shutdown (Fig. 8).

During steady-state operation of the magnet and cryopanels, and cryogenic system will supply the required quantities of liquid helium and nitrogen to the local use points or local storage dewars. Estimated heat loads for the magnet, cryopanels, and transfer lines appear in Table 4.

To meet the heat-load requirements the helium-refrigeration capacity will be 3 kW at 4.5 K. In a liquifier mode it will produce 700 litres/h. The helium system, in the normal mode of operation, will be closed-loop with a purification stage for helium recovery.

The nitrogen subsystem will be open-loop. A liquid use rate of 5800 litres/h will be furnished by a commercial supplier; nitrogen boil off will be gas vented. An onsite storage dewar, having at least one-day capacity, will be provided.

Sustaining Neutral-Beam Injectors. Each injector is driven by an 80-kV power supply consisting of five separate elements to drive the experimental neutral-beam source module. Each power-supply unit includes an acceleration de power supply, acceleration modulator and gradient-grid network, filament power supply, arc power supply and suppressor power supply. To allow for extensions in duration the high-voltage sustaining system has a maximum pulse duration of 30 s. MFTF initial operation will provide a duration of 0.5, but the power supplies could handle longer durations. Each supply will be capable of a maximum operating

Table 4. Estimated heat loads (in watts).

At 4.5 K		At 77 K	
Magnet	565	Cryopump shields	115 000
Cryopanels	1400	Other shields & liners	50 000
Transfer lines	300	Transfer loss	40 000
Cryopumps	30		205 000
Liquid-helium Dewar losses	20		
	2315

Fig. 8. Floor plan of cryogenic system intended for Bldg. 431. This view shows the flow paths of liquid helium and liquid nitrogen into the vacuum vessel. Liquid helium cools the magnet and cryopanel; liquid nitrogen cools the thermal shields.

duty cycle of 10%. A new 230-kV, 250-MW power line will serve the primary pulsed power needs of MFTF.

A dedicated substation will be the terminal point of the 230-kV power line. The 230-/13.8-kV transformer secondaries provide power to the 80-kV high-voltage rectifiers for acceleration power. Each of the 24 power supplies is independently operable, with its local control interfacing to the control and diagnostic system for integrated operations.

The substation and acceleration dc power supplies will be located 150 m to the east of Bldg. 431. The acceleration modulator and gradient-grid networks plus the filament, arc, and suppressor power supplies will be in the building.

Startup Injectors. The 20-kV neutral-beam injectors (similar to those used on 2XIB) are adequate to provide the 1000 A beam current for MFTF. This application requires 24 startup neutral-beam injectors operating for 10 ms (the 2XIB duration). The power supply is a capacitive-storage "pullman" providing a design capability of 50 A at 20 kV. Since the source modules tend to degrade after initial conditioning for beam injection, the 24 startup injectors are included to provide the essential performance for adequate plasma performance.

Plasma Streams. The titanium-washer guns used on 2XIB could provide sufficient target particles for the startup. Development efforts are underway to provide improved plasma guns and to improve performance of the current designs. If we use the 2XIB washer guns, up to 100 units could be required to stream along the fan-shaped field lines into the plasma target region inside the coils. The plasma generators are mounted on the top dome of the vacuum vessel.

The current MFTF design provides a magnet collar around each washer gun near the plasma injection plane to concentrate magnetic field lines and improve injection effectiveness.

It may be necessary to put a gas box at the mirror throat, as with 2XIB experiments, to minimize loss-cone plasma ions escaping from the mirror and to enhance plasma stability.

This experimental addition will interface with MFTF's magnet case. Also, the increased gas load will require more pumping capability in the vacuum-vessel cryopumps. Continued assessment of this option is planned during the preliminary design phase of the facility.

Table 5 shows the neutral-beam injector module specifications.

Control and Diagnostic System. MFTF will be controlled and monitored by an integrated system

Table 5. Neutral-beam injector module specifications.

Parameter	Startup module	Sustaining module
Operating number	24	24
Maximum neutral-beam energy (keV)	20	80
Avg neutral-beam energy (keV)	~16	56
Extracted-ion current (A)	80	80
Pulse length (ms)	10	up to 0.5 s
Deuterium-gas inlet ($\text{Pa} \cdot \text{m}^3/\text{s}$)	4	4
Beam divergence (width by height)	$2^\circ \times 0.5^\circ$	$2^\circ \times 0.5^\circ$
Neutral-beam current at plasma (equiv. A)	50	32

capable of automatic and manual operation. This control and diagnostic system includes data acquisition, reduction, and analysis to support operation of the facility and to guide experimental activities.

The nine minicomputers in our distributed hierarchical system allow independent operation of various subsystems and coordinated action of the subsystems, when appropriate. These supervisory computers are the vessel supervisor (magnet, vacuum, getter control system); three beam supervisors (streaming, startup, sustaining); injector supervisor (coordinates operator interfaces with the three beam supervisors); facilities supervisor (control room interface to the cryoplat, primary power, safety interlocks); system supervisor (coordinating interface for injectors, facilities, machine, physics diagnostics); experimental physics (diagnostics) data processing system; and the data-base management system.

A block diagram of the CDS configuration (Fig. 9) shows a set of small computer systems interfacing with local control and instrumentation subsystems for each functional element. Control, diagnostics, data processing, and monitoring tasks are performed by interconnecting with a bus structure. This arrangement allows both vertical and horizontal communication in the hierarchy. Graphics displays at the central and local consoles minimize display-area requirements and optimize operator-machine interfaces.

The distributed control system benefits in operating flexibility and reliability by using microcomputers in the local control and instrumentation subsystems. The diverse subsystem control and monitoring requirements, along with data processing and storage needs, lead naturally to the combination of distributed and supervisory functions. The system, which will accommodate data

Fig. 9. Hierarchy of nine minicomputers for control and diagnostic system. Such supervisory computers will control and monitor physics experiments run on the Mirror Fusion Test Facility (MFTF) device.

from each shot, will have a 5-min turnaround to the next run.

Safety System. Our safety system, which meets operating requirements, is an inherent part of each MFTF system and building. Subsystems for personnel-access control, fire detection and control, and radiation protection reach across the systems and buildings. Safety interlocks, flashing warning lights, and warning horns control access to hazardous areas or conditions. Hazardous areas provide safe/run switches for shutdown by anyone nearby.

Fire detection and control is provided by smoke detectors, sprinklers, firewalls, Halon fire retardant, and high-expansion foam in the vault area. MFTF's radiation protection system uses monitoring and alarms to prevent inadvertent exposures to hazardous levels of radioactivity. Operational and safety interlocks provide hardwire controls. Such a control system maintains interlock status knowledge by monitoring several hundred safety interlock switches hardwired into protective chains. Local control systems gather and transmit the status information on the safety systems to the supervisor and control-console displays. Thus, facility operators and system controllers get the information needed to operate safely. Because of the fail-soft design of the control system and the independence of the safety interlock chains from the monitoring supervisors, we can confirm a high degree of MFTF operating safety at all times.

Building 431. Our existing Bldg. 431 will be modified to house the MFTF experiment. Most of the supporting research activities now in the building will be relocated to Bldg. 441.

Building 431 is $50 \times 70 \times 30$ m and contains a vault-like enclosure of 2-m-thick concrete blocks surrounding an area $20 \times 32 \times 22$ m. The floor of this enclosure is 6.4 m belowground. A high bay that contains the vault and runs the length of the building is served by an existing 55 000-kg bridge crane. Two mezzanine floors (aboveground) run the full length of the building and along both sides of the bay. Total floor space presently usable for equipment placement is about 4100 m^2 . Building modification will take place in three phases: demolition, preparation, and integration.

Figure 10 shows the completed MFTF device inside the shielded vault in Bldg. 431. This conceptual design has been updated during the past year. The vacuum-vessel housing the magnet sits in the central area (the vault cutaway shows the 27 000-kg bridge crane serving the pit region). The roof has thick concrete beams to reduce "skyshine" effects. The reinforced concrete foundation supports 850 000 kg, the combined weight of the vacuum

vessel, magnet, and other attached hardware.

Building 441. The new laboratory/office structure, Bldg. 441, will have a gross area of $\sim 9000 \text{ m}^2$. Located on the south side of LLL's Inner Loop Road, this building will be constructed of fire-resistant and low-maintenance-cost materials. Corridor partitions will be permanent, with partitions between offices easy to remove for flexible office modifications.

Building 441 will be designed to provide office space for ~ 300 scientists, engineers, administrative people, and visitors. A breakdown of building space appears in Table 6.

The floor plan will provide a central location for Magnetic Fusion Energy (MFE) scientific research effort, with engineering and support functions located to optimize interaction among divisions and assure close proximity of supporting groups. Planning and layout of the building will integrate it with other MFE facilities. This new facility will have a functional and attractive working environment for the research staff.

Landscaping of Bldg. 441 will offer relief from the generally industrialized environment of the adjacent area and present use of the site.

Primary Electric Power. Pulse-power requirements will be supplied by a new 230-kV power line from the Pacific Gas and Electric Co. (PG&E) Tesla switching station. The line will run to a terminal structure at the new LLL substation and terminate in a 230-kV circuit switcher. An environmental impact statement for the line will be prepared and submitted by PG&E to the California Public Utilities Commission (PUC). PG&E will obtain approval for line construction from PUC. Required easements for line construction will be obtained by PG&E. The line will start at an existing 230-kV bus position at Tesla. It will require construction of a short 230-kV aluminum conductor section of transmission line to tower 80/555 of the existing Tesla-Newark section of the Tiger Creek-Newark

Table 6. Bldg. 441 floor space.

	Net area (m^2)	Gross area (m^2)
Office & drafting	3400	
Laboratory & computer	2400	
Miscellaneous		
Lecture & conference	400	
Library	200	
Storage	140	
Other	330	
Total	6870	9300

Fig. 10. MFTF device inside Bldg. 431. Arcs for electrical power supplies, computer controls, and diagnostic equipment encircle the con-

line: a single circuit (three-phase) on a vacant position of the Tiger Creek-Newark line from tower 80/555 to tower 87/596; and a 230-kV tap line consisting of a single-circuit line from tower 80/555 to the LLL substation site (where it will terminate on a 230-kV circuit switcher). Metering equipment will be installed in the substation. Also included will be two communications channels required by PG&E between LLL and the PG&E load dispatcher.

A temporary 13.8-kV overhead pole line will be installed for testing of rectification power supplies before the new 230-kV line is on stream. The line will run from the main LLL 115-/13.8-kV switchyard (south of Bldg. 431) to a central location at the 80-kV dc rectification yard (adjacent to the new 230-kV substation). Line length is ~550 m.

Three 13.8-kV underground feeders will serve as primary distribution to Bldg. 431. New loads in Bldg. 431 will require modification of the existing primary distribution system. This will include high-voltage splicing, switching feeder positions, reconnecting to match loads, and adding some high-voltage cables in the distribution tunnels.

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Tandem Mirror Experiment

Introduction

We designed the Tandem Mirror Experiment (TMX) to test a new principle for improved plasma confinement in open-ended, or mirror, systems. The basic tandem mirror idea is to reduce plasma-loss rate by electrostatically plugging the ends of a solenoidal central confinement region. We use the high positive ambipolar potential of minimum-B-type mirror end cells to create our plugs. Each end plug is driven by neutral-beam injection from 12 source modules in a manner similar to that done on the 2X11B Experiment.

Extrapolation of the tandem principle to a reactor configuration yields a power balance (nuclear-power output to beam-power input) substantially improved over a conventional mirror-type reactor. (Studies of tandem mirror reactors appear in Section 2 of this report.)

The tandem mirror concept originated at Lawrence Livermore Laboratory (LLL) in 1976.¹ Following a series of studies of the concept, we selected an experimental configuration that would provide a test of the basic ideas involved. The TMX Major Project Proposal,² based on this configuration, was submitted to the U.S. Energy Research and Development Administration (ERDA) in January 1977. (That proposal contains a full description of the tandem mirror principles and the TMX experiment.) Preliminary TMX design began immediately, and ERDA reviewed and approved the project proposal early in 1977. An administrative plan³ for the project was prepared and adopted in August 1977 to provide a basis for planning and reviewing construction progress. The project entered a design and fabrication phase, with completion of construction planned by October 1978.

What follows is a brief description of TMX; refer to the project proposal² for more complete information. A set of recent reports,⁴⁻¹¹ presented at the Knoxville Symposium on Engineering Problems of Fusion Research, October 1977, gives a detailed description of the machine design. A recent issue of LLL's monthly journal contains a simplified description of TMX.¹²

Physics Parameters

The purpose of TMX is to provide a proof-of-principle evaluation of the tandem mirror concept as rapidly as possible. To accomplish this, we have set three main physics objectives for the experiment:

- Demonstrate the establishment and maintenance of a potential well between two mirror plasmas.
- Develop a scalable magnetic geometry while keeping macroscopic stability at high β .
- Investigate the microstability of the plug-solenoid combination to maximize the plug-density/injection-power ratio.

These objectives, further discussed in Ref. 2, lead to a set of key physics parameters for the experiment (Table I). The TMX major-device-fabrication project is designed to provide an apparatus (Fig. 1) and facility that meet the parameter requirements of Table I and have sufficient flexibility to meet the physics objectives above.

Fig. 1. Assembled view of apparatus for Tandem Mirror Experiment (TMX). The plug magnets and transition coils reside in stainless-steel vacuum chambers that have mounted neutral-beam modules. These large plug tanks provide high-speed vacuum pumping of source gas and beam and plasma particles.

Engineering Description

Magnet System. The magnet system (Fig. 2) will consist of two quadrupole-well plug sections, a solenoidal central section, and transition coils. Its

Table 1. Key physics parameters.

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	10 kG
Confinement product, $(n\tau)_p$	$3 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$
Central cell	
Density (assumed uniform over V_c), n_c	$1.2 \times 10^{13} \text{ cm}^{-3}$
Ion temperature, T_c	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	0.5 kG
Confinement product, $(n\tau)_c$	$3.1 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$

construction material will be cooled copper conductor, energized by line-powered rectifiers. The magnet system will be capable of being energized at rated current for a time ≥ 1 s with a duty cycle of 3 min. The field is being designed for magnetohydrodynamic stability by having the high-pressure, minimum-B plugs stabilize the central cell in a pressure-weighted average, as discussed in Appendix A2 of Ref. 2. We began field calculations to optimize the transition between plug and solenoidal sections.

Each of the two plug magnets will consist of a baseball-type coil with a C-shaped coil inserted in each lobe. The central field, B_0 , will be 1.0 T with axial mirror ratio $R_{||} = 2.0$ and perpendicular mirror ratio $R_{\perp} = 1.04$ at a radius $r = 10$ cm. Length between plug mirrors will be ~ 120 cm. The plug magnet will be sized for clear access of neutral beams based on a neutral-beam "footprint" of 10×33 cm at the target. The baseball coils and C-coils are being fabricated.

The central cell will consist of a set of six existing solenoidal units, 185-cm i.d. The length of the central region will be ~ 530 cm between inner plug mirrors.

The magnetic-field transition between each plug

Fig. 2. TMX coil set. Massive baseball-shaped coils in the ends create mirror fields for the plugs. Large ring-shaped coils form the central solenoid. C-shaped and octupole coils smooth the transition of field lines between plugs and solenoid.

magnet and the central solenoidal section will be accomplished by a set of transition coils. Each transition set will consist of two C-coils and an octupole coil. These are being designed to transform a plug flux bundle out to $r \times 10$ cm (in the midplane of the plug) into the solenoidal region.

Each component of the magnet system will be powered individually for maximum flexibility in field shaping. Power supplies will be modular rectifier units.

Vacuum System. The plug magnets and transition coils will be housed in large stainless-steel vacuum chambers that also provide mounting for the neutral-beam modules (Fig. 1). These tanks will be lined with a set of liquid-nitrogen-cooled baffles, on which we will sublimate titanium to provide high-speed vacuum pumping of source gas and beam and plasma particles. Surfaces subject to bombardment by energetic particles will be separately cooled to hold a selected temperature between 20 and 100°C. We will mount the large solenoidal coils outside the central vacuum chamber (Fig. 1).

The vacuum system external to the vacuum vessel will consist of mechanical vacuum pumps, Roots blowers, and diffusion pumps (together with associated plumbing, valving, and gaging).

Injection System. A set of 12 neutral-beam modules of the type in use on 2X11B will be mounted on each plug tank. To facilitate maintenance, we will individually valve each beam module from the plug tank by means of a rectangular gate valve. Each module and neutralizer cell will be magnetically shielded to maintain a field of ≤ 0.5 mT perpendicular to the beam axis, at full-rated plug field. Modules will be mounted on bellows for individual aiming at the plug-axis centerline or aiming as much as 10 cm off (radially). On each plug tank, eight modules will be rated at 20-kV maximum extractor voltage. These modules will be designed to deliver rated neutral-beam current of 50 A per source of deuterium (D^0) atoms within a target area of 10×33 cm at the plasma. The other four modules on each plug tank will be rated at 40 kV and will be designed to deliver 40 A per source of D^0 to the same area. All modules will be

capable of operating for a pulse duration of 25 ms, and their associated power supplies will be matched to this pulse duration.

A pulsed streaming-plasma gun of the loaded titanium-washer type will be mounted on the magnetic axis at each end of the vacuum chamber to provide a target plasma for startup. A gas box, similar in design to that in use on 2XIIB, will be located in the inner mirror region of one plug coil with suitable valving to introduce a controlled amount of gas into the system. This gas box will provide plasma to fill the central region. This plasma ultimately streams out of each end and helps stabilize the plug plasma.

Facility. The TMX apparatus will be in an existing building within a 9.8-X-17.1-m pit (Fig. 3). The pit will be surrounded by concrete walls 0.6-m thick aboveground to provide personnel shielding from deuterium-deuterium neutrons. Tiers on three sides of the pit place the neutral-beam power supplies close to the neutral-beam modules. Magnet power supplies in an adjacent building connect by cable through a tunnel. Machine control racks will be adjacent to the pit.

Diagnostic System. This system will be based on that used for 2XIIB. It will be augmented by additional equipment as needed. Raw-data storage and archiving, as well as online data processing, will be accomplished by a minicomputer. Data processing and readout between each injection period will enable the experimenter to evaluate the data and direct the course of the experiment.

Additional instrumentation beyond the existing system will be needed because there are three plasma regions (two end cells, one central cell) on TMX. Also, some new measurements will be required (see Appendix A8 of Ref. 2 for a discussion of diagnostics), including those of space potential and low-energy ion spectra.

Diagnostic Development. A major effort will be required to have diagnostics systems that measure the TMX electrostatic potential. Heavy-ion-beam probing systems appear to offer the best means of making these measurements.

We began two joint efforts with Rensselaer Polytechnic Institute, experts in beam probing. The potential in the central cell will be measured with a heavy-ion beam injected transversely (as in the usual application of the technique). The complex magnetic field of the end plug will require careful computer study to identify suitable component locations and to define the plasma volume that can be probed.

Potential will also be measured by probing along the symmetry axis. We ordered some equipment for

this measurement (some is available from the Baseball II-T surplus).

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Fig. 3. Experimental facility housing TMX apparatus. The thick concrete walls of the pit shield personnel from neutrons. Tiers on three sides of the pit place the power supplies close to the neutral-beam modules.

SECTION 2. DEVELOPMENT AND TECHNOLOGY

Introduction and Summary

Mirror-confinement experiments have always required state-of-art technology in many areas. Thus, we are developing in our laboratories intense neutral beams, superconducting magnets, high-vacuum techniques, and methods for direct recovery of plasma energy escaping through "mirrors." Also, several developments are required for eventual application to all fusion concepts. These developments, which use the unique facilities of Lawrence Livermore Laboratory (LLL), include research on tritium technology and on the effects of a 14-MeV neutron source on reactor materials. The RTNS-II (Rotating-Target Neutron Source), a new 14-MeV neutron source, is under construction to obtain data on reactor materials at higher doses.

Conceptual design studies of fusion reactors and components form a basis for guiding the program and for establishing technology goals.

Superconducting Magnets

Production amounts of superconducting core for the Mirror Fusion Test Facility (MFTF) coil were obtained from four manufacturers and evaluated. We built a production line and operated it successfully for adding a "wraparound" stabilizer to the core. A cold-weld technique was successfully developed for making joints.

We investigated mechanical strain effects on multifilamentary niobium tin (Nb_3Sn) tests using fields up to 12 T indicated no degradation for strain less than 0.8%. We concluded that Nb_3Sn could tolerate practical strain and that it could be used in high-field magnets.

Construction proceeded on the High-Field Test Facility (HFTF): the cryostat was fabricated and installed; two of the 1-m-bore niobium-titanium (Nb-Ti) "backing" coils were wound; and the refrigerator liquifier from the discontinued Baseball-II experiment was relocated next to the HFTF.

Direct Energy Conversion

Following success at 15 keV, a 120-keV beam-direct convertor was built and installed in the Lawrence Berkeley Laboratory (LBL) IIIA facility. Initial tests indicated that high gas pressures prevented proper operation; thus fabrication began on a 150 000 litres/s cryopump to pump gas produced in both the direct convertor and the beam dump of the test facility.

Magnetic suppression of electrons that tend to enter the direct convertor is being investigated in the 15-keV facility, using iron pole pieces; a field of about 0.3 T is required. If successful, magnetic suppression will allow the application of direct conversion to much thicker beams than is possible using electrostatic suppression.

Reactor Studies

We completed a conceptual design of a 100-MWe, vertical-stacked reactor that has 12 cells. An alternative horizontal-axis design, which was started, might have structural and serviceability advantages. Alpha-particle heating studies showed an optimum alpha retention of about 30%. In-place startup, using neutral beams, requires a large pulse of beam current; thus startup of the field-reversed plasma in an external chamber seems preferred.

A preliminary 1000-MWe Tandem Mirror Reactor (TMR) design was completed. The central cell is 100 m long and is geometrically simple; the end cells require high magnetic fields (17 T) and high energy beams (1 MeV) but are small relative to the central cell and have low neutron production. A plasma Q (fusion power/injection power) of about 5 is possible, and it appears that ash buildup will reach an equilibrium that allows steady-state burn.

We completed a reference conceptual design for a fusion-fission hybrid reactor based on a classical mirror plasma and a depleted uranium blanket. The neutrons from a 400-MW fusion plasma can produce 1900 kg/yr of plutonium, which would provide makeup fuel for about six 1000-MWe light-water reactors. Preliminary parametric studies of a hybrid based on a "low technology" tandem mirror indicate improved economics and geometrically simpler design. A preliminary evaluation was made of a no-reprocessing fuel cycle based on uranium-233 produced in a mirror hybrid and burned in high-temperature, gas-cooled reactors.

We initiated a "small mirror reactor" project under Electric Power Research Institute (EPRI) sponsorship to design a reactor that could be operated in the late 1980's. Parametric studies started on the standard mirror hybrid (with cylindrical shape and Toffe bar magnets), the tandem mirror, and field-reversed mirror. In all cases, emphasis was on near-term technology, small size, and significant power production.

Major studies were done of reactor-scale, intense neutral-beam injectors based on negative ions. These included injectors for the Reference Mirror

Reactor delivering 1800 A at 150 keV and 81% efficiency and for the TMR injector delivering 123 A at 1.2 MeV and 73% efficiency. The injector design for the Hybrid Mirror Reactor is based on positive ions and delivers 2600 A at 125 keV and 60% efficiency. The main considerations in these designs were efficiency; reliability; long life; and evaluation of high-voltage arc suppression, gas pumping, and neutron bombardment. A 120-keV helium-3 neutral-beam injector for heating and fueling a deuterium/helium-3 reactor was designed as part of an ERPI-sponsored advanced fuels reactor study. We emphasized a minimum 6-month operating life of direct converters and use of cryotrapping for pumping of helium-3 gas.

Neutral Beams

Our major test facilities were significantly improved. Facility IIIA at LBL, which is rated at 120 keV, 20 A, 0.5 s, and for long pulses, was improved as follows: We successfully evaluated "magnetic core snubbers" for control of spark damage, with shunt-control using silicon-controlled rectifiers, and we greatly expanded our computer diagnostic and control systems. Facility IIIB, the first all-solid-state, high-power neutral-beam system built, became operational, powering and controlling our first full-current Tokamak Fusion Test Reactor (TFTR) source. The High-Voltage Test Stand, rated at 200 keV and 20 A, dc, neared completion at LLL.

Highlights of the development program included the successful test of a fractional-area TFTR source at the IIIA facility. Similar tests began on sources for MFTF (80 kV, deuterium) and the Doublet-III tokamak (80 kV, hydrogen). A full-scale TFTR source was tested to 60 kV at Facility IIIB. To improve our basic source designs, a "MacKenzie bucket" plasma source was built and is being evaluated and long-life electron sources, such as hollow cathodes, are being developed.

The negative-ion program, aimed at developing efficient beams for future applications, is based on the high efficiency with which negative-ions can be neutralized. A 100-mA negative deuterium ion (D^-) beam, produced by double charge exchange in cesium, was accelerated to 60 keV. Technical problems being actively worked on include the production of an intense high-quality beam of neutral deuterium at 1 keV, for subsequent conversion to D^- in cesium vapor. At these low energies control of space-charge neutralization to prevent excessive beam divergence has not yet been achieved. Calculations are also being done on background plasma space-charge effects in the transport distance required for electrons to leave the

1 keV D^- beam before reaching the high-voltage D^- accelerator; theoretically, this technique appears to be feasible. We began an experimental investigation on an alternate method for making a high intensity D^- beam using a magnetoplasma-dynamic arc jet.

RTNS-II

Construction of this facility, which contains two 14-keV neutron sources for fusion materials studies, continued on schedule. The building is 80% complete, 400-kV power supplies were delivered, and one complete accelerator was assembled. We tested the terminal to 400 kV and tested the source at 150 to 200 mA of molecular hydrogen ions. A full-scale tritium scrubber was tested, and testing began on a 500-rpm, 50-cm-diam target.

Neutron Irradiation Studies

We made exploratory studies on the nature and magnitude of radiation damage effects produced by neutrons from the RTNS and beryllium (d,n) sources. On the basis of calculated damage energy, the two sources show the same strengthening effect on copper, vanadium, and niobium; where ..., for fission-reactor neutrons (Livermore Pool-Type Reactor at LLL), about 2.3 times more damage energy is needed to produce the same strengthening.

Tests on cold-worked 316 stainless steel showed measurable effects at a 14-meV fluence of 3×10^{21} n/m²; strength increased by about 5%. For annealed material the effects were much greater, with a 60% increase in yield strength.

Helium doping of niobium samples was done; creep tests gave results similar to those of undoped niobium. Doping increased the yield strength of niobium/1-wt% zirconium specimens.

We irradiated Nb-Ti superconductors at 4.2 K to a fluence of 8×10^{20} n/m²; the critical current decreased by 24%. This is a far greater sensitivity to 14-meV neutrons than would be expected from using damage-energy correlations and published data on fission neutron effects. Annealing at room temperature produced recovery to within 7% of unirradiated values.

The effects of 14-meV neutron irradiation on low-temperature resistivity were measured to get data from which to develop models of the displacement process. Based on preliminary data on vanadium, niobium, and molybdenum, we reached a speculative conclusion that theoretical damage ratios are about 20% higher than those measured.

In a computer-modeling study of radiation damage, we completed a dynamic study of collision cascades in tungsten.

Tritium Technology

Tritium control was studied as part of all our major reactor studies. Several new methods were considered and described for the Mirror Hybrid Reactor. We calculated that emissions can be kept to below 9.4 TBq/d (10 Ci/d).

We made an economic study on a large scale (70 m³/s) cleanup system using our oxidation-absorption models; data was not sufficient to make a proper choice from among alternative concepts. Experimental apparatus is being built for testing tritium cleanup using various catalysts and absorbents.

We are continuing our investigation of active metal "getters" for tritium cleanup. We have studied uranium and cerium. With cerium the tritium concentration in a gas stream could ideally be reduced to less than 3.7×10^{-12} Bq/m³ (10^{-19} mCi/m³), about 10^2 times lower than that with uranium. Preliminary data on cesium is encouraging.

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Superconducting Magnet Development

During FY 1977 we directed our development program toward three main aims:

- Developing the conductor and designing the superconducting coils for the Mirror Fusion Test Facility (MFTF).
- Developing multifilamentary niobium tin (Nb₃Sn) superconductors for large fusion devices.
- Building the High-Field Test Facility (HFTF) for testing (a) the MFTF test coil and (b) Nb₃Sn insert coils.

MFTF Conductor Development

A special cryostatically stabilized niobium-titanium (Nb-Ti) conductor will meet the needs of the MFTF magnet coils. We investigated two possible fabrication routes: (a) a four-element type comprising an Nb-Ti/copper composite core soldered to three copper conductors, in which cooling channels have been rolled, and (b) one in which a wide stabilizer strip (also in which cooling channels have been rolled) is wrapped around and soldered to a similar superconducting core. The latter alternative, which proved to be more successful, was adopted.

Suppliers extruded 250-mm-diam billets of sample Nb-Ti/copper composite material and drew them to the final size of 6.5×6.5 mm for the super-

conducting core. Performance of the wire from three of the four suppliers met or came close to meeting the preliminary specification of 11 kA at 4.2 K and 7.5 T. The MFTF Project sent the final specification for this material out for bids.

Airco developed the wraparound stabilizing process, building on their existing expertise and wrapping equipment. They set up an electroplating line to plate ~0.08-mm thickness of solder (90 lead, 10 tin) onto the central core. The stabilizer was separately prepared by passing oxygen-free high-conductivity (OFHC) copper ~45 × 4.5 mm through a series of rolling and punching processes, interspersed by some annealing. The two components were then brought together in the final fabrication line. Flux was added, and the stabilizer was wrapped around the core, with the cooling channels against the core, as the components passed through a series of forming rolls. A "Turk's head" sized the conductor before it continued into the furnace, where the solder was melted. The conductor was compressed horizontally and vertically by chilled caterpillar tracks, which maintained pressure until the solder froze. The conductor then went through ultrasonic washing baths, drying and an ultrasonic bond-analyzing system before being coiled onto the supply reel. The ultrasonic detection system continuously monitored the quality of the solder bonds on all sides. It was typically set to sound an alarm when less than half a chevron was bonded. Figure 1 shows the stabilizer ready for wrapping around the core and the finished conductor.

Sample core material (~2000 m) is being stabilized and will then be wound in 18 pancakes to produce a coil 1-m bore, 1.7-m o.d., and 250-mm long. This coil will be assembled between two similar-sized coils already wound for HFTF (see later). Heaters to produce controlled quenching and diagnostics to analyze propagation of the normal zones will be inserted in the test coil. We will use the test results on this coil to choose the operating current and current density of the MFTF coils and other aspects of the coil design.

The conductor for the MFTF coil will need several hundred joints because of the limited length that can be extruded and because joints are required between adjacent pancake coils. The mechanical and electrical integrity of every one of those joints is vitally important, and a variety of possible joining techniques have been considered and investigated. The technique we finally selected is to cold-weld the Nb-Ti/copper composite core with a butt joint, then resolder the stabilizer back onto the core in this region. The strength of the cold-weld joint is close

Fig. 1. Wraparound copper stabilizer for superconducting magnet. We soldered the copper to a niobium-titanium/copper core.

to that of the conductor itself, and the technique, which uses a commercially available machine, is extremely reliable. Virtually no preparation or skill is required to produce consistent results. Under operating conditions the joint will have some resistance, but it is an acceptable low value.

Multifilamentary Nb_3Sn Development

We investigated the relationship between mechanical strain and critical current in detail, using the cryogenic tensile-test apparatus constructed over the past two years. The apparatus proved to be versatile and ideally suited for this type of investigation.

We made strain measurements on Airco material that used either copper/10 wt%-tin or copper/13 wt%-tin bronze and niobium filaments $\sim 4 \mu m$ diam. The bronze/niobium ratio was always 2.9/1. All samples showed an initial increase in critical current as load was applied. The critical current peaked at $\sim 0.3\%$ strain; it only fell below its zero-strain level for strains $> 0.6\%$. The changes in critical current were always reversible for strain levels $< 0.8\%$, with permanent degradation occur-

ing at strains $\geq 0.9\%$. This type of behavior could be explained by the Nb_3Sn being initially in compression due to the differential contraction between it and the copper and bronze matrix. The initial application of external strain relieved this internal Nb_3Sn compression. The peak in the critical current corresponded to the Nb_3Sn being strain-free. The application of either true tensile or compressive strain on the Nb_3Sn thus caused a reduction of the critical current. A series of measurements, where we applied combined bending and tensile strains to the sample, further confirmed this explanation.

We used the results of the critical current-strain work as a basis to design a cryostabilized 5-kA conductor for the first Nb_3Sn insert coils in MFTF. Fabrication of a prototype length of this conductor will begin at Airco during FY 1978.

We conclude that these "bronze process" multifilamentary conductors can tolerate high enough mechanical strain and have high enough current density to be useful in large, high-field coils. There are three remaining tasks:

- Develop an appropriate stabilizing scheme (which may be different for each application).
 - Further develop the most economical manufacturing techniques for large billets.
 - Demonstrate satisfactory operation of the conductor when wound into a coil.
- Fabrication and operation of the HFTF insert coils should accomplish these.

The work associated with the use of metal-foil strain gages in temporary experimental installations, such as for Nb_3Sn strain measurements, was completed. The extension of this work to permanent installations, such as the MFTF magnet system, will be completed next year as part of the MFTF Project.

Manufacturing development work continued over the past year at both Airco and Supercor, and a new program was initiated at Magnetic Corporation of America (MCA). The program at Airco included a study of alternative tantalum-barrier fabrication techniques and the fabrication of a 3.5-kA conductor with increased copper content. The tantalum-barrier study included the assembly of a billet, which had seamers and welded tantalum tubes and wrapped tantalum foil as barriers. This work was not completed because of problems in acquiring suitable tantalum. A 3.5-kA conductor with 62% copper (rather than the standard 34%) was produced but exhibited center-bursting problems during the final drawing states. Airco solved this problem on a similar conductor by changing the heat treatment and die schedules.

Supercor fabricated a 3.5-kG conductor using

niobium tubes containing copper/13 wt%-tin bronze. The fabrication process involved two 20-cm extrusion billets. After the second extrusion, the niobium tubes broke over most of the conductor cross-section. Attempts to measure the critical current of heat-treated samples of this conductor were unsuccessful because of resistance at low current levels.

A program was initiated at MCA to investigate the manufacturing possibilities of the tin-infiltrated sintered-niobium process. A number of sintered rods are now being prepared for a trial 5-cm billet.

High-Field Test Facility

We made considerable progress on H_{ir}TF. A hatch was built into the roof of the cryogenics laboratory to allow the new 2-m-diam cryostat and the refrigeration units released from Baseball II-T to be brought in. We insulated the cryostat with super-insulation, fitted it with liquid-nitrogen shields, leak-tested it, then installed it in the existing pit. The styrofoam heat plug, vapor-cooled high-current leads, and auxiliary fittings were fabricated and fitted to the cryostat top plate; the whole assembly is now ready for its first cooldown to 4.2 K.

The Baseball II-T refrigerator, 10 000-litre liquid-helium storage Dewar, and helium purifier were dismantled, reassembled, and commissioned in the cryogenics laboratory. New transfer tubes were fabricated and fitted between all the various units.

We wound the first two Nb-Ti backing coils with 15 000 m of surplus conductor from Princeton. These coils are each 1-m bore, 1.7-m o.d., and 224-mm long. They will be assembled initially with the MFTF test coil to enhance its maximum field. We ordered a further 23 000 m of similar conductor from Supercon to wind two similar, but 50% longer, coils. After we complete testing the MFTF test coil, we will remove it from the assembly and assemble all four Nb-Ti backing coils to provide the background field for testing Nb₃Sn insert coils.

We ordered and began assembling the power supplies, circuit breakers, protective resistors, and auxiliary equipment and controls to operate the first two backing coils and the MFTF test coil.

Magnetic-Field Computer-Code Development

EFFI, a new computer code, is now available for general use. It calculates magnetic-flux lines, fields, forces, and inductances for an arbitrary system of coils made from circular arcs and/or straight segments of rectangular cross-section conductor bundle. In addition to printed output, one can also obtain plots of forces, field contours, field profiles, flux lines, and field magnitude along a flux line.

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Direct Energy Conversion

Beam Direct Conversion

In last year's annual report we described a prototype experiment at 15-keV that proved the principle of inline beam direct conversion with electrostatic suppression of background electrons. During the

past year we scaled up the 15-keV experiment to a 120-keV system and investigated magnetic suppression of electrons to overcome the electrostatic limitations due to beam-space charge. We recently reported the engineering status of this work.¹

Magnetic Suppression of Electrons. The limits on beam density and thickness imposed by electrostatic electron suppression can be relaxed if the electrons are magnetically suppressed. We used our 15-keV facility to test different magnetic-field configurations. In one approach we used an iron yoke and narrow pole pieces (Fig. 1) to produce a localized field perpendicular to the beam. Figure 2(a) shows the location of the magnet relative to the collector. A plot of the magnetic field strength on the beam axis is in Fig. 2(b). We found that a field of about 300 G was needed to stop the electrons when the collector was biased positively.

Our present effort in this series of tests is being directed toward the understanding of mechanisms by which the magnetically confined electrons are arriving at the collector.

120-keV Beam Direct Conversion. We constructed a larger converter (Fig. 3) based on DART-code calculations and the 15-keV prototype with electrostatic energy suppression. This system was installed in the Berkeley 120-keV test stand (Fig. 4) and operated with a beam of maximum total power of over 1 MW. Initial operation provided information on several phenomena requiring further work.

We determined that additional pumping speed would be required to attain high efficiency of beam direct conversion. The most critical gas-pressure requirement is imposed by

- The power load resulting from the acceleration and collection of slow ions and electrons produced by ionization.
- Charge-exchange of background gas and by the secondary electrons thus produced.

Fig. 1. Magnet used to produce a field perpendicular to the beam for magnetic electron suppression.

Fig. 2. (a) Beam direct converter with a perpendicular magnetic field to suppress the electrons. (b) Field strength along the beam axis.

Fig. 3. Beam direct converter electrode assembly.

Fig. 4. Lawrence Berkeley Laboratory 120-keV test stand with the direct converter and cryopump.

For this reason we started fabrication of a 150 000 litre/s cryopump to maintain a pressure of 2×10^{-5} Torr under a gas load equivalent to several amperes of ions and fast beams atoms. The cryopump will be installed in the position shown by Fig. 4 to pump the gas produced in the beam dump and in the direct converter.

In addition to the diffuse background gas that can be pumped away there will be a gas component collisionlessly streaming from the neutralizer. We calculate that a drift space of about 50 cm between neutralizer and converter will be required to attenuate this streaming component and to provide space for gas pumping.

The last series of 120-kV tests showed that the collected ion current was able to bias the collector up to 40-kV by the IR drop across a load resistor. This appears to be limited by the 40-keV and 60-keV dissociation products of molecular-hydrogen ions, which are more abundant than the converter was designed for. Beam analysis has shown several amperes of such products in the Lawrence Berkeley Laboratory beam.

The most certain way of eliminating problems caused by molecular ions will be to operate the beam on helium gas rather than on hydrogen. It may ultimately be necessary to use a helium cryotrap for this reason. There are other advantages to using helium rather than hydrogen for high-

energy neutral injection (e.g., deeper penetration into a confined plasma).

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Advanced-Fueled Fusion Reactors Suitable for Direct-Energy Conversion *

We designed a 120-kV helium-3 neutral-beam injector for fueling and heating deuterium/helium-3 reactors. The design was an extrapolation from existing Lawrence Berkeley Laboratory (LBL) injectors for deuterium. We paid special attention to (a) attaining a 6-month operating life, (b) incorporating direct conversion and (3) adopting recently developed cryotrapping technology to the problem of pumping helium-3.

The injector is 6-m long, the source ion aperture is 100×7 cm, and the 22-A neutral beam has about an 88×30 cm cross section when measured 10 m from the source. The injector employs conventional positive-ion acceleration (no satisfactory helium-3 negative-ion sources have been demonstrated). We have concluded that sputtering is the life-limiting process, and only by reducing the source's ion-current density (below the electrical-stress-limited value) to 108 mA/cm^2 and adding extra acceleration grids can excessive sputter damage be avoided before 6 months pass. At this reduced current, electrical stresses are comparatively modest. The grids require some form of active cooling (we have chosen to use heat pipes as grids).

Conventional hairpin filaments of the type used in experimental ion sources do not provide for 6 months of operating life. Instead we have incorporated an indirectly-heated, hollow matrix cathode of the type under development jointly by Lawrence Livermore Laboratory and LBL.

The gross input power to the injector is 5.1 MW. Of this, 1.3 MW is supplied from the direct converter. The direct converter is a lowered design that was analyzed with the DART code and found to

* Work sponsored by Electric Power Research Institute under contract No. RP645-2.

capture 89% of the incident ions. Injector efficiency is 63%, assuming 90%-efficient power supplies.

This project has supported, in part, the helium-3 cryotrapping studies that demonstrated success this year. Helium-3 vacuum pumping is a serious problem. Indeed, injector size is dominated by the required cryotrapping panel area. Argon-sprayed, liquid-helium-cooled cryotrapping panels (11 m^2) surround the beam. Thirty argon atoms are sprayed on the LHe-cooled surface for every helium-3 atom removed. The enthalpy change associated with the argon is the principal refrigerant load; this makes the LHe refrigerator the principal cost item in the design. Further the additional argon causes the LHe panel to frost (to a $100\text{-}\mu\text{m}$ thickness) in 4 min at high pressures (1.5×10^{-4} Torr). To allow the use of cryotrapping at these pressures, we extended the normal LHe surface by a factor of 10 and postulated a short (10-min) defrost time. While otherwise satisfactory, the cryotrapping designs need to be improved to avoid the excessive frosting rate if used at pressures above 10^{-5} Torr.

Author

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Neutral-Beam Conceptual Studies

We completed two major studies of neutral-beam injectors. One injector, for the Reference Mirror Reactor,¹ will deliver 1800 A of 150-kV neutral particles at 81% efficiency; the other, for the Tandem Mirror Reactor,² will deliver 122.5 A of 1.2-MeV neutral at 73% efficiency. The beams in both injectors will originate as negative ions, formed in cesium double charge-exchange cells. The Reference Mirror Injector will use photodetachment to convert the negative ions to neutrals, where the Tandem Mirror will use a cesium plasma stripper. We presented information about these injectors at several meetings during the year.³⁻⁷

A third study, just completed, concerns an injector for the Hybrid Mirror Reactor.⁸ This unit will deliver 2600 A of 125-keV neutrals at 60.5% efficiency. It will use a positive-ion beam, with a neutralizer formed from a cesium-vapor cell. The cesium vapor will reduce the area of cryopumps needed along the beam line by blocking the flow of low-temperature gas. A favorable efficiency will be obtained by means of energy-recovery electrodes.

The primary objective of these designs was to evolve viable methods to generate the beams at reasonable efficiencies. Reliability and long life also concerned us. We considered high-voltage arc suppression,^{9,10} continuous cryogenic pumping, grids designed for continuous operation,¹¹

shielding insulators from neutron bombardment, and redundancy to obtain reliability.¹² In addition, we conducted an experiment on a long-life cathode for the Berkeley-type ion source.¹²

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* On loan from Westinghouse Electric Corporation

Reactor Studies

Field-Reversed Mirror Reactor

Our chief effort in FY 1977 on the Field-Reversed Mirror (FRM) reactor was directed toward completing the conceptual design of the vertical-stacked multicell reactor (Fig. 1). The final design was a 12-cell unit producing roughly 100-MWe net electric output.¹ Using design concepts developed for the tandem mirror study, we started a conceptual design of a modular, horizontal-axis multicell reactor. This approach leads to simpler overall structure and serviceability, but involves more difficulty in changing the inner Ioffe bar-mirror assembly, which may have to be replaced roughly twice as often as the blanket/first wall assembly. Effort on the horizontal design will continue in FY 1978.

In addition to the detailed designs, we continued to do parameter studies to investigate the sensitivity of our reactor cost estimates to various assumed input parameters. One effect neglected in the past was the heating of the plasma by fusion products. Analytic estimates² and computer calculations indicated that 30 to 60% of the fusion alpha-particle energy could be retained in the plasma, depending on plasma size, temperature, and plasma conditions in the boundary region along the separatrix. A parameter study of the effect of alpha heating on reactor economics showed that too much heating was unfavorable. Circulating power and beam costs would be reduced by retaining a large fraction of the alpha energy, but the electron temperature and pressure would be driven up, requiring stronger and more expensive magnets for a given fusion power.

Fig. 1. Our Field-Reversed Mirror (FRM) reactor's final conceptual design features 12 cells stacked vertically. This multicell reactor will produce roughly 100 MWe net electric output.

The optimum alpha-energy retention appeared to be about 30% (Fig. 2).

Parameter studies showed the reactor costs were relatively insensitive to assumptions about neutral-beam absorption (Fig. 3; "Plasma thickness" is the ratio of minor radius to beam absorption length). However, the costs are sensitive to assumed plasma pressure and higher ratios of plasma pressure to magnetic pressure (beta) are desirable (Fig. 4). Based on these findings, we decided not to devote a great deal of effort to neutral-beam deposition calculations; rather, we will concentrate, in FY 1978, on developing an accurate method for calculating plasma pressure.

Finally, we examined several schemes for reactor

startup. In-place startup was found to require an impractical amount of neutral-beam current. We also investigated a concept in which a field-reversed plasma is generated in an external chamber and moved into place by pulsed field coils. This appeared to involve a small cost additional to the reactor; it is at present our preferred method of reactor startup.

Fig. 2. The effect of alpha heating on FRM reactor economics shows that too much heating is unfavorable. Optimum alpha-energy retention appears to be about 30%.

Fig. 3. Data for an 11-cell FRM reactor show that reactor costs are relatively insensitive to assumptions about neutral-beam absorption. Plasma thickness represents beam attenuation in e-folds to the plasma's center.

Fig. 4. Data for an 11-cell FRM reactor reveal that higher ratios of beta are desirable.

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Preliminary Design Study of the Tandem Mirror Reactor

The concept of the Tandem Mirror Reactor (TMR), as developed by Dimov, *et al.*,¹ and by Fowler and Logan,² employs the positive electrostatic potential of two ordinary (standard) mirrors to plug the loss of plasma from the ends of a long solenoid. The combination results in Q values of 5 or so (where Q = fusion power/injection power), whereas the standard mirror Q is at most slightly more than 1. The concept looks sufficiently interesting for us to have initiated a major experiment called the Tandem Mirror Experiment to check out and explore the underlying physics questions.

A reactor based on this concept produces 1000 MW and consists of a solenoidal magnet about 100-m long. A cylindrical blanket is used for energy recovery and tritium breeding. Thus the reactor itself is simple and of low technology. The end plugs, however, are of high technology, having the high magnetic fields needed to confine the high-pressure plasma and the high injection energy (~ 1.2 MeV) needed to achieve good magnetic confinement. The plasma density in the plug ($\sim 8 \times 10^{14}$ cm⁻³) is considerably higher than that in the central cell ($\sim 1 \times 10^{14}$ cm⁻³) to provide a potential barrier at each end ($\phi = T_e \ln n_{\text{plug}}/n_{\text{solenoid}}$). Because the function of the end-plug plasma is to provide a potential barrier and not to produce power, only deuterium (or even hydrogen) need be injected. Therefore, neutron production in the end plugs is relatively low. The end-plug magnets are

small (the size of the Mirror Fusion Test Facility coil), but of high field strength (17 T). Thus what high technology is required for the TMR is concentrated in the end plugs.

A detailed report³ describes how a 1000-MW TMR would look, based on our present understanding. Because the design is based on rapidly evolving physics and engineering ideas, this report is a preliminary description of a TMR; we will address design problems in a later version of the design. For example, at the beginning of the study, we did not understand the problem of ash (helium-4) buildup; consequently, we ignored this in most of the design. On the basis of much new understanding of steady-state equilibrium concentrations of ash, as discussed in Ref. 3's chapter on physics (Ch. 3), we believe steady state may be possible from the ash-buildup point of view. The design consequences, however, are as yet unknown.

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Fusion-Fission Hybrid-Reactor Studies

Point-Design Studies. Our hybrid-reactor studies reached a milestone this year with the completion of a reference conceptual design for a fusion-fission hybrid reactor based on a classically con-

* Participating guest from Pacific Gas & Electric Company, San Francisco, California.

* On loan from Westinghouse Electric Corporation.

lined mirror plasma and a depleted uranium blanket. The design study, a joint activity between Lawrence Livermore Laboratory (LLL) and General Atomic Company (GA), culminated several years of research on the standard mirror hybrid. This research involved a series of iterations on point designs, optimization studies, and reactor-subsystem designs.

The major design choices for the reactor are in Table 1; the major reactor parameters are in Table 2. We optimized these reactor parameters for fissile-fuel production. Plutonium production of 1900 kg/y, resulting from the neutron output of the 400-MW fusion plasma, is sufficient to provide make-up fuel for about six 1000-MWe light-water reactors. Figure 1 is a cutaway view of the reactor. Its fusion components (magnet, blanket, and injectors) and its primary heat-transfer-loop components are mounted in a prestressed-concrete reactor vessel; end tanks for plasma leakage are mounted above and below the confinement region. A report describing the details of the conceptual design is in preparation.

Table 1. Reference-mirror hybrid-reactor design choices.

- Minimum-B mirror confinement.
- Yin-yang coil design, niobium-titanium superconductor.
- Positive-ion injectors with direct recovery.
- Fast-spectrum blanket neutronics.
- Single-stage, plasma direct converter.
- Cryocondensation vacuum pumping.
- Blanket:
 - U₃Si fuel (depleted uranium).
 - Lithium hydroxide tritium breeder (natural lithium).
 - Inconel-718 structural material.
- Helium primary heat-transfer loop (PHTL).
- Prestressed-Concrete Reactor Vessel:
 - Magnet restraint.
 - PHTL restraint.
 - Blanket support and restraint.
- Steam thermal-conversion system.

Table 2. Reference-mirror hybrid-reactor parameters.

Property	Value
Fusion power (MW)	400
Thermal power, avg (MW)	3600
Injected neutral power (MW)	625
Net electric-output power (MW)	525
First-wall 14-MeV neutron current (MW/m ²)	2
Annual fissile production (kg)	1900

Fig. 1. The fusion components for this standard mirror hybrid reactor are mounted in a prestressed-concrete reactor vessel. End tanks for plasma leakage sit above and below the confinement region.

As an extension of our interest in the breeding of fissile fuel with hybrid reactor, we undertook a preliminary evaluation of an alternate nuclear-breeding option, the accelerator breeder. This study resulted in the preparation of a conceptual accelerator breeder-reactor design.²

Activities. Fiscal year 1977 was one of increased interest in the hybrid reactor concept as compared with past years. Two members of the mirror-hybrid design team (D. J. Bender of LLL and K. R. Schultz of GA) participated in a US/USSR workshop on hybrid-reactor studies in Moscow, where the mirror hybrid design was reviewed.³ We learned that the hybrid reactor has become the near-term reactor goal of the Soviet fusion program. The LLL hybrid-study group also participated in an evaluation of Rand Corporation of various nuclear breeding options,⁴ which included the hybrid reactor and the accelerator breeder reactor.

A summary of our reference hybrid reactor design was presented at the summer American Nuclear Society meeting⁵ at New York and the International Atomic Energy Agency Conference and Workshop on Fusion Reactor Design⁶ at Madison, Wisconsin. Details of the design of selected reactor components were presented at the 7th Symposium on Engineering Problems of Fusion Research⁷ in Knoxville, Tennessee and the winter American Nuclear Society Meeting^{8,9} in San Francisco. We also participated in two workshops on hybrid reac-

tors sponsored by the Division of Magnetic Fusion Energy, Department of Energy.¹⁰⁻¹²

New Directions. The concerns expressed by the current administration regarding the proliferation risk of the plutonium fuel cycle, as required for plutonium-recycle light-water reactors and the liquid-metal fast-breeder reactor, has prompted us to begin examination of alternate fuel cycles incorporating the hybrid reactor. We completed a preliminary evaluation of a no-reprocessing scenario based on uranium-233 produced in a mirror hybrid and burned in a high-temperature, gas-cooled reactor¹³; it forms the basis for our studies for FY 1978.

Our parametric studies also indicated that a plasma-confinement configuration exhibiting a higher fusion power/injector power (Q) than the classical mirror plasma would result in improved hybrid-reactor economics. Thus, we initiated a study of a hybrid based on a low-technology version of the tandem mirror reactor (Fig. 2). The reactor's parameters are in Table 3. This reactor requires neutral-beam injection at 125 keV in the end plugs and central cell and a maximum magnetic field of 8 T, which results in a plasma with a Q of 1.8 and a first-wall loading of about 3 MW/m².

Table 3. Parameters of a tandem mirror hybrid reactor.

Parameter	Value
Fissile-fuel-breeding central cell:	
<i>Cylindrical shape</i>	
length (m)	27
outside radius (m)	3.5
Magnetic-field strength (T)	3
Neutral-beam injection of deuterium & tritium (A)	1070 @ 125 keV
First-wall neutron loading (MW/m ²)	2.8
Fusion power (MW)	260
Blanket thermal power (MW)	1700
End plugs:	
Spherical shape outside coil radius (m)	2.0
Magnetic-field strength (T)	8
Neutral-beam injection of deuterium (T) into each plug (A)	42 @ 125 keV
Performance:	
Overall plasma Q	1.8
Recirculating power fraction	0.29
Net electrical output (MWe)	500
Annual fissile production, Uranium-233 (kg)	1000

Fig. 2. This tandem mirror hybrid reactor requires neutral-beam injection at 125 keV in its end plugs. Based on a low-technology version of the tandem mirror reactor, this hybrid requires a maximum magnetic field of 8 T.

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Small Mirror Reactors

We joined with General Atomic Company and Pacific Gas and Electric to work on a "small reactor" project funded by the Electric Power Research Institute. The objective of this project was to

evaluate mirror fusion concepts that might result in small reactors for the production of electrical power or fuels. The two-year program goal was to develop a conceptual design of a particular mirror concept that could provide a useful output from fusion and be built and operated in the late 1980's. Our first year's work (which officially began in May 1977) involved a scoping study of several reactor options. The second year's work will consist of a conceptual design study of one selected option.

One of the early accomplishments was the adoption by the three contractors of a set of general guidelines for the project. We agreed that "small" meant physically small and low cost, and that the mirror reactors to be designed should be as small as possible consistent with a requirement for net product production and commercial upgrade potential. Recognizing the attractiveness of a low-power commercial reactor, we agreed that commercial upgrade could be through replication of small units, addition of modular elements, possible near-term advances in technology, or (as a last resort) scaleup beyond 100 to 200 MWe or the equivalent. We also agreed that it would be highly desirable if the technologies to be incorporated into the designs be limited to those expected to be available by the mid-1980's, based on presently committed research and development programs.

For the period covered by this annual report, we directed our effort on the project mostly at parameter studies of three basic mirror confinement concepts: the standard mirror, the tandem mirror, and the field-reversed mirror. In each case our goal was the specification of a set of plasma parameters and technological parameters (field strength, injection energy, etc.) appropriate for design of the small reactors.

Our previous studies indicated that for the standard mirror to have a commercial future it must be a fusion-fission hybrid. Our parameter studies thus concentrated on hybrid standard mirror reactors.

The proposed design for the small standard mirror hybrid is significantly different than that for previous standard mirror reactors (the magnet shape is cylindrical rather than spherical). The minimum-B magnetic well is provided by the combination of a pair of solenoidal magnets and four Ioffe bars. We believe we can design a smaller reactor with this magnet than with the spherical (yin-yang) magnet. We are designing this machine as a net-product producer (power generation by bred fissile fuel in fission reactor > electrical input into hybrid), rather than a net-electric power producer.

The Tandem Mirror Reactor we designed for the Department of Energy had high end-plug

technology—1.2-MeV beams and 17-T coils—well beyond the goals of our presently committed beam and magnet programs. Relaxation of the plug technology quickly resulted in a system that didn't work for the mode of operation chosen, i.e., energetic injection of the end plugs only. This led us to consider another mode of operation—energetic injection of the end plugs and the central cell. We are now investigating the use of a two-component tandem mirror with central-cell injection as a basis for a small hybrid reactor.

For the field-reversed mirror (FRM) concept, we are investigating a single-cell version of the multicell FRM reactor design. Most of the work to date has involved incorporating various improvements in the parametric design code for the FRM (especially adding "end effects" so that it can correctly treat the one cell case). Our conclusions are not yet final, but it appears that we can still expect a high fusion power/injector power ($Q \sim 4$ or 5) for the FRM plasma.

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Neutral-Beam Development and Technology

Introduction

The injection of intense beams of hydrogen and deuterium atoms is at present the best way to heat and fuel mirror and tokamak plasmas. Experiments now operating, or under construction, require injection energies of 20 to 120 keV. Ten years from now energies as high as 1 MeV may be needed. (Beam power from a single injector is in the range from 1 to 9 MW.)

The neutral-beam program to develop these injectors has several elements, including

- Design, construction, and operation of test facilities.
- Development and testing of neutral-beam systems based on the acceleration and neutralization of positive hydrogen and deuterium ions (H^+ , D^+).
- Development and testing of neutral-beam systems based on the acceleration and neutralization of negative ions (H^- , D^-).
- Design and testing of prototype beam lines.
- Transfer of technology to industry.

Test Facilities

These continue to be the pacing items of the program, as we go to higher currents and longer

pulse lengths. Table 1 lists the test stands suitable for development of high-power beams with energies of 80 to 200 keV. These test stands must have high pumping speeds to handle the gas loads from the ion sources and neutralizers. Because the accelerator structures are relatively fragile and must handle very high power, one must use reliable diagnostic and control techniques to prevent damage to the injectors and experiments to which they are attached.

Test Stand IIIA. The only high-voltage, high-current, long-pulse operational neutral-beam test stand in the U.S., IIIA has been used for testing a variety of beam-line concepts and components for about a year. In the process, the viability of a new approach to the regulation and switching of the high-voltage power-supply output has been proven. Conventional designs require tubes that don't exist yet, but necessity led to the development of "shunt controlled" systems¹ using off-the-shelf silicon-controlled rectifiers (SCR's). The later IIIB and the Tokamak Fusion Test Reactor (TFTR) Neutral-Beam System Test Facility high-voltage systems² use the same basic design. The IIIB SCR switches³ appear in Fig. 1.

A second electronic innovation successfully tested on IIIA is a "magnetic core snubber."⁴ Our tests show that injector performance degrades if more than a few joules of energy are deposited in the accelerator electrodes when a spark occurs. At 120 kV the energy stored in the stray capacitance of the source, cables, and other electronics exceeds this limit by an order of magnitude or more. Figure 2 shows a circuit to limit the damage caused by a spark. The magnetic core snubber limits peak current during a neutral-beam source spark to ≤ 200 A and limits the energy delivered to such a spark to a few joules. The snubber absorbs the remainder of the stray-capacitance energy in core losses governed by time-dependent eddy-current and hysteresis processes.

Table 1. High-voltage test facilities.

Facility	Vacuum system				
	Electronics (kV)	(A)	(s)	Deuterium-gas vol (litres)	Pumping speed (litres/s)
Test Stand III A	120	20	0.5	170 000	60 000
Test Stand III B	120	80	0.05		
High-Voltage	80	85	30	20 000	650 000
Test Stand	120	65	30		
(HVTs)	200	20	dc

Fig. 1. Silicon-controlled rectifier switches for Test Stand IIIB (the IIIA system uses the same basic design). The series switch is on the right, the shunt switches are center and left.

The capability of our computer installation to process diagnostic data and control power supplies and other system components has been expanded considerably. Members of the Draper Laboratory, in cooperation with the Lawrence Berkeley Laboratory (LBL) Real-Time Systems Group, have developed software to optimize and condition injectors.⁵ The computer has successfully interpreted diagnostic signals and has adjusted power-supply controls, but has not yet been allowed to "push the button." This step is imminent.

Test Stand IIIB. This test facility has the first all-solid-state, high-power neutral-beam system built. It became operational in the summer of 1977, powering and controlling our first full-current TFTR source.

High-Voltage Test Stand. The neutral-beam High-Voltage Test Stand (HVTS) neared completion at the end of the reporting period. Most components had been installed or were being bench tested, and much of the stand had been tested in place.

Fig. 2. "Magnetic core snubber" circuit for limiting spark damage in neutral-beam injector. The snubber limits peak current during a neutral-beam source spark to ≤ 200 A. It also limits the energy delivered to such a spark to a few joules.

Fig. 3. High-Voltage Test Stand (HVTS) for development of high-power neutral beams. To shield personnel from neutron radiation, we placed the beam line in a concrete room. A high-voltage power supply (not shown) sits in a pad area about 30 m to the left of the main cryopump.

An artist's concept (Fig. 3) shows the beam line installed in a concrete room to protect personnel against neutrons from D-D reactions in the beam dump. A large control room is adjacent to the shielded room. In a smaller adjacent room, we produce liquid helium for the cryopumps. Low-voltage power supplies (arc and filament) are mounted on a high-voltage deck near the main cryopump. High-voltage power comes from a supply constructed in a pad area outside the building.

Building modifications to accommodate the HVTS facility are complete and all major components are in place. The high-vacuum system, which combines cryopumping and high-speed mechanical pumping, is essentially complete and all components have been tested. The entire beam line has been assembled and leak tested. Figure 4 shows the beam line during assembly.

Fig. 4. Beam line for HVTS. The view shows the beam line during assembly; the beam dump is mounted in the open tank (right).

We operated the main cryopump and its associated refrigeration system for ~1000 h without serious problems. Pumping speeds of the main cryopump for deuterium and hydrogen were measured on two occasions; these speeds exceeded the predicted value (500 000 litres/s for deuterium), although variations in gas pressure through the system made accurate measurements difficult.

We made liquid-helium boil-off tests on the main cryopump. Measurements indicated a heat load of at least twice the predicted load of 4 to 8 W. We could not explain this by poor estimates of surface emissivities. Visual inspection, during and after final assembly, indicated no glaring deficiencies. Since the system is operational and meets pumping requirements, the problem was corrected by increasing the liquifier capacity by adding a third compressor.

A thermal inertia-type beam dump was designed and is under construction. This consists of two large water-cooled copper plates in a V-type configuration having a variable half-angle of from 7 to 10 degrees. It will be instrumented with an array of thermistors into a computerized readout system yielding beam-profile information. The target is designed to handle a pulsed beam load of as high as 8 MW for 30 s.

A neutralizer was fabricated and is currently mounted on the test stand along with a 20-kV source (Fig. 5). Preliminary testing with this source is underway.

The main power supply (Fig. 6) is designed for operation in three modes:

- 200 kV, 20 A, dc.
- 120 kV, 65 A, 30 s.
- 80 kV, 85 A, 30 s.

Power can be provided with either polarity. We have completed the power supply and tested it at

Fig. 5. Neutralizer and 20-kV source mounted on HVTS. We began preliminary testing with this source.

Fig. 6. Main power supply for HVTS. Designed to operate at three voltages (80, 120, and 200 kV), the supply has already been tested at low voltage.

low voltage.

Delivery of the newly developed switch/modulator was delayed by complications during construction at the factory. A lower voltage tube, usable to 40-kV source voltage, is being installed for preliminary operation.

We used arc and filament supplies to operate an arc in a chamber. The supply ratings are

filament: 12 V, 7500 A.

Arc: 60 V, 7500 A.

The supplies can operate at full load for 30 s, with a duty cycle of 10% for cooling. Power comes from battery banks rated at 120 V, 200 A-h for the arc and 24 V, 5000 A-h for the filament. Recharging is done between operating pulses and/or during evenings or other test shutdown times.

Positive-Ion-Based Program

We made a large, encouraging step upward in voltage and pulse length by achieving successful operation of a fractional-area TFTR source. TFTR sources are rated at 120 kV, 65 A, 0.5 s, deuterium.

To minimize cost and time, we do our basic development with structures that correspond to the full-size sources in all respects, except that they are reduced in one dimension (transverse to the beam direction). In this case, the fractional-area source current (power-supply drain) is 12 A.

With grids shaped to focus the beam 8.5 m from the source, we obtained angular divergences, characterized by half-widths to the 1/e power points, of $\pm 0.42^\circ$ parallel and $\pm 1.28^\circ$ perpendicular to the long dimension of the accelerator slots.

These divergences, while acceptable for near-term applications (i.e., TFTR, Doublet III tokamak (DIII), Mirror Fusion Test Facility (MFTF)), are somewhat larger than predicted from 20- and 40-kV-source operation. A new spectroscopic technique⁶ for measuring neutral-beam divergences, species mixtures, and energies has given preliminary evidence that the angles increase as the beam transverses the neutralizer: i.e., we may be seeing the result of a beam-plasma interaction.

Figure 7 shows a fractional-area TFTR source, enclosed in a pressurized sulfur-hexafluoride shroud and mounted on our IIA test facility. A plasma source provides the ions for acceleration (Fig. 8). Figure 9 gives a cross section of the plasma source and accelerator structure.

Similar structures are being built and tested for MFTF (80 kV, deuterium) and DIII (80 kV, hydrogen) applications. The main differences are in the shapes and spacings of the accelerator electrodes.

We built a full-scale TFTR source module and tested it to 60 kV. The accelerator structure (Fig. 10) uses epoxy insulators, which will be ceramic in the next model.

The plasma sources operate reliably and produce uniform, noise-free plasmas (Fig. 11), in part because they do not have magnetic fields in the center. Unfortunately the atomic (most desirable) fraction of the hydrogen ions is approximately proportional to the arc power. In the progression from 40- to 120-kV sources the atomic fraction has dropped, partly because of a deliberate decrease in ion-current density, and hence, arc power. We have shown previously⁷ that an extension of the source barrel (in the beam direction) can raise the atomic fraction from 65 to 88% and that the addition of multipole magnetic fields (to form a "MacKenzie bucket") can maintain the required plasma uniformity. The Oak Ridge National Laboratory Neutral-Beam Group has had good experience with these multipole arrays, and the Divertor and injection Tokamak Experiment (DITE) group at Culham also reports good preliminary results with sources of the general LBL configuration, but with MacKenzie-bucket magnets on the surface. In addition

Fig. 7. One-half of beam line mounted on Test Stand IIA. The sulfur-hexafluoride pressurized shroud (right) encloses a fractional-area Tokamak Fusion Test Reactor (TFTR) 120-kV source.

Fig. 8. Plasma source for TFTR injector. This source provides ions for acceleration.

tion to the possibility that the atomic species mixture may be better, we should be able to use fewer and thicker filaments or hollow cathodes (either one desirable for continuous and dc operation) as electron sources. Consequently, we have built a MacKenzie-bucket plasma source (Fig. 12) to evaluate with our 40-, 60-, 80- and 120-kV accelerator structures.

We tested several other neutral-beam-line design principles and components during the year. A cryopump was built and installed in the IIA beam line to see if secondary particles from an intense, nearby beam would desorb condensed gas⁸; no effect was observed. We prepared an experiment to expose this same pump to intense neutron and gamma fluxes at the pulsed Triga reactor of the University of California, Berkeley, Dept. of Nuclear Engineering.

We measured trajectories of the charged components of intense beams deflected by a sweep-magnet. These measurements were compared with calculations⁶ to determine if there are defocusing electric fields caused by incomplete space-charge neutralization. No defocusing effects were observed.

Efficient Beams

Work continued on the efficient-beam (negative-ion) program, whose purpose is to obtain intense, negative-deuterium beams: accelerate them to 10 to 200 keV; and strip the attached electrons to yield a neutral-deuterium (D^0) beam produced at high power efficiency. A 100 mA, D^- beam, produced by double charge exchange in cesium, was accelerated to 60 keV.⁹⁻¹¹ We also worked on other beam-line components, on analysis of the beam, and on studies of a system using surface production of D^- .

1-keV D^+ Source. As reported last year,¹²

Fig. 9. Accelerator structure and plasma source (left). We are building and testing similar versions of this neutral-beam injector module for the Mirror Fusion Test Facility and the Compact H- tokamak.

Fig. 10. Full-size accelerator structure for TFTR. This structure uses epoxy insulators, which will be ceramic in the next model.

~20% of a 1-keV D^0 beam was converted to D^- in cesium vapor. We used a modified LBL source to obtain intense (~ampere) D^0 beams at 1 keV. Since the current density increases with the voltage between the first and second grid ($I \propto V_{12}^{3/2}/d_{12}^2$), we operated the source in a strong acceleration-deceleration configuration. In Fig. 13, a new grid,

Fig. 12. "MacKenzie Bucket" plasma source for 10-X-10-cm, 80- and 120-kV ion-source modules.

designed with the aid of the computer code WOLF to optimize beam divergence, is compared with the previous grid. For the configuration shown here, the calculated beam divergence is 3.5° , better than that observed in the experiment. A possible explanation for the poor beam divergence is that the beam must create its own background plasma for space-charge neutralization, and at 1 keV this

Fig. 11. Ion-current density profiles for 10-X-40-cm extraction region. These profiles show that the current density is uniform to $\pm 5\%$ throughout the region. Oscilloscope traces (top right) indicate saturated-ion current waveforms of the three vertical probes. The bottom right traces give the arc voltage and current.

Fig. 13. Acceleration grids for 10-keV D^+ beam. We designed a new grid (c) with the aid of the computer code WOLF. This compares with the previous grid (a & b) at different currents.

process is inefficient electron production cross sections are small. To compensate for this incomplete space charge neutralization, we are installing a set of emitting filaments directly behind the cathode. Each filament (0.052 cm) will emit a current density of 2 A/cm^2 at a temperature of 2700 K, thus providing the electrons required to provide charge neutralize the beam.

High-Energy Beams. The high-voltage accelerator, described in last year's report, was tested during the past year. It accelerated negative deuterium beams to 60 keV. Figure 14 shows horizontal and vertical profiles for the accelerated D^- beam. Beam divergences were $\sim 2.4^\circ$ along and across the accelerator slot. Calculations for a slot predicted 1.6° divergence. The electrons accelerated with the D^- ions were, for this measurement, swept out of the beam by a weak magnetic field and did not contribute to the measured signal. A comparison of the relative magnitude of the two sets of data shows that the electron current was significantly less than the negative-ion beam current. Investigations on accelerator design will continue through the next year.

Fig. 14. Beam profiles at end of diagnostic tank (as measured by a Faraday cup). Solid dots: negative deuterium ion (D^-) beam current; open dots: sum of D^- beam current and electron current, obtained without a magnetic field.

Plasma in the Negative-Ion Beam. Background plasma is essential to prevent space-charge blowup of the negative-ion beam. We extended the ion-dimensional calculations of plasma flow (reported last year) to two dimensions.^{13,14} Charge-exchange and stripping cells were modeled by an axial region

of high gas pressure and ionization rate. The pressure outside the cell may be made low, corresponding to the region near a high-voltage accelerator.

Typical computational results appear in Fig. 15. Note that plasma density is high only in the region

Fig. 15. Plasma densities in two-dimensional flow: $n_e = 2 \times 10^9 \exp(-r^2)$ and $n_i = 0.26 n_e [1 + 3 \exp(-z^2)]$. Note that plasma density is high only in the region of high ionization.

of high ionization. Electrons and ions formed in that region escape to the walls within axial lengths of a few beam radii. We used this transport mechanism in the negative-ion experiment to limit electron current into the accelerator.

Similar results were seen in the experiment. Figure 16 shows Langmuir-probe measurements; note that electron density was reduced to about the beam density. As we calculated, the electric field within the beam was small, which corresponded to the flat electron profile, and the residence time of plasma ions was long, which corresponded to a low production rate.

In this experiment, the low-energy (1-keV) D^- beam was required to propagate 1.3 m from the cesium cell to the entrance of the high-voltage accelerator. The low-energy beam must be quiet in the region of the accelerator grids. We found that the background gas in the transport region must be greater than $\sim 4 \times 10^{-5}$ Torr of deuterium for stable propagation. Figure 17a and 17b show Faraday-cup signals in the region of the accelerator entrance. In Figure 17a, there is a background deuterium-gas density of 4×10^{-5} Torr. Beam intensity is 3 mA/cm², and the beam is quiescent. Figure 17b shows the D^- beam propagating in an ambient background-gas density of $\sim 1 \times 10^{-6}$ Torr. The average beam intensity is ~ 1 mA/cm². Noise on the beam has two "characteristic" frequencies: a high-frequency mode (~ 3 to 5 MHz) superimposed on the low-frequency mode (~ 200 kHz). These

Fig. 16. Plasma densities in a plasma generated by a 10-keV D^- beam. A shielded Langmuir probe, which measured the densities, was scanned radially (25 cm from the entrance of the drift tank). The upper curve shows the ion current collected at -30 V bias (scale on left); the lower curve shows the electron current collected at +5.5 V above the floating potential (scale on right).

parasitic oscillations can be removed simply by adding the appropriate amount of background gas. Preliminary analysis^{15,16} suggests that the unstable mode is an acoustic wave traveling almost transverse to the beam.

Jet Surface Conversion. We also studied an alternate approach for making D^- beams: the jet surface-conversion system¹⁷ shown in Fig. 18. Its essential features are a supersonic jet of deuterium atoms and a separate, specially treated cathode. The jet impinging on the cathode is converted to D^- ions, which are accelerated and neutralized as shown. A magnetoplasmadynamic (MPD) arc¹⁸ and neutralizer¹⁷ efficiently produce the jet. For a cathode with an optimum coating of cesium, the surface-conversion efficiency (D^0 to D^-) may approach 50%.¹⁹ Reference 19 discusses a method for producing and maintaining an optimum cathode under working conditions. The acceleration grids, roughly indicated in the figure, are similar to the TFTR grids being tested at LBL; for a 200-keV system the current density would be about 0.25 A/cm².

Potentially, high power and gas efficiencies may be possible for the overall system.¹⁷ At present, LBL is conducting surface-conversion measurements and LLL is testing an MPD arc jet.

Prototype Beam Lines

Prototype neutral-beam lines, based on the positive-ion neutral-beam development and technology described above, are being built at LBL by the Engineering and Technical Services Division. Members of LBL's Research and Development Group interact on a regular basis with the engineering groups and with the staffs at Princeton Plasma Physics Laboratory, General Atomics, and the Department of Energy's Division of Magnetic Fusion Energy.

Technology Transfer

Many fusion experimental devices and reactors will use large, multiple neutral-beam systems. A demonstrated industrial manufacturing capability is desired to determine reliable cost estimates and schedules. Three firms have completed industrial manufacturing studies of 120-kV, 65-A, 0.5-s injector modules for us; we will receive hardware for evaluation near the end of 1978.

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Fig. 17. Faraday-cup signals in entrance region of high-voltage accelerator. These traces reveal oscillations on a negative-ion beam propagating at low gas pressure (b); (c) and (d) show expanded portions of (b).

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Fig. 18. Proposed neutral-beam system based on surface source of D^- ions. It features a supersonic jet of deuterium atoms (moving from right to left) and a specially treated cathode (left of center).

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Rotating-Target Neutron Source-II

Construction of the Rotating Target Neutron

Source-II (RTNS-II) facility continued through FY 1977. This facility was an FY 1976 federal-budget line item to provide two 14-MeV neutron sources, each producing 4×10^{13} neutrons/s for Division of Magnetic Fusion Energy (Department of Energy) investigation of fusion-reactor materials. During FY 1977 we brought the new building that houses the neutron sources to ~80% completion. Bids received during the phased-construction sequence were so favorable that it was possible to expand the users' work area of the facility by 150 m² and remain within the original cost estimate for the building. Overall size of the facility (Fig. 1) is now 1800 m²; occupancy by the project is expected before the end of calendar 1977.

During FY 1977 we focused the parallel R&D effort on performance testing of neutron-source components. After acceptance of the 400-kV power supplies, high-voltage enclosures, and isolation transformers from the supplier, we assembled one complete prototype accelerator (Fig. 2) for tests with hydrogen-ion (H_2^+) beams. The modified high-voltage terminal ran at 400 kV; the ion source produced 150 to 200 mA of magnetically separated H_2^+ beams suitable for injection into the acceleration column; and all accelerator power supply, vacuum, telemetry, and control systems tested successfully at 400 kV. The acceleration column is being installed for testing with the beam transport system in early FY 1978.

We built a full-scale tritium scrubber and tested it for efficiency, component lifetime, and likely failure

Fig. 1. Rotating-Target Neutron Source-II (RTNS-II) facility in Building 292. We expect to occupy this 1800-m² area before the end of calendar 1977. The first neutron source (in target room 1404) will be operational in late April 1978.

modes. Mechanical testing of a 5000-rpm, 50-cm-diam target also began. We used the RTNS-I source to develop noninteractive beam-current and beam-profile devices.

Assembly of the neutron sources in the new building will require 4 to 6 months. The first source will be operational in June 1978. Initial experiments will begin in August 1978.

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Radiation Damage

Correlation of Neutron Damage with Neutron Sources

Introduction. The high-energy neutron sources* planned for the radiation effects program are the Rotating-Target Neutron Source-II (RTNS-II), currently under construction at Lawrence Liver-

* For this report, neutron sources that produce a spectrum with neutron energies $E > 4$ MeV are high-energy neutron sources.

Fig. 2. Prototype accelerator for RTNS-II tests with hydrogen-ion beams. Its ion source produced magnetically separated beams suitable for injection into the acceleration column.

more Laboratory (LLL), and a lithium(d,n) stripping source, which is in the design stage. We expect these sources to provide a neutron flux of from 10^{17} to 10^{19} neutrons/m²·s.

Presently, we are using low-flux prototypes of these sources:

- RTNS-I at LLL, which has a maximum flux of 10^{16} neutrons/m²·s.

- Beryllium(d,n) stripping sources. One of these, at the University of California at Davis (UCD), has a flux of 7×10^{16} neutrons/m²·s.

Radiation-damage experiments on these low-flux prototype sources cannot produce the high neutron fluence ($> 10^{26}$ neutrons/m²) for evaluating the structural integrity of materials in a fusion reactor's first wall. They can, however, provide a basic understanding of the nature and magnitude of high-energy neutron-damage effects. They also allow direct comparison and correlation of high-energy neutron-damage effects with ion damage effects and fission-reactor neutron-damage effects.

This section reports the results of some exploratory studies on the nature and magnitude of radiation-damage effects produced by high-energy neutrons from RTNS and beryllium(d,n) sources.

Copper, Vanadium, and Niobium Irradiations. Results for the increase in yield stress vs neutron fluence for tensile specimens of copper, vanadium, and niobium irradiated with neutrons from RTNS, beryllium(d,n), and Livermore Pool-Type Reactor (LPTR)[†] sources appear in Fig. 1. The neutron-energy spectra for the sources are in Fig. 2. Most of the strengthening results are for ambient irradiation temperatures of 25°C for RTNS and beryllium(d,n) and about 65°C for LPTR. We show some results for irradiation of copper at 210°C in the RTNS and LPTR spectra.

These plots indicate that high-energy neutrons from RTNS and beryllium(d,n) sources are considerably more effective than fission-reactor neutrons in strengthening copper, vanadium, and niobium at 25 and 210°C. About 20 times more fission-reactor neutron ($E > 0.5$ MeV) fluence is required to produce the same strengthening in copper as is produced by fusion neutrons. If LPTR neutron fluence is expressed in terms of $E > 0.1$ MeV, this ratio reduces to 10. In niobium, the fluence ratios are ~ 17 for $E > 0.5$ eV and ~ 9 for $E > 1.0$ MeV. For copper, vanadium, and niobium, the ratios of beryllium(d,n) to RTNS neutron fluence for the same strengthening are about 1.3.

When the strengthening results for copper are replotted vs damage energy (Fig. 3), the data for

RTNS and beryllium(d,n) irradiations fall on the same curve. This shows that strengthening scales directly with the damage energy of these two sources. Comparison with the results for LPTR irradiation shows that it takes about 2.3 times more damage energy from fission-reactor neutrons to produce the same increased in yield strength produced by the higher energy neutrons.

The nature and magnitude of radiation-damage structures are being compared by transmission electron microscopy. We show dark-field three-dimensional stereo microscopy of the radiation-damage structures for copper irradiated to a fluence of 3.3×10^{22} neutrons/m² at 65°C in LPTR (Fig. 4) and for copper irradiated to a fluence of 1.27×10^{21} neutrons/m² at 25°C in RTNS (Fig. 5). Electron microscopy observations reveal that LPTR, RTNS, and beryllium(d,n) sources produce the same kind of primary structural defects, i.e., vacancy and interstitial point-defect clusters and small Frank and prismatic dislocation loops.

Differences in radiation strengthening produced by high-energy and fission-reactor neutrons appear to result from a greater rate of accumulation of those structural defects during high-energy neutron irradiation. Irradiation with high-energy neutrons from RTNS and beryllium(d,n) sources produces many high-energy cascades (> 100 keV) that spontaneously create stable vacancy clusters. Fission-reactor neutron irradiation produces few high-energy cascades, and the majority of structural defects form by diffusion-controlled coalescence of point defects. The fraction of displacement damage at room temperature retained in the form of primary structural defects appears to be greater during irradiation with high-energy neutrons. This is primarily caused by increased recombination of diffusing vacancies and interstitials during irradiation with fission neutrons.

Future irradiation studies will be conducted on refractory metals and alloys at elevated temperatures and higher fluences.

Type-316 Stainless-Steel Irradiations. The Department of Energy's breeder reactor development program has provided considerable data on the behavior of stainless steels in a radiation environment. Consequently, stainless steels have been proposed as candidates for fusion first walls. We are investigating the behavior of stainless steel in a fission-reactor environment.

Specimens of annealed and cold-worked type-316 stainless steel will be irradiated at room temperature and elevated temperature at RTNS and the beryllium(d,n) source at UCD. We will relate

[†] Fission-neutron source.

Fig. 1. Increase in yield stress for copper, vanadium, and niobium irradiated at various neutron sources. Temperatures refer to irradiation temperature. Irradiation increases yield stress in all cases, with Rotating-Target Neutron Source (RTNS) and beryllium(d,n) sources more effective than the fission-reactor source on a fluence basis.

Fig. 2. Spectral comparison of various neutron sources used in radiation-damage experiments. RTNS and beryllium(d,n) sources have a significant component above $E = 4$ MeV; LPTR and other fission reactors do not.

fluence and damage energy to changes in tensile properties and use electron microscopy to analyze the size, density, distribution, and morphology of radiation-induced defects. Strengthening mechanisms governing deformation behavior will be determined and the results interpreted in terms of damage microstructure. Data from tensile tests and electron microscope studies of specimens irradiated with high-energy neutrons will be compared with similar data from fission-neutron irradiation experiments. We will then compare the relative damage effectiveness of neutrons from different radiation sources.

Current Progress. We conducted tensile tests on type-316 stainless-steel specimens irradiated with 14-MeV neutrons at room temperature. Two types of material were tested. The first was cold rolled with 33% reduction in thickness; the second was annealed at 1050°C and water quenched. Table I gives the chemical composition of these materials.

Fig. 3. Change in mechanical properties for irradiated copper replotted vs damage energy. The data from RTNS and beryllium(d,n) irradiations correlate well on a damage-energy basis; the data from LPTR irradiation do not correlate with the others.

Fig. 4. Transmission electron micrographs of radiation-damage structures produced in copper after LPTR irradiation to 3.3×10^{22} neutrons/m² ($E > 0.5$ MeV). The micrographs are a three-dimensional pair produced by tilting the specimen slightly between exposures. This allowed us to obtain depth perspective with the proper viewing equipment.

Stress-strain curves for cold-rolled material appear in Fig. 6. Irradiation increased the yield stress and ultimate stress of the cold-rolled specimen by about 5%. Elongation decreased from 15 to 13.5% and reduction in area decreased from 50 to 45% after irradiation to a fluence of 3.0×10^{21} neutrons/m² ($E = 14$ MeV). Figure 7 has stress-strain curves for annealed material. Irradiation produced much larger changes in tensile properties of annealed material than in cold-worked material. The yield strength of the specimen irradiated to a fluence of 2.5×10^{21} neutrons/m² increased about 60%; its elongation decreased from 70 to 47% after irradiation. The reduction in area of the irradiated specimen was 60% as compared with a reduction in area of 70% for the unirradiated specimen.

A fluence of 1.3×10^{21} neutrons/m² also caused changes in the tensile properties of the annealed material. Thus, the threshold for irradiation-induced changes in strength and ductility of an-

nealed Type-316 stainless steel is below a fluence of 10^{21} neutrons/m² for 14-MeV neutrons.

Higgy and Hammad reported the effect of fission-reactor neutron irradiation on the tensile properties of Type-316 stainless steel.¹ They irradiated specimens at a temperature less than 100°C with fast-fission neutrons ($E > 1$ MeV). Comparison of tensile data from that study with our results showed that it takes ~20 times more fission neutrons than 14-MeV neutrons to produce equivalent changes in tensile properties of annealed Type-316 stainless steel.

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Fig. 5. Transmission electron micrographs of radiation-damage structures produced in copper after RTNS irradiation to 1.27×10^{21} neutrons/m² ($E = 14$ MeV). Comparison with Fig. 4 shows that the amount of displacement damage retained in the form of primary structural defects appears to be greater in the 14-MeV neutron case. The defects marked by circles appear to be multiple clusters originating from the same neutron event. This phenomenon seems to occur more frequently in high-energy neutron irradiations.

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Table 1. Composition of Type-316 stainless steels used in radiation damage studies.

Chemical element	Commercial Type-316 stainless steel annealed at 1050° C and water quenched (%)	Low-carbon Type-316 stainless steel cold rolled 33% ^a (%)
Copper	0.08	0.001
Chromium	16.7	17.0
Nickel	13.7	16.7
Molybdenum	2.5	2.5
Manganese	2.1	0.03
Silicon	0.9	0.5

^aObtained from J. Stieglyer (Oak Ridge National Laboratory).

Fig. 6. Change in mechanical properties of cold-worked Type-316 stainless steel after irradiation to 3.0×10^{21} neutrons/m² ($E = 14$ MeV). After irradiation, yield strength increases 5% and elongation decreases 15%. Similar changes are not evident when this material is irradiated to this fluence level with fission neutrons.

Fig. 7. Change in mechanical properties of annealed Type-316 stainless steel after irradiations to 1.3×10^{21} and 2.5×10^{21} neutrons/m² ($E = 14$ MeV). At the latter fluence, yield stress increases 60% and elongation decreases 33% with respect to the unirradiated values. We did not observe changes of this magnitude after irradiation to these fluence levels with fission neutrons.

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Authors

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Helium Effects on Mechanical Properties

Introduction. High-energy neutrons not only do displacement damage, but also produce helium atoms in metal matrices by interacting with metal atoms by means of the (n, α) reaction. Helium gas bubbles trapped and accumulating in the microstructure can alter the mechanical properties and lead to embrittlement. To separate and study helium effects on mechanical properties, we are doping niobium and niobium-1-wt% zirconium (designated Nb-1Zr) tensile and creep specimens with various concentrations of helium-3.

To do this, we dissolve tritium in niobium at 400°C and allow it to decay to helium-3. When a predetermined concentration of helium has been incorporated into the microstructure, the mobile tritium is removed by high-vacuum pumping at 400 to 550°C.

Helium Doping of Test Specimens. Niobium and Nb-1Zr specimens are heated to 400°C under vacuum and then equilibrated with a predetermined volume of tritium so that a 1.3-kPa equilibrium partial pressure is obtained. This gives a tritium-to-niobium atom ratio of 0.05 in the metal. The specimens are held at 400°C while the tritium decays to helium-3. These experimental conditions produce about 7 atomic parts per million (appm)

helium-3 each day in the metal. When a predetermined amount of helium-3 has been "doped" into the specimens, the tritium is removed. The material is baked at 400°C for 16.7 h at 4 Pa, then at 500°C for 16.7 h at 13.3 mPa. This reduces the tritium in the material to a level we can safely handle in subsequent experiments.

We doped niobium and Nb-1Zr tensile and creep specimens with from 10 to 500 appm of helium.

Creep Testing. We creep tested pure niobium in high-vacuum, high-temperature units to get reference information of pure niobium. At 800°C under various stresses, we found the following stress dependence of creep rate: $\dot{\epsilon} = K\sigma^{10.0}$, where

$\dot{\epsilon}$ = secondary (minimum creep rate),

σ = axial stress, and

K = constant.

Creep tests on niobium specimens doped with 25 appm of helium-3 gave creep behavior similar to that of the reference material (Fig. 1).

Tensile Testing. We completed a number of tensile tests on Nb-1Zr specimens in a high-vacuum clamshell furnace.

Mechanical properties from baseline tests on annealed Nb-1Zr specimens and from tests on Nb-1Zr specimens doped with 25 appm helium-3 (Table I) indicated that yield strength of a doped specimen increased and elongation slightly decreased. However, the effects on the tensile properties were not deleterious when we added 25 appm helium-3 to the microstructure of the Nb-1Zr alloy.

Fig. 1. Creep behavior of niobium doped with 25 atomic parts per million (appm) of helium-3. This behavior is compared with that of undoped niobium at 800°C and a 65.12-MPa load. Helium at the 25-appm level appears to have little effect on the creep behavior of niobium.

Table 1. High-vacuum tensile tests on Nb-1Zr.

Helium-3 (appm)	Temperature (°C)	Yield stress (MPa)	Ultimate stress (MPa)	Strain (%)
0	23	150	260	50.8
25	23	165	279	46.4
0	600	68	217	35.2
25	600	85	208	32.8
0	800	60	199	32.0
25	800	78	221	27.0

Authors

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Radiation Damage in Superconductors

Introduction. To properly design the magnet shielding for magnetic fusion reactors now in the planning stages, one must know the effects of radiation on candidate superconducting materials as a function of fluence. Present reactor designs use either niobium-titanium (Nb-Ti) or niobium tin (Nb₃Sn) as the superconducting material. Calculations for a tokamak reactor predict a total neutron flux of between 4×10^{12} and 4×10^{13} neutrons/m²·s and a 14-MeV neutron flux of between 10^{11} and 10^{12} neutrons/m²·s, depending on the reactor parameters chosen. Calculations for a mirror reactor predict a total neutron flux of 3×10^{14} neutrons/m²·s and a 14-MeV neutron flux of 6×10^{12} neutrons/m²·s at the superconductor. In both cases, we based flux calculations on uniform shielding. As we make more refined calculations, which incorporate neutron-beam injection ports and vacuum ports, the calculated flux values at localized areas of the magnet will be higher. It is essential that the magnets be used for many years. Also, the radiation tolerance of the magnets may be an important factor.

We presently know that a catastrophic reduction in Nb₃Sn critical current (I_c) occurs at fluences greater than 3×10^{22} neutrons/m² (fission-reactor neutrons) at an irradiation temperature of 60°C and with an applied field of 4 T. We do not know the corresponding fluence at which such a reduction might occur under fusion-reactor conditions of 4.2-K operating temperature, applied fields to 12 T, and neutrons having energies up to 14 MeV. Such measurements have not been performed, and the theory does not exist to make accurate predictions. However, one can infer from present knowledge

that these conditions are likely to be more severe in every case.

The response of Nb-Ti to irradiation differs from that of Nb₃Sn. Degradation in Nb₃Sn critical current is attributed to a degradation in the intrinsic properties T_c (transition temperature) and H_{c2} (upper critical field), which in turn affect I_c . The degradation in I_c for Nb-Ti is attributed to a modification of flux pinning by irradiation. Experiments have shown that I_c degradation for Nb-Ti is gradual rather than catastrophic; the threshold fluence for I_c degradation, however, is lower for Nb-Ti. Low-temperature irradiations of Nb-Ti with fission neutrons have shown¹ a threshold of $\sim 10^2$ neutrons/m² for I_c degradation. Our irradiations of Nb-Ti with 14-MeV neutrons at 4.2 K show a threshold for I_c reductions of $\sim 2.5 \times 10^{20}$ neutrons/m².

The magnitude of the decrease in I_c under irradiation depends on irradiation temperature. Soell² found that multifilamentary Nb-Ti irradiated at 5 K to a fluence of 7.5×10^{22} neutrons/m² underwent a twofold decrease in I_c . After annealing, only 15% reduction in I_c remained; this is consistent with Parkin and Schweitzer's³ 12% reduction in I_c in Nb-Ti irradiated at 60°C to the same fluence. These results show that it is important to evaluate Nb-Ti, as well as Nb₃Sn, under fusion-reactor operating conditions.

Our work in progress has the following three objectives:

- Determine the effects of neutron irradiation (from about 4 to 14 MeV) on the critical current of Nb₃Sn, Nb-Ti, and other superconductors at liquid-helium temperatures and in the presence of magnetic fields up to 12 T.
- Correlate the electrical properties of these materials with both initial microstructure and radiation-induced changes in microstructure.
- Measure the recovery of the changes in the critical current during annealing at temperatures up to room temperature.

Current Progress. Two samples of Nb-45-wt% Ti superconductor were irradiated at 4.2 K for 2 weeks at our Rotating-Target Neutron Source. The critical current of the samples was measured periodically during the irradiation. At the end of the irradiation we measured the critical current as a function of annealing temperature.

At a maximum fluence of 8×10^{20} neutrons/m² critical current decreased by 24% (Fig. 1). Published data for fission-neutron irradiation of Nb-Ti at 5 K showed a decrease in critical current of 25% at a fluence of 4.5×10^{22} neutrons/m² ($E > 0.1$ MeV). The large difference between the fluences of fission

Fig. 1. Steady decrease in critical current for niobium-titanium (Nb-Ti) superconductors irradiated at 4.2 K at Rotating-Target Neutron Source. We measured the two samples of Nb-45 wt% Ti in an 8-T magnetic field.

and fusion neutrons required for a similar change in critical current (i.e., a factor of 50) is surprising. On the basis of damage-energy calculations by Parkin and Goland,⁴ we would expect about a tenfold difference in the fluences required for similar changes. One possible explanation for this discrepancy is that the particular property being measured (i.e., critical current) is sensitive only to changes produced by high-energy primary recoils, which are much more numerous for 14-MeV neutrons than for a fission-neutron spectrum. Microstructural characterization by transmission electron microscopy (TEM) is presently underway to identify the defects responsible for the critical-current changes. The TEM results may also aid in explaining the observed change in critical current.

After irradiation we annealed the samples to 273 K and found that critical currents recovered to within 7% of the unirradiated values. This recovery was consistent with the behavior found after fission-neutron irradiation. This result was encouraging from the standpoint of fusion-reactor operation: it showed that a reactor with an Nb-Ti magnet could be warmed periodically to ambient temperature to recover the critical-current carrying capacity.

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Author

R. M. Scanlan

Resistivity Measurements of Radiation-Damage Rates

Introduction. The measurement of resistivity at low temperatures can provide a basis for comparing the total number of defects produced by variety of irradiation sources. We hope to use the data from tests on a wide range of materials and radiation sources to develop models of the displacement process.

The results presented here are part of an interlaboratory effort to measure the damage rates in dilute alloys of zirconium in vanadium, niobium, and molybdenum at 4 K for electron, proton, fission-neutron, and 14-MeV neutron irradiations. A list of participants and specifications for sample preparation appears elsewhere.¹ Oak Ridge National Laboratory prepared foils (25-μm thick) of vanadium, niobium, and molybdenum containing 0.03% zirconium for all experiments.

Current Progress. In the present experiments, we cut samples into ribbons 150-μm wide by 100-mm long. Three ribbons, one of each alloy, were wound onto a sample holder in the form of a helix 3.3-mm diam by 6-mm long. To suppress the superconductivity of vanadium and niobium at 4.2 K, we inserted the samples holder in a superconducting niobium-titanium (Nb-Ti) solenoid with a critical current of 12.35 A at 1.2 T. During irradiation the assembly was immersed in liquid helium. Fields of 0.275 T and 1.1 T respectively, were applied to the vanadium and niobium during measurement. Figure 1 is a photograph of the sample holder and superconducting solenoid.

We inserted the sample holder and solenoid in a conventional upright cryostat, with a specially designed 2.5-cm diam tailpiece. To ensure uniformity of flux at the Rotating-Target Neutron Source-1 (RTNS-1), we continuously oscillated the samples and solenoid back and forth 360° about their axes during irradiation. We used conventional depolarization techniques with a sensitivity of ±10 nV. The measuring current was 100 mA. Noise levels were ±100 nV at RTNS and ±20 nV at the Livermore Pool-Type Reactor (LPTR).

To check out the system, we irradiated vanadium and molybdenum for 11 h at RTNS. All three alloys were irradiated for 55 h in the second experiment. Following this second irradiation, we maintained

(a)

(b)

Fig. 1. Sample holder with spiral resistivity specimen (a). A 1.2-T superconducting solenoid (b) slides over the resistivity specimens. To ensure uniform exposure, this unit allows specimens to be rotated at 4.2 K during irradiation.

the samples at 4.2 K and moved the cryostat to LPTR. An incremental irradiation of 28 h was carried out with the samples 25.4 cm from the fission plates in the Fast-Neutron Irradiation Facility-10 (FNIF-10).

Neutron Fluences. At RTNS, 16 mm from the source, the neutron spectrum is nearly monoenergetic, with an average energy of 14.9 MeV.² Relative fluences during the runs were monitored with a fixed-geometry proton recoil counter. We determined absolute fluences after the runs by measuring the activation of the niobium samples from the niobium-93 (n,2n)niobium-92m reaction. We used an activation cross section of 458 mb for this reaction.³

At FNIF-10 the neutron spectrum is a partially moderated fission spectrum.⁴ The iron-54 (n,p)manganese-54 reaction was used to determine the total neutron fluence. Relative fluences were monitored by a delayed neutron counter. The fluences are reported as $E > 0.54$ eV, for which the spectrum-averaged iron-54 (n,p)manganese-54 cross section is 32.3 mb (Ref. 5).

Resistivity Changes. The vanadium, niobium, and molybdenum samples have resistance ratios of 110, 68, and 88. The initial resistivity at 4.2 K, ρ_0 , change in resistivity, $\Delta\rho$, total fluence, $\Delta\phi$, and damage rate, $\Delta\rho/\Delta\phi$, are in Table 1. With the exception of the second RTNS irradiation of molybdenum, we observed no detectable change in damage rates. With molybdenum the damage rate decreased 3%, for a total resistivity change of 8.60 neutrons/cm.

The relative precision of the damage-rate measurements is 1% for molybdenum, 2% for

vanadium, and 6% for niobium. These are about the same at both RTNS and FNIF-10; the decrease in noise level at LPTR compensated for the smaller resistivity changes. The poorer precision for niobium results from its large magnetoresistance coefficient and its smaller overall changes in resistivity.

Damage Ratios. The ratios of experimental damage rates at RTNS-I to those at FNIF-10 are in Table 2 for the second set of samples. The uncertainties result from measurement errors and uncertainties in absolute fluence (7.5% for RTNS and 10% for FNIF-10).

Theoretical damage ratios based on damage-energy cross-section calculations with the DON Code⁶ have been made for both RTNS-I and FNIF-10.⁷ These also are in Table 2, with uncertainties estimated at 10% in each damage-energy cross section.

With the exception of niobium the comparison is well within uncertainties. In the case of niobium, the bounds just miss overlapping.

Taken as a whole the theoretical damage ratios are higher by 20% on the average as compared with those measured at 4 K. This might indicate that the

Table 2. Damage ratios.

Sample	RTNS-I/FNIF-10	
	Experiment	Theory
Mo-0.03Zr (2)	4.23 ± 0.53	4.54 ± 0.64
V-0.03Zr (2)	3.68 ± 0.47	4.32 ± 0.61
Nb-0.03Zr (2)	4.28 ± 0.65	5.78 ± 0.82

Table 1. Experimental results from resistivity measurements of neutron-irradiated samples.

Source: sample	Initial resistivity at 4.2 K, ρ_0 (neutrons/cm)	Change in resistivity, $\Delta\rho$ (10^{-2} neutrons/cm)	Total fluence, $\Delta\phi$ (10^{19} neutrons/m ²)	Damage rate, $\Delta\rho/\Delta\phi$ $\left(\frac{10^{-12} \Omega \cdot \text{cm}}{\text{neutrons} \cdot \text{m}^{-2}} \right)$
RTNS-I: Mo-0.03Zr ^a (1)	0.739	2.364	2.338	1.011
RTNS-I: V-0.03Zr ^b (1)	1.878	4.517	2.338	1.932
RTNS-I: Mo-0.03Zr (2)	0.711	8.604	8.630	0.997
FNIF-10: Mo-0.03Zr (2)	-	0.176	0.746	0.236
RTNS-I: V-0.03Zr (2)	1.865	16.370	8.630	1.897
FNIF-10: V-0.03Zr (2)	-	0.384	0.746	0.515
RTNS-I: Nb-0.03Zr ^c (2)	2.173	2.717	8.630	1.126
FNIF-10: Nb-0.03Zr (2)	-	0.196	0.746	0.263

^aMolybdenum-0.03-wt% zirconium.

^bVanadium-0.03-wt% zirconium.

^cNiobium-0.03-wt% zirconium.

moderated fission-spectra neutrons are somewhat more efficient than fusion neutrons. At the present time, however, this conclusion could only be regarded as speculative because of uncertainties in the measurements, spectra, and damage-energy cross sections.

Current Plans. A similar set of experiments has been completed at the University of California, Davis, cyclotron with neutrons from a 30-MeV beryllium(d,n) source. The results will be reported when final spectra evaluation and damage-energy calculations are complete. Late this year further experiments are planned on a series of face-centered cubic metals.

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Authors

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Computer Modeling of Radiation Damage

Introduction. Modeling the production of displacement damage plays an important role in the overall effort to correlate radiation damage produced in different environments. The successful simulation of, or extrapolation to, fusion-reactor conditions will depend on a reasonable understanding of the processes involved in a high-energy collision cascade.

Our modeling efforts involve the study of

- Defect properties, such as mobility, displacement thresholds, and stability.
- The interactions of defects with impurities and transmutation products.
- The production and distribution of defects in energetic collision cascades.

Current Progress. We completed a fully dynamic study of 2.5-keV collision cascades in tungsten. Preliminary results¹ of the study were presented at the American Nuclear Society annual meeting in Toronto, 1976.

Sixteen cascades with random primary-knock-on (PKO) directions were initiated in a crystal containing ~4000 atoms ($13 \times 13 \times 13$ body-centered cubic cells) with periodic boundary conditions. Since this work was primarily undertaken to study the influence of transient thermal effects on final defect configurations, we applied damping to the boundary layer to simulate the cooling of the cascade region by the surrounding lattice. The damping constant was chosen to match cooling rates observed for small crystals imbedded in a larger matrix. The tungsten-tungsten potential is the same as that used in previous studies of displacement thresholds² and defect diffusion³ in tungsten.

At high-energy transfers, damage production is considerably more complicated than that occurring near the damage threshold. PKO atom produces a cascade of secondary knock-ons as it collides with surrounding atoms. The time development of such a collision cascade can be separated into two relatively distinct time scales. Displacements are produced for about 10^{-13} s, at which time none of the recoiling atoms have sufficient energy left to create additional displacements. At this point the collision cascade has produced what is known as a displacement spike.

We produced a large number of displacements, not all of which were stable, in a relatively small volume. Displacement spikes were studied extensively, using the binary collision approximation in which the cascade was treated as a series of sequential two-body collisions. We continued the sequence until displacements ceased, at which point the calculation was terminated and unstable pairs eliminated.

The development of the cascade, however, is not yet completed. Only ~10% of the PKO energy was tied up as potential energy of the stable Frenkel pairs. The remainder of the energy ceased at state of intense agitation in the cascade region, which gradually cooled until thermal equilibrium with the surrounding lattice was reached. This portion of cascade development is often referred to as the thermal spike. Times of the order of 10^{-12} s are required to reach local thermal equilibrium. During this time the energies are too low to be treated by binary models and the lattice too disturbed to be treated by equilibrium thermodynamics. The initial phase of the thermal spike must be treated by many body dynamics methods. The two regimes are seen clearly

Fig. 1. Time history of a single displacement cascade, showing number of Frenkel pairs as a function of time. We observed no further changes during remainder of runs (to 10^{-11} s).

in Fig. 1, in which we plot the number of Frenkel pairs as a function of time.

Dynamic many-body calculations can be compared with the binary-collision model by noting the defect configuration at the end of the displacement spike. Unstable pairs can then be manually eliminated using an appropriate static recombination volume as is done in binary calculations.

In Table 1 we compare the present results for 2.5-keV collision cascades in tungsten with the binary calculations of Beeler and Besco.³ Note the effect of choosing different values for the recombination volume. The 52-site recombination region is the correct one for the present potential.² The larger cascade size and number of stable Frenkel pairs in the binary calculation are the direct result of longer replacement sequences. Whether this reflects the somewhat softer potential of Beeler and Besco or the handling of replacement sequences in the binary calculation remains to be seen.

At the end of the thermal spike, only 37% of the stable pairs created survive. The observed defect

transport is more than an order of magnitude greater than expected from the known³ equilibrium transport coefficients. This survival rate in the thermal spike appears consistent with recent experimental work.⁵

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Authors

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Rotating-Target Neutron Source-1 Irradiations and Dosimetry

During FY 1977 we performed 16 irradiations with 352 samples. The irradiations supported research on the effects of 14.8-MeV neutrons by 16 individuals representing eight institutions. Although most of the experiments were carried out at room temperature, five were at elevated temperature (up to 600°C) and two were at cryogenic temperatures. Maximum flux in any of the room temperature runs was 9×10^{11} neutrons $\text{cm}^{-2}\text{s}^{-1}$ for an 80-h run.

Irradiated materials included the following elements, alloys and compounds:

Elements

Nickel
Niobium
Pyrographite

Alloys

Stainless steel
Niobium-1-wt% zirconium
Niobium-titanium

Compounds

Calcium fluoride

Table 1. Comparison of 2.5 keV collision cascades in tungsten.

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

Aluminum oxide
Magnesium oxide
Yttrium aluminum garnet
Spinel
Silica suprasil
Niobium-tin
Vanadium-gallium

We designed the experiments to study the effects of 14.8-MeV neutrons on mechanical properties, critical parameters of superconductors, defect production, radiation-enhanced diffusion, microstructural features, and helium generation. Experimental techniques included tensile testing, transmission electron microscopy, optical absorption, dilatometry, electrical resistivity, mass spectrometry, and gamma spectroscopy.

The niobium-93(n,2n) niobium-92m reaction was used to determine 14.8-MeV neutron fluences. For each irradiation the experimenters received a report detailing experimental conditions and irradiation history as well as individual sample dosimetry.

Author

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Tritium Handling and Control

Tritium Containment and Blanket Designs for a Mirror Fusion Central Power Plant

Introduction. A long-term goal in the fusion-reactor engineering community¹ is to reduce the total tritium loss to the environment to below 37 GBq/d (1 Ci/d). The accumulated tritium emissions from the 1500 1-GW fusion power plants that might be built in a world fusion economy by the year 2025 would not significantly (~10%) add to the present tritium background. But by the 2050, with 10 000 1-GW plants, the emissions per plant would have to be 3.7 GBq/d (0.1 Ci/d) to stay safely below the natural tritium production of 400 to 80 TBq/d (10 to 20 000 Ci/d) [Ref. 2].

For a reactor vessel of about 350 000 m³, losses could only be kept to such a low level if tritium concentration within the gas cover (area between blanket and containment vessel) were kept low. For this reason we are investigating ways of removing tritium from the gas cover and reducing tritium losses from the blanket and coolant to low levels.

Current Progress. In one conceptual design of ours there is air between blanket and vessel. A continuous catalytic-oxidizer/molecular-sieve adsorber cleanup system maintains a 14.8 MBq/m³ (40 μ Ci/m³) tritium level [1.9 MBq/m³ (5 μ Ci/m³) of

tritiated water vapor (HTO)] against 6.7 TBq/d (180 Ci/d) leakage from reactor components, energy recovery systems, and process piping.

In this design the blanket contains submodules with a lithium beryllium oxide-beryllium mixture (Li₂Be₂O₃-Be) for tritium breeding and submodules with beryllium for mostly energy production. We obtain tritium by scavenging the containers that hold the breeding material with lithium-vapor-doped helium gas. The container consists of molybdenum alloy (TZM) tubes and tube sheets. The breeding material is packed and sintered in the shell surrounding the tubes. Potassium-vapor (also lithium-doped) coolant passes through these tubes to recover the heat at 900°C. Tritium leakage from the scavenging helium into the potassium vapor within the blanket submodule can be reduced to 133 TBq/d (3600 Ci/d) for the TZM case. This leakage after an intermediate TZM exchanger would result in loss into the stream by means of Haynes-25 alloy/boiler (potassium boiling) of 25.9 GBq/d (0.7 Ci/d). We use a moving getter bed to recover the tritium from the lithium tritide (LiT and Li₂T) scavengers in both the helium-blanket scavenging flow and the potassium-vapor coolant. The increase in leakage resulting from replacement of the TZM with niobium is being examined.

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Tritium Control in Mirror Hybrid Reactor

Introduction. Tritium control in the mirror hybrid reactor is possible with emissions to the environment below 0.4 TBq/d (10 Ci/d), while still maintaining worker safety and cost effectiveness. We employed a number of new methods to achieve such low levels in a near-term machine with today's technology. Figure 1 summarizes the various tritium leak-source terms and the associated processing loops.

Current Progress. The tritium-breeding pins, designed as tritium-containment vessels filled with lithium deuteride, are constructed of a special low-permeability, high-temperature strength aluminum alloy. In the hybrid reactor these tritium breeding pins are "harvested" with the plutonium pins. Tritium is extracted from these tubes in-plant, and the lithium deuteride-filled tubes are remanufactured and reinstalled for the next cycle. A breeding-

pin failure rate of 10^{-1} is assumed, thus releasing 1.5 MBq/d (448 Ci/d) into the helium coolants, which is then scavenged by a slip-stream processor handling 2% of the helium flow. The tritium-contaminated helium will permeate about 90 GBq/d (3 Ci/d) into the steam generators, which is lost to the cooling towers and then to the environment.

The next major source of tritium leakage is from tritium neutral-beam injectors, where 55-KeV energetic tritons implant tritium onto the surface of the electrode tubing. Once within the tube, metal permeation produces a flux of tritium into the electrode helium-coolant flow at about 200 TBq/d (70 560 Ci/d). We then process a 10% fraction of the coolant flow to remove 99.9% of the tritium. The resulting residual tritium leaks into the steam generators at about 90 GBq/d, where it eventually passes into the cooling water and then to the environment. The deuterium injector uses deuterium with a maximum 1% tritium impurity level; it creates a leak to the steam of 10 GBq/d (0.3 Ci/d).

A similar tritium-loss phenomenon occurs in the hybrid's direct converter, where 55-KeV energy tritons produce a loss of 320 TBq/d (8800 Ci/d) into the helium flow. Again, a 99.9% processor is used. It handles 5% of the flow to reduce this source of tritium in the main helium coolant to less than 90 GBq/d.

We take all the remaining miscellaneous leaks from the process equipment and piping or ducting directly into the reactor hall—totaling a maximum of 6.7 TBq/d (180 Ci/d). The reactor-hall atmosphere is processed and kept at low humidity to maintain tritium gas levels of below 15 MBq/m³ (40 μ Ci/m³) and tritium water of below 2 MBq/m³ (5 μ Ci/m³). We expect this reactor-hall processing design to result in routine as well as credible accident losses through the reactor-hall containment of less than 37 GBq/d (1 Ci/d).

In this way tritium loss to the environment is designed to be less than 90 GBq/d from breeding pin losses, 90 GBq/d from injectors, 90 GBq/d from the director converter, and less than 37 GBq/d from reactor-hall containment permeation. This is some 40 times lower than that required by Nuclear Regulatory Commission regulations for all nuclear fuel cycle operations, but about the level suggested by the ALARA (As Low As Reasonably Achievable) cost/benefit analysis (an expenditure cut off at the \$66 000 level). We found that no further reductions in emissions could be accomplished by such an expenditure.

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Tritium Processing and Control Systems

Introduction. Proposed fusion reactors call for 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. Available performance characteristics and basic data for the design of tritium/air cleanup systems, however, are inadequate. Our program seeks to:

- Develop mathematical models for the engineering design of tritium cleanup systems.
- Obtain data on the kinetics of oxidation and adsorption-bed dynamics.
- Develop instrumentation for real-time discrimination of tritium gas and tritiated water vapor.

Cleanup-System Concepts and Calculations. Equipment size and cost were estimated for a large-scale (70 m³/s) tritium cleanup system using oxidation-adsorption models previously described.¹ We prepared these calculations for a meeting at the Savannah River Plant. Savannah River is considering a large-scale processing system to contain accidental spills. Various processing concepts were discussed: online continuous, once-through standby, and vacuum-tank holdup with subsequent low-flow-rate recycle processing. Attendees concluded that data are insufficient to permit rational choice of a cost-effective concept for tritium removal from air.

Cost-Benefit Model. One must ask how much investment is justified to prevent (contain) a postulated accidental release or to reduce a continuous release. Assuming that onsite personnel exposure is not significant, the problem reduces to an estimation of the maximum permissible dose to the offsite population. For the release of tritiated water vapor, the calculation is complicated by meteorological parameters. The effect of gas release is easier to estimate, assuming eventual dispersion over the Northern Hemisphere. Our calculations show an estimated justifiable investment of \$70/TBq to prevent a single release and \$540/(TBq/y) to prevent a continuous release of tritium as gas. We primarily based the method of estimation on Bennett's² model for tritium dose due to atmospheric production.

Bench-Scale Experiment Design. We are designing experimental apparatus and related instrumentation to test catalysts and adsorbent beds for tritium cleanup. Component design and fabrication are nearing completion, and experimentation will begin early in 1978. Two Betatec tritium monitors

with dual 2-liter ionization chambers were calibrated electronically with a picoammeter source. The instruments gave a stable, reproducible, nearly linear output over the six-decade range ($\sim 10^{-5}$ to 10 GBq/m³). Calibration with tritium gas remains to be done. The instruments, with associated flowthrough bellows pumps and plumbing, were prepared for installation in the experimental area.

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Tritium Processing and Control

Using Active Metal Getters

Introduction. Our investigation is directed toward selecting and characterizing the hydriding behavior of suitable getter materials. Many metals, intermetallic compounds, and alloys form hydrides. Their hydrogen dissociation pressures and capacities vary widely. We are interested in selecting and studying the behavior of the hydride formers that would best fulfill Lawrence Livermore Laboratory magnetic fusion energy requirements for tritium cleanup. For easy recovery of the tritium, the hydride should have a low dissociation pressure (<0.3 mPa) at hydriding temperatures and a high dissociation pressure (>100 kPa) at a moderately elevated temperature.

Current Progress. Uranium is a getter used for years to collect, store, and purify tritium gas. Uranium metal is activated by heating with hydrogen to form uranium hydride, which is a finely divided powder. The hydride is then heated to 400°C *in vacuo* so it can decompose to uranium powder. This hydriding/dehydriding cycle can be repeated indefinitely with no deleterious effect on the reactivity or capacity of the uranium for hydrogen. For uranium hydride the dissociation pressure of hydrogen is <0.3 mPa at room temperature and ~ 100 kPa at 700 K as shown in the pressure-temperature-composition diagram (Fig. 1).

We studied uranium hydriding behavior under varying flow conditions, using a specially designed uranium trap to prevent channeling and promote maximum reaction rates with the gas. To test the trap we used mixtures of deuterium in argon at room temperature at several concentrations and

Fig. 1. Pressure-composition isotherms for uranium-hydrogen system. This hydride has a low dissociation pressure at 300 K and a high dissociation pressure at 700 K, which allows easy recovery of hydrogen (or of tritium).

flow rates. The concentrations of deuterium in the argon stream above and below the trap were measured by mass spectrometry (Fig. 2). Results were expressed as the purification factor, which is the ratio of deuterium concentration at the inlet of the uranium trap to the concentration at the outlet. We found purification factors to vary inversely with both the atom% ratio of deuterium to uranium already contained in the trap and with the rate of flow of gas through the trap. These purification factors, however, appeared to be independent of deuterium concentrations in the ranges studied¹ (0.1 to 5 vol%).

Uranium studies form the basis of our current investigations into suitable getters for tritium cleanup. We selected cerium as the second metal to test mainly because it has a low dissociation pressure² for tritium at temperatures between 25 and 250°C (10^{-23} Pa at 25°C). By using cerium we could ideally reduce the tritium concentration in a gas stream to <4 pBq/m³, whereas the lowest achievable concentration using uranium would be 370 MBq/m³. Cerium also reacts rapidly with tritium, has large tritium capacity, and is reasonably cheap and available. It is, however, highly pyrophoric in air and reacts with nitrogen, carbon monoxide, carbon dioxide, and water. Because it could be poisoned by exposure to these gases, it must be handled in an inert atmosphere.

We purchased powdered cerium and prepared it for use by cleaning with organic solvents, vacuum drying to 400°C , and grinding to ~ 200 - μm particle size. All handling was done in an argon glove-box. Characterization included vacuum fusion, spec-

Fig. 2. Experimental apparatus for measuring deuterium removal from an argon stream. The specially designed uranium trap prevents channelling and promotes maximum reaction rates between getter and gas stream.

trochemical, x-ray diffraction, differential thermal, and photomicrograph analyses. The principal impurities appeared to be hydrogen, oxygen, and nitrogen in the amounts 9.6% cerium oxide, 7.5% cerium dihydride, and 1.2% cerium nitride. All other impurities totalled about 250 ppm.

A trap containing 699 g of cerium was both assembled and welded under argon. Our initial experiments used the same apparatus described for the uranium work. When the trap was in place in the system, we heated it to 400°C for 4 h to activate cerium for rapid reaction with hydrogen. We added deuterium to the trap to bring the deuterium/cerium atomic ratio to 0.20; the reaction went to completion immediately. Subsequent hydriding experiments were at 200, 100, and 25°C. No temperature dependence was noted in the hydriding

behavior in the first series of runs (deuterium/cerium < 0.6).

Preliminary results are encouraging, but we do not have sufficient data to draw any definite conclusions. Although at one point the cerium became passive to deuterium, we achieved reactivation by heating to 400°C *in vacuo*. Some purification factors attained were greater than our experimental limits of detection (core in/core out = 30 000). We can presumably improve the limits of detectability by using tritium instead of deuterium in the argon stream and by measuring the concentrations above and below the trap with high-sensitivity ionization chambers.³ These ionization chambers have been fabricated, and we are in the process of remodeling the system for tritium use.

Since cerium forms a eutectic with iron at 595°C,

we are conducting some compatibility studies with stainless steel (Type 316) to determine the limits to which cerium can be heated in this trap. Cerium powder was sealed under argon in stainless-steel containers and heated in a resistance furnace to 600°C. The two samples prepared so far were heated for 10 min and 6 h, respectively. Photomicrographs of the samples show some small reactions at the cerium-steel interface. Microprobe scans, being prepared, will help us determine the extent of this reaction. The sample heated for 6 h showed signs of some cerium-steel container interaction. A photomicrograph of a cross section of this sample and the container shows the change in character of the cerium at the interface and along the side of the sample area (Fig. 3). We are also considering possible new trap designs and materials.

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Fig. 3. Photomicrograph (100X magnification) of cerium powder in stainless steel, heated to 600°C for 6 h. The change in appearance of the cerium adjacent to the stainless steel (the corrosion interface) indicated an interaction with the stainless-steel container.

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Improved Equipment and Production Procedures for Rotating-Target Neutron Source-II Tritide Targets

Introduction. Analysis of production and operations data for Rotating-Target Neutron Source (RTNS) targets (fabricated by Oak Ridge National Laboratory) was terminated early in the fiscal year. We revived developmental efforts later in the year, with an emphasis on producing several high-quality, internally cooled titanium tritide targets for use on RTNS-II. Primary goals are to produce targets having (a) more repeatable operating characteristics than the one currently used and (b) a long life (~100 h). Such an effort should provide for higher average neutron strengths and less downtime for target changes.

Current Progress. Target substrate fabrication, titanium evaporation, and tritium loading will be accomplished by Lawrence Livermore Laboratory. The first target is scheduled for production during mid-FY 1978. Special emphasis will be on keeping the evaporated titanium film clean and active before tritiation. To reach this goal we took certain precautions in system design and fabrication procedures. Such an approach includes using ultrahigh vacuum compatible hardware for construction, keeping the titanium layer under good vacuum or high-purity inert gas, and minimizing time need from initial titanium evaporation to final tritium loading. The target will be exposed to air only during a short time between its removal from the titanium evaporation system and encapsulation in a transfer container.

A detailed log of each target's production and operating history will be kept. Also, considerable metallographic microscopic and surface analytical data will be collected for further correlation with target performance.

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SECTION 3. RESEARCH

Theory and Computations

Introduction and Summary

This year has seen the mirror program focus on two alternate mirror paths, the tandem mirror and the field-reversed mirror. Consequently there has been a moderate change in emphasis in the theory program. The fact that single-cell mirror physics is common to both paths necessitates continued studies in this area, which is now referred to as standard-mirror theory.

In this area we have seen improvements in the linear theory of drift-cyclotron loss cones (DCLC) and the concomitant quasilinear theory. This latter study assumes that diffusion due to fluctuations leads to stochastic behavior. An in-depth study of the effects of waves on particles has produced refined conditions, vis-a-vis wave amplitude, for the onset of stochasticity. Along these same lines a general formalism has been developed that determines adiabatic invariants and generates equations that determine the magnitude of breakdown of these same invariants. Since, in mirror configuration, confinement relies on the presence of adiabatic invariants, such analyses lead ultimately to configurational limitations.

In the tandem mirror area we completed a detailed proposal in which we delineated the major problem areas in theory and performed first-cut analysis of many of these. Since that time we performed further work in such areas as field design and rotational instability. Further studies of the limitation of anisotropy due to the Alfvén ion-cyclotron (AIC) mode in the central cell were completed.

Field-reversal studies have led to an understanding of the role electron currents play on the buildup to and maintenance of this configuration. Finally there have been continuing studies of negative-deuterium-ion formation on alkali-coated surfaces.

We primarily devoted our computational activity to understanding the 2X11B Experiment, with emphasis on continued explorations of field reversal, modeling for the Tandem Mirror Experiment (TMX); and some work on the Mirror Fusion Test Facility (MFTF). The primary codes used were SUPERLAYER, Fokker-Planck, and McGus (a 3-D magnetohydrodynamic equilibrium code).

A large effort went into SUPERLAYER for modeling rf drift-cyclotron loss-cone (DCLC) diffusion. The basic quasilinear description was assumed, and a Monte Carlo technique for random

scattering of the particles in $v_{\perp}$ was implemented. The presence of diffusion was absolutely essential for SUPERLAYER to produce ion-velocity distributions peaked near the beam-injection energy (as observed in 2X11B). With no rf diffusion, a drag-dominated ion distribution would have resulted, which was clearly not occurring in 2X11B.

Using rf diffusion and a proper beam-deposition algorithm, we undertook a variety of parametric studies to accurately model 2X11B and to determine model sensitivities. Comparison with 2X11B still showed marked differences in such gross features as plasma length and achieved field depression for a given beam current and electron temperature. We believed these differences could not be explained by inaccuracies in the present model, i.e., numerical errors. This negative result strongly indicated the importance of physical effects not yet in the model; it clearly pointed out that we did not yet completely understand the physics that determines the scaling of the present 2X11B regime to higher beam currents and electron temperatures.

As part of our ongoing theoretical effort to better understand the 2X11B Experiment, we continued to design and implement new particle-simulation algorithms to study low-frequency phenomena in magnetized plasma. We applied these algorithms to the examination of microinstabilities and the buildup of plasma currents related to reversal of the magnetic field in a mirror plasma. For particle simulation of high-beta (plasma pressure/magnetic pressure) mirror plasma with no closed magnetic field lines, we demonstrated that SUPERLAYER II provided a satisfactory physics description of the self-consistent magnetic and inductive electric fields and ion motion. To this simulation model we added an external-quadrupole magnetic field consistent in magnitude with 2X11B.

We made further progress on the development of physics models and new simulation methods that describe important electron physics features in a high-beta plasma. We introduced a new family of algorithms for quasineutral, hybrid (particle ions and fluid electrons) simulations. This model was thoroughly tested for a variety of linear examples: compressional Alfvén waves; electrostatic instabilities with some finite-beta effects, e.g., the DCLC mode; and electromagnetic instabilities, e.g., the Alfvén ion-cyclotron (AIC) mode. The model produced new results for finite-geometry stabilizing efforts on the AIC mode. We also studied the excitation and relaxation of electron-return currents by means of the excitation of compressional Alfvén

waves when a weak current is injected perpendicular to an externally applied magnetic field in a cold, uniform plasma. Our results agreed well with theory. Some results were also obtained for large-amplitude currents.

Using a 2-D multispecies Fokker-Planck code (HYBRID II) we undertook a number of studies on tandem mirror systems. Detailed results involved effects of advanced fuel cycles (e.g., catalyzed deuterium-deuterium), electron heating, two-component operation, and helium injection in the solenoid for field-reversal experiments.

The bounced average Fokker-Planck code was partially rewritten in a μ -I form.

A large effort went into continued investigation of DCLC quasilinear studies. We investigated in detail the effect of the radial-density gradient driving term and its stabilization, caused by combining the plasma stream with electron damping/or outgoing wave damping or both. This work used fixed spatial-gradient codes and a self-consistent radially dependent code.

Electron heating stabilized the DCLC instability in a couple of experiments. We studied the conversion of electron-beam energy into a hot distribution of electrons by means of beam-plasma instability and quasilinear diffusion of the electron beam.

We converted the axial flow code for the plasma stream to an implicit different scheme so it could be efficiently coupled to the quasilinear code.

We extended the Monte Carlo scheme (used to simulate the effects of DCLC turbulence on the phase-space trajectories of individual particles in SUPERLAYER¹) to two dimensions in both velocity and configuration space. Spatial diffusion is now properly calculated. We incorporate this spatial scheme in a Monte Carlo version of the 1-D quasilinear transport model of Berk and Stewart; it qualitatively reproduced their results. This code demonstrated the computational feasibility of determining turbulence level self-consistently in a particle code such as SUPERLAYER (which made it possible to put the Monte Carlo diffusion scheme in energy-conserving form).

We thoroughly applied the 3-D guiding-center fluid-equilibrium code, McGus, to studies of MFTF, the TMX plugs, and several reactor designs. We had two main results for TMX:

- A good magnetic well was preserved up to the design B (magnetic-field) values for the experiment. This magnetic well ensured gross stability of the linked mirror plasmas.

The 2-D equilibrium code CYLEQ was applied to field-reversed and near-field-reversed equilibria at parameters close to 2X11B. The qualitative connec-

tion between the code and the experiment agreed with the conclusion that 2X11B was close to, but not at, a field-reversed state with the beam current used so far.

We completed initial versions of Monte Carlo codes for neutral particle transport.

Other work this year included

- Development of a MACSYMA program for generalized adiabatic invariants.
- Development of an incomplete Cholesky conjugate-gradient 3-D Poisson solver.
- Adaptation of a fluid code to the modeling of negative-ion beams.
- Examination of stochastic behavior resulting from collisionless motion of a particle in the presence of two waves.

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Authors

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Quasilinear Codes for Ion Transport in Mirrors

This year we continued development of the quasilinear codes that describe the saturation of the drift-cyclotron loss-cone (DCLC) instability and of the associated ion transport. We now have three codes that complement each other in the sense of making different approximations. The codes are the 1-D in $v_{\perp}$ velocity space, the 2-D in $v_{\perp}$ and $v_{\parallel}$ velocity space, and the 2-D in $v_{\perp}$ velocity space and radial position r . Last year's annual report¹ gives our results for the first two codes.

A major accomplishment this year was the development of the $(v_{\perp}, r)$ code to the point where it produced quasilinear marginal stability that included self-consistent spatial diffusion. The equation solved by this code for the ion-distribution function F is

$$\frac{\partial F}{\partial r} = \left(\frac{2n\omega_{ci}}{\partial v_{\perp}^2} + \frac{q}{\omega_{ci}} \frac{1}{r} \frac{\partial}{\partial r} \right) D(v_{\perp}^2, r) \\ \times \left(\frac{2n\omega_{ci}}{\partial v_{\perp}^2} + \frac{q}{\omega_{ci}} \frac{1}{r} \frac{\partial}{\partial r} \right) F \\ + \nu_D \frac{\partial}{\partial v_{\perp}^2} (v_{\perp}^2 F) - \nu_L F + Q(v_{\perp}^2, r) \quad (1)$$

This first term on the right is due to quasilinear-wave diffusion in velocity and in radius, where ℓ and n are the azimuthal and harmonic mode numbers, respectively. The last three terms are electron drag, finite transit loss in the unconfined region of phase space, and an external-source term due to neutral-beam and stream injection. Figure 1 shows results from a typical run of this code.

The influence of the spatial-density gradient is destabilizing. This effect can be modeled approximately in the two velocity-space codes by adding terms representing a fixed gradient in the growth-rate expression and in the rf diffusion operator. All the codes confirm that the density-gradient term causes the DCLC to be more difficult to stabilize than in the case when the gradient is neglected. In fact, when we obtain the wavenumber of the unstable mode by solving the dispersion relation; in detail, the rf potential grows to a large level. The distribution is driven to a Maxwellian form for these high rf diffusion levels. We found, however,

Fig. 1. Typical results from 2-D $(v_{\perp}, r)$ quasilinear code showing (a) radial density and (b) radial ion-temperature profiles initially ($t=0$) and at self-consistent marginal stability. The rf causes the density profile to flatten and the ion-temperature gradient to persist.

that only a small amount of additional damping of the DCLC mode gives results in line with the 2XIIIB Experiment. The case shown in Fig. 1 has an added damping of $0.1 \omega_{ci}$. We considered several mechanisms that can give this amount of damping, including outward-going waves at the end of the mirror machine, electron damping due to classical collisions enhanced by large radial wavenumber, and nonlinear electron damping. The $(v_{\perp}, r)$ code indicates that the shape of the radial eigenfunction also has an important effect on final stability. Models for these damping mechanisms will be investigated in detail during FY 1978. In addition, the $(v_{\perp}, r)$ code shows the development of a self-consistent temperature gradient; its effect on stability will also be studied.

Another area of investigation concerns the phenomenon of rf bursting. The rf potential observed in 2XIIIB is often characterized by periodic pulsations instead of a steady rf level. We also found this type of behavior in the quasilinear codes. There is a threshold that depends on neutral-beam current and the magnitude of the growth rate. This oscillatory nature of the final state, obtained using quasilinear theory, is an interesting departure from the usual case of a time-independent final state.

In relation to using the codes for predicting the detailed behavior of the Mirror Fusion Test Facility's mirror machine, we verified that the approximate way in which the dispersion relation is solved in the codes is an accurate representation of the more rigorous solution. Our quasilinear codes assumed that the most difficult modes to stabilize were those nearly at the ion-cyclotron harmonics. Exact solutions to the dispersion relation have shown this to be a good assumption.

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Marginal-Stability Studies of Drift-Cyclotron Loss-Cone Mode

In the previous annual report ¹ we discussed the effects of warm plasma and orbit diffusion on stability boundaries. Stability boundaries were seen to be strongly modified by ion-orbit diffusion due to the highly resonant nature of the mode. This great sensitivity was somewhat disquieting since the non-

linear theory from which this term arose was not rigorous; thus these distortions were only reliable in a qualitative sense. More recent studies included the effects of orbit distortion on these resonant modes. These distortions are important since at marginal stability the modes are so resonant ($\omega \approx n \omega_{ci}$). How one includes this effect is sketched below.

First, break up the response of the plasma into its asymptotic and nonasymptotic pieces so the differential equation along a field line² can be written

$$\frac{1}{g} \frac{\partial}{\partial s} g \frac{\partial \phi}{\partial s} + q_{\text{asympt}}^2(s) \phi = F \phi$$

$$\left\{ \int_{-\infty}^{\infty} dv_{\parallel} f(v) i \omega \int_{-\infty}^t dt' \right. \\ \left. \exp \left[-i \int_{t'}^t dt'' \{ \omega - n \omega_c(t'') \} \right] \right. \\ \left. - \frac{\omega}{\omega - n \omega_c(s)} \right\} \equiv \Lambda(s) \phi(s). \quad (1)$$

In this expression we removed $\phi(s)$ from under the integral because the perturbation slowly varies compared with the exponential. Note that q^2 contains the asymptotic response of the ions, the form standardly used, and that rhs vanishes in the asymptotic limit. Near marginal stability the modes occur at the harmonics of the central cyclotron frequency. Consequently, except near the midplane, the rhs vanishes. That is, $V(s)$ is a sharply peaked function of short range [compared with $\phi(s)$]; consequently

$$\left[\frac{1}{\phi} \frac{\partial \phi}{\partial s} \right]_{s=0} = \int_{-\infty}^{\infty} \Lambda(s) ds, \quad (2)$$

and the lhs is computed by setting the rhs of Eq. (1) equal to zero. For a parabolic well ($B = B_0 [1 + S^2/L^2]$) we have

$$\int_{-\infty}^{\infty} \Lambda(s) ds = L \frac{\omega}{n \omega_{ci}} \sqrt{\pi} \int_0^{\infty} \frac{d\tau}{\sqrt{\tau}} \\ \exp \left(i \frac{\omega - n \omega_{ci}}{\omega_{ci}} \tau \right) \\ \times \left[\left(1 + i \frac{\tau^3 \rho_1^2}{n^2 L^2} \frac{T_{\parallel}}{T_{\perp}} \right)^{-1/2} - 1 \right] \quad (3)$$

The τ^3 term contains the transiting-orbit distortions (both dispersive and dissipative). Competition between this negative dissipation and electron Landau damping (outgoing waves) provides the stability boundaries.

In Fig. 1 we show critical radii in terms of the Larmor radius as a function of plasma pressure/magnetic pressure (β) and density for a spherical plasma. Figure 2 plots the magnitude of warm density transiting the Tandem Mirror plugs (subscript w), required for stability, in units of hot density for two hole sizes ($T_{\text{hole}}/T_{\text{hot}}$). In all cases the density in the solenoidal region is 30% of the plug density. All other parameters refer to the plugs.

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Fig. 1 Critical radii for a spherical plasma. We plotted these radii in terms of the Larmor radius as a function β or density.

Fig. 2. Required warm density-transiting Tandem Mirror Experiment plugs. Density in solenoidal region is 30% of plug density, $\epsilon = 0.5$; mirror ratio = 1.5; $R_p/\rho_1 = 3$; axial scale length/ $\rho_1 = 4$; central-cell density/plug density = 0.3.

M = 1 WOBBLE Instability Driven by Rotation

In theta pinches and in the central cell of a tandem mirror, rotational instabilities are expected to be one controlling factor for allowable equilibria. Recent theta pinch experiments¹ show that an $m = 1$ (aximuthal-mode number) rotation ("WOBBLE") is a common occurrence. Early calculations² show that the most difficult mode to stabilize is the $m = 2, n = 0$ (radial-mode number) rotating flute. The $m = 1$ rigid displacement is marginally stable (consequence of angular momentum conservation). More recent numerical calculations³ show that a departure from flute perturbations ($k \cdot B > 0$) relaxes this later constraint and that an $n = 0, m = 1$ rotational instability sets in when the ions are rotating.

Here the properties of this mode are solved analytically: the resultant dispersion relation follows:

$$L = i n (\Omega_1 \Omega_2 + \beta), \quad (1)$$

$$F'(L) = -1, \quad (2)$$

and

$$\omega^2 + k^2 V_a^2 \beta = \frac{k^2 V_a^2}{2} \ln \left(\frac{\Omega_1 \Omega_2}{k^2 V_a^2} + \beta \right) \times \left(\frac{1}{1 - \frac{\pi i \operatorname{sign}(\Omega_1)}{\ln \left(\frac{\Omega_1 \Omega_2}{k^2 V_a^2} \right)}} \right) \quad (3)$$

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Electron Effects in Ion-Current Field Reversal

Existing calculations of magnetic-field reversal using an ion current injected with neutral beams have neglected all electron effects other than drag. Because ion orbits are generally comparable with plasma dimensions, while the electron orbits are small, one assumes the generation of a current by ionization of neutral-beam atoms results from the charge separation induced by the magnetic field. In this picture, all plasma currents are carried by the ions. More realistically, electron currents can be generated by two means:

- The electron-ion drag tends to equalize the ion and electron average velocities, partially canceling the ion current. This mechanism is particularly effective at the field null.

- Radial electric fields can be set up either by the charge separation that results upon ionization or by nonequal transport rates. In the presence of these fields, electrons can drift in a way to cancel the ion current.

We calculated electron currents in the presence of assumed ion species of charges Z_i and average velocities V_{i0} , using a model of simple electron momentum balance

$$0 = e E + \frac{1}{c} v_e \times B + \frac{1}{n_e} \nabla p_e$$

$$= \frac{m_e v_{ei}}{n_e} \sum_i n_i Z_i^2 (V_i - v_e), \quad (1)$$

where

$$v_{ei} = \frac{4}{3} \sqrt{\frac{2\pi}{m_e}} \frac{n_e c^2 \ln \Lambda}{T_e^{3/2}} \quad (2)$$

is the electron-ion collision frequency. The following are our general conclusions for an axisymmetric configurations:

- The existence of a field null in steady state requires a net current at the null. This may be accomplished in a plasma composed of more than one ion species having different charges and average velocities. Most simply, a nonrotating species offers a resistant background so the electrons cannot accelerate to nullify the current of a rotating ion species. In an experiment this nonrotating species may be present in the form of impurities or may be supplied directly. In a reactor α -particles might play the same role.

- Away from a field null an azimuthal electron-drift velocity arises only because of a radial electric field. The magnitude of this field is determined by both the neutral-injection profile and the transport.

- On open magnetic lines electron end-conduction to grounded boundaries constrains the variation in potential across the magnetic flux to the order T_e/e . The resulting azimuthal electron-drift currents are small compared with the ion current; so calculations neglecting electron currents are justified on open lines.

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

A quantitative calculation of these effects requires inclusion of a prescription for calculating electric fields in ion-particle codes, such as SUPERLAYER at Lawrence Livermore Laboratory. This inclusion is currently being implemented.

Author	Major Contributor
D. E. Baldwin	M. E. Rensink

Reassessment of Requirements to Obtain Field Reversal in Mirror Machines

We re-examined requirements to obtain field reversal by neutral injection. Our approach took account of a cancellation of currents at a field null caused by electron-ion collisions that drag the electrons along with the moving ions. We found that for cases of interest even a small admixture of higher-Z ions generates a residual current (Ohkawa current) sufficient to maintain field reversal in steady state with a lifetime comparable to the usual magnetic-diffusion time. An approximate prescription was given for buildup to such a state; namely, the neutral injection current had to be sufficient to reduce the field to zero on axis with open confinement for an initial plasma radius of $r_1 = 4r_{Li}$, where r_{Li} was the ion-Larmor radius in the vacuum field. Again, high-Z ions were needed to bring about the transition to a field-reversed state, $r_1 = 4r_{Li}$ being the initial radius that minimized the injection current needed to do this for a reasonable higher-Z ion content (10% helium, or less of a higher-Z gas). Since $4r_{Li}$ was about twice the radius in past 2X11B experiments, we concluded that either the injection current or the energy confinement time had to be substantially increased, by about a factor of three if field reversal was to be achieved in 2X11B. Auxiliary injection by pulsed ion sources or plasma guns

might reduce the current requirements significantly if 2 kJ of energy could be deposited in the plasma.

Author	Major Contributor
D. E. Baldwin	T. K. Fowler

Theory for Tandem Mirror Experiment Proposal

The Tandem Mirror Experiment (TMX) Proposal¹ contains a number of topics relevant to the physics of tandem mirror confinement. Included are studies of classical energetics, microstability, magnetohydrodynamic stability, and adiabaticity, as well as a preliminary evaluation of a tandem mirror deuterium-tritium reactor.

The TMX experiment has been designed so that, in its initial mode of operation, its plugs operate as 'close' as possible to the stream-stabilized 2X11B operation. In this mode the end-loss current from the central solenoid will supply the stream necessary to stabilize the plugs against the drift-cyclotron loss-cone mode.

All tandem mirror magnetic fields have regions of bad curvature. Flute interchange stability, however, is strongly influenced (and usually assured, as in TMX) by the high-pressure minimum-B plugs. A curvature-driven ballooning interchange sets β -limits (i.e., limits for plasma pressure/magnetic pressure) between 0.4 and 0.7 in the bad curvature regions. Rotational instabilities driven by radial electron fields would be potential problems for very long solenoids, although not for lengths such as that for TMX or current conceptual reactors.

Reference

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Monte Carlo Neutral-Transport Code

We wrote a Monte Carlo code to study the transport of neutral particles in mirror-machine plasmas. Neutral particles emitted by simulated neutral-beam sources were followed in three dimensions through a target plasma assumed to be in a steady state consistent with the neutral-beam input. We simulated ionization and charge-exchange events using Monte Carlo techniques. Descendent

generations of incident neutral particles were followed until lost either through ionization or escape from the plasma.

The code presently uses a SUPERLAYER steady-state distribution of $\sim 20\,000$ individual superparticles as the target plasma; but an arbitrary target, given either in particulate or distribution-function form, can be used.

Presently available diagnostics include

- Neutral density as a function of the cylindrical coordinates (r, z) .
- Mean neutral energy as a function of (r, z) .
- Flux of neutral particles emerging from the plasma in any particular direction as a function of position.
- Mean energy of the emerging flux as a function of position.
- Fraction of input power from neutral beams deposited in the plasma.
- Fractional attenuation of incident neutral beams.

We are presently using the code to interpret the neutral analyzer, beam attenuation, and other measurements used as diagnostics in the 2XII-B Experiment.

Author

T. B. Kaiser

Monte Carlo Simulation of the Effects of Drift-Cyclotron Loss-Cone Turbulence on Single-Particle Orbits

We extended to two dimensions (in both velocity and configuration space) the Monte Carlo scheme^{1,2} used to simulate the effects of drift-cyclotron loss-cone (DCLC) turbulence on the phase-space trajectories of individual particles in SUPERLAYER. This generalized an earlier treatment that considered only diffusion in particle energy. Polarization of the turbulent electric fields that can be treated was generalized to include linear as well as gyrotopic distributions of k -vectors. The turbulence level can now be self-consistently determined from the ion distribution function and from the linear dispersion relation; or it can be fixed arbitrarily at a predetermined steady-state value.

Using this scheme, our inclusion of the effects of DCLC turbulence in SUPERLAYER resulted in improved agreement between the plasma steady states predicted by the code and those observed in the 2XII-B Experiment. Detailed comparisons of code results with experimental observations are discussed in the section "Computer Calculations of 2XII-B Field-Reversed Mirror configurations".

Although the Monte Carlo scheme has thus far been used to simulate the effects of only the DCLC mode, it is applicable in principle to magnetized plasma in the presence of weak flute-type electrostatic turbulence of arbitrary origin. The basic approach follows.³ We used the fully 2-D (2-space, 2-velocity) quasilinear kinetic equation to derive the probability density governing the evolution of the four-dimensional phase-space trajectory of a single particle. This probability density (the Green's function of the kinetic equation) served as the basis of an intrinsically stochastic particle pusher. We simplified the kinetic equation by exploiting the fact that the diffusion timescale is much longer than the gyroperiod. This made possible a multiple-timescales expansion. The result of this analysis was that on the fast (gyroperiod) timescale a particle's initial conditions were convected along the unperturbed orbit; on the slow (diffusion) timescale the phase-space coordinates of a particle diffused away from the convected initial conditions in a manner determined by the fast-timescale-averaged quasilinear diffusion tensor.

The structure of the gyroperiod-averaged diffusion tensor depended on the details of the electric-field fluctuation spectrum and on the particular choice of phase space coordinates. If coordinates $(x_g, y_g, v_{\perp}, \phi)$, where (x_g, y_g) was the position of a particle's guiding center, $v_{\perp}^2 = v_x^2 + v_y^2$, and $\phi = \text{TAN}^{-1}(v_y/v_x)$, were used, it turned out that for at least two polarizations, the gyroperiod-averaged diffusion tensor was diagonal. This had the important consequence that the random perturbations in different coordinates were mutually uncorrelated. The cases of interest were

- A distribution of k -vectors rotationally symmetric about the magnetic field.
- All k -vectors parallel or antiparallel to some fixed reference direction.

An interesting finding of this work was that spatial diffusion was not correctly simulated by simply propagating the stochasticity resulting from velocity diffusion through the equations of motion to a particle's position coordinates. In the coordinates $(x_g, y_g, v_{\perp}, \phi)$, for example, such a scheme would result in no spatial diffusion at all, while in other coordinate frames, important correlations represented by off-diagonal elements of the diffusion tensor would be neglected.

We incorporated this diffusion scheme in a Monte Carlo version⁴ of the 1-D quasilinear transport model of Berk and Stewart,⁵ which also includes neutral-beam injection, electron drag, end loss, and low-energy stream. The turbulence level can be self-consistently determined as a function of

time from the ion-distribution function. The growth rate can be obtained from the linear dispersion relation or fixed arbitrarily at a predetermined steady-state value. When run in the self-consistent mode, the code reproduced the results of Berk, Rognlien, and Stewart⁶, depending on the value of a critical parameter, the turbulence level reached either a state of marginal stability or one with large-amplitude oscillations (bursts).

The above behavior is illustrated in Figs. 1 and 2, which give the time dependence of the turbulence

Fig. 1. Monte Carlo simulation of drift-cyclotron loss-cone (DCLC) turbulence for a marginally stable steady state. This plot gives the time dependence of the turbulence level, $|q\phi|$.

Fig. 2. Monte Carlo simulation of DCLC turbulence for a time-asymptotic state with large-amplitude oscillations (bursts). This plot gives the time dependence of the turbulence level, $|q\phi|$.

level, $|q\phi|$. Figure 1 shows a marginally stable steady state, while the time-asymptotic state in Fig. 2 exhibits bursting. When operated in this mode the code demonstrates the computational feasibility of self-consistently determining the turbulence level in a particle code such as SUPERLAYER. This means that the Monte Carlo diffusion scheme in such a code can be put in energy-conserving form.

An illustration of the strong effect turbulence has on the ion-distribution function appears in Figs. 3 and 4, which plot the ion perpendicular-energy distribution. In Fig. 3 we set the turbulence level at a value typical of that observed in the 2XIB Experiment. Figure 4 compares the 2XIB charge-exchange energy spectrum with the result of a SUPERLAYER code run identical to that in Fig. 3, except that we set the turbulence level to zero.

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Fig. 3. Ion perpendicular-energy distribution shows turbulence level typical of that observed in the 2XIB experiment. The solid curve gives the ion distribution generated by the SUPERLAYER code; the dashed curve is an energy spectrum obtained from the 2XIB charge-exchange analyzer, normalized to the same area.

Fig. 4. Ion perpendicular-energy distribution that compares same 2VHB charge-exchange spectrum used for Fig. 3 (dashed curve) with result of ST PERLAYER code run identical to that in Fig. 3 (solid curve), except turbulence level was set to zero.

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Author

T. B. Kaiser

Adiabaticity in Tandem Mirror Systems

The advent of the tandem mirror concept has motivated both applied and basic work on magnetic-moment jumps. The plugs, being conventional mirror machines, can be studied using the theory described previously.¹ In particular, the plugs in the Tandem Mirror Experiment (TMX) are adiabatic due to the small radial size of the plasma.

The central cell is quite different from a conventional mirror machine. Its field strength, in particular, is nearly constant near the middle; hence, in contrast to the usual situation, magnetic-moment jumps may be expected near the ends, rather than the middle, of the cell. Several questions arise: for a cell of fixed length and total mirror ratio, how does changing the shape of the field profile affect the number, location, and size of magnetic-moment jumps and is there an optimally adiabatic shape for which nonadiabatic are minimized?

To probe these issues we considered a model field of the form

$$B_z = \xi_z B_z(z) - \xi_r (dB_z/dz) r/2, \quad (1)$$

where

$$B_z \approx B_0 \left[\frac{\tanh \frac{z^2 - z_0^2}{\Delta^2}}{(R-1) \frac{\Delta^2}{\tanh \frac{z_0^2}{\Delta^2}} + R} \right] \quad (2)$$

and where z_0 and Δ are constants related to cell length and sharpness of the field change, respectively. Plots of B_z for several values of z_0/Δ are in Fig. 1.

According to theory, near the axis the jumps are governed by the location of the zeros of B_z in the complex z -plane. More direct information can be gained by locating the zeros in the upper-half complex ψ plane, where

$$\psi \equiv (q/mc v) |B_z| - (v_{\perp 0}/v)^2 B_z/B_0]^{-1/2} dz \quad (3)$$

is the lowest order approximation to the gyrophase. The jumps are proportional to $\exp[i \Psi(B=0)]$. Figure 2 shows a plot of the zeros as a function of z_0/Δ . Based on this figure, one may predict the following:

- A single magnetic-moment jump per machine transit, at the midplane, for small values of z_0/Δ ,

Fig. 1. Plots of axial field profile $B_z(z)$ for model magnetic field, with $R = 8$ and $z = 275$. The large z_0/Δ corresponds to a flat-bottomed well.

Fig. 2. Zeros of B in complex z -plane for $R = 8$. The zero is at $i\omega$ for $z_0/\Delta = z_0/\Delta_0 = 1.1636258...$

where there is only a single zero of B .

- Two jumps for large z_0/Δ , where these are two well-separated ($|\Delta\Psi| > 2\pi$) zeros.

- A transition from one jump to two at $\Delta \sim \Delta_0$, where Δ_0 is the value of Ψ such that the two zeros are separated by $|\Delta\Psi| = 2\pi$.

- A pronounced minimum in the magnetic-moment jump size at the value of Δ , where $\text{Im } \Psi(B = 0)$ is maximum.

- For $\Delta \sim \Delta_1$, nulls in plots of $|\Delta\mu|$ vs v , due to destructive interference of the two zeros.

- When there are two jumps, they occur at predictable positions, namely, where $\Psi = \text{Re}\{\Psi(B = 0)\}$.

These predictions have been verified by comparison with results from the TIBRO orbit code. Quantitative agreement with theory on the size of jumps has been fair (good for purposes of determining adiabatic energy limits, not so good for $\Delta\mu$ values). This agreement should improve when the analytic expression for finite midplane guiding-center radius r is evaluated. So far, only the $r \rightarrow 0$ version of the theory has been used.

Adiabaticity is an issue for the central cell of a tandem mirror only for species with energies above the confining potential energy, e.g., hot ions injected to provide supplemental heating to the central cell or alphas produced by fusion. In the latter example, it may be advantageous to arrange the field so that alphas are strongly nonadiabatic (by making the field steep-edged, i.e., x_0/Δ is large). Using a one-dimensional (pitch angle) kinetic code, we find that, with minor modifications, the tandem

mirror reactor design given in the TMX proposal² could be made to nonadiabatically lose 80% of its alphas.

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Potential-Aided Confinement in Mirror Machines

We considered the basic problem of particle end-loss in a magnetic mirror field that has an electrostatic confining potential. This is a subject of interest in the context of the tandem mirror machine.

Two analytic approaches to the problem appeared in the literature. Both were directed at finding the solution to the high-velocity expansion of the linearized Fokker-Planck equation that vanishes at the loss boundary. Pastukhov¹ constructed loss-rate expressions from an approximate solution that vanishes on a surface that matches the position and radius of curvature of the (hyperbolic) loss boundary at its vertex (minimum-energy point). Chernin and Rosenbluth² replaced the loss boundary by one consisting of line segments of constant pitch-angle or energy; they approximately matched solutions in different regions of velocity space. Pastukhov's expressions were derived for electrostatically confined electrons in the presence of a singly charged ion species; Chernin and Rosenbluth's result applied to a singly charged electrostatically confined ion species. Both calculations were done for square-well fields.

We extended both calculations¹ to apply to any electrostatically confined species in a multispecies, multicharged plasma. This extension was achieved by carrying an extra constant that multiplied the pitch-angle term in the Fokker-Planck equation through both calculations. Additionally, we generalized the Pastukhov approach to apply to the bounce-averaged Fokker-Planck Equation, allowing consideration of arbitrarily shaped magnetic wells.

We also treated this problem by using three multispecies Fokker-Planck codes: A nonlinear 2-D (v, θ) code; a linearized 2-D code, in which a tenuous test-particle species interacts with a fixed Maxwellian background; and a linearized 1-D code, in which the pitch-angle distribution is assumed to be

the lowest normal mode. We considered the non-linear code as a test for the (faster) linear 2-D code. We found that they agreed well when the confining potential energy was more than about twice the species temperature.

Comparing the 2-D codes with the other approaches, we found that the closest agreement was with the generalized Pastukhov results. Values of nr agreed within 10 to 20% over a wide range of confining potentials and mirror ratios, for both electron and ion problems. The most glaring discrepancy was that the generalized Pastukhov result varied more slowly with mirror ratio than with code result. The Chernin-Rosenbluth nr values were consistently lower, by as much as a factor of two, and the 1-D code values were higher, by a factor of about two.

We made a series of tests to estimate the errors in the Fokker-Planck code due to the finite-mesh representation of the loss boundary. These tests involved varying the mesh spacing and making small changes in the mirror ratio and potential (to look for jumps in nr as the loss boundary crossed a grid point). We concluded that the uncertainty in the code values was about $\pm 10\%$.

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Tandem Mirror Rate Code

We developed a fast-running rate code for tandem mirror systems. Electrons and thermalized center-cell ion species were described by generalized Pastukhov expressions for number and energy endloss rates.

The code describes plug ions by assuming they are dragged by electrons from their injection energy to an energy proportional to $T_e^{3/2}/E_p^{1/2}$, at which point they are lost due to pitch-angle scattering. An option is provided where the plug loss rate is enhanced, if necessary, to provide marginal stability for the drift-cyclotron loss-cone mode (partially stabilized by center-cell endloss). The code also provides for injection of ions (e.g., fusion-produced

alphas) in the center cell above the ambipolar energy. Charge exchange is included but is presently described only by constant cross sections.

We compared this code with results from a code in which ion species are described by coupled Fokker-Planck equations and electrons are described by generalized (bounce-averaged) Pastukhov expressions. We found the results to be in good agreement for steady-state and time-dependent test cases.

The code was used to study (a) buildup of thermalized alpha particles in a tandem mirror reactor and (b) cyclic schemes for limiting the alpha population. We had three principal findings:

- Q (fusion power/injection power) was drastically reduced (from ~ 8 to ~ 1 for the case considered) as alphas built up from a steady state in which they were artificially eliminated.
- Pulsed-mode purging schemes helped somewhat (time average $Q \equiv Q_{av} \sim 2$).
- Elimination of 80% of the alphas by non-adiabatic loss in combination with running the code in pulsed mode helped more ($Q_{av} \sim 4$).

The code will be used to study startup modes for the Tandem Mirror Experiment.

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Author

R. H. Cohen

Basic Studies of Dynamical Systems

Plasmas of interest in Lawrence Livermore Laboratory's magnetic fusion energy program frequently have the following characteristics:

- Particle motion is nearly collisionless.
- Instabilities cause certain waves to grow to large amplitudes.

Thus, we often study the collisionless motion of particles in the presence of one or more waves. The simplest problem of this type is one-dimensional motion in the presence of two waves.

We carried out a numerical study¹ of this problem for a particular ratio of the amplitudes of the two waves. We varied two parameters, related to the ratio of the wavelengths and the difference of the phase velocities of the two waves, to determine the nature of the particle motion. Stochastic motion, which can have important physical consequences, was observed rather often. Certain resonances, not necessarily those expected initially, were quite prominent. Our understanding of this

simple problem aids us in our work on the more complicated dynamical systems in the magnetic fusion energy program.

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G. R. Smith

Axial Flow Code for Warm Plasma in a Mirror Machine

We used the time-dependent axial flow code PHLOW to model the flow properties of warm plasma formed by the gas box in the 2XIIIB Experiment. The model was improved to include the following effects:

- A rate equation that describes the ionization of the neutral gas in the gas box with electron-temperature-dependent ionization rate.
- A spatially dependent electron-energy equation.
- Modification of the magnetic-field profile by a high-beta hot plasma.
- A source term at the end walls that can account for reflux of neutrals off the walls.

We coupled the axial flow code to the HYBRID-II Fokker-Planck code. At each time-step, the PHLOW code calculated warm plasma current, flowing axially, which was fed into HYBRID II as a low-energy source of particles. Likewise, HYBRID II fed back to PHLOW the level of hot plasma density. This density level acted like a potential barrier

for warm ions flowing axially. As an example of output from the coupled codes, Fig. 1 shows the measured temporal evolution of density in 2XIIIB for a large gas-box-current case and compares it with the computed results. For this case, warm plasma current was large enough for the drift-cyclotron loss-cone to be stable.

In combining the PHLOW and HYBRID-II codes, we found that the PHLOW code actually took a majority of computer time. This occurred because PHLOW was written in an explicit type of numerical algorithm; it thus required a small time-step to prevent numerical instability.

We are rewriting the code, using an implicit numerical algorithm that will be much faster. During FY 1978 we also plan to investigate the effect of including a modified Poisson's equation. This equation, which would adjust Debye length to the order of grid size, would help us determine if sheath-like shocks form. Currently, the code uses an artificial viscosity to allow for shock formation.

Author

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Monte Carlo Simulation of Neutral Particles

We developed an efficient Monte Carlo method for treating neutral particles in cylindrical plasmas.¹ Our primary objective was to couple the Monte Carlo code with the radially dependent quasilinear code so we could include the physical processes associated with neutral particles, e.g., neutral-beam injection and charge-exchange loss.

The Monte Carlo method is well-suited for treating an arbitrary number of generations of neutral particles produced by successive charge-exchange collisions. Employing the sampling technique for calculating mean free paths, one can use our method to treat any plasma velocity distribution, such as a loss-cone distribution with an arbitrary spatial dependence, in an efficient manner.

We developed a code based on this method. Our numerical results agreed well with analytical results, verifying our method and the code. Figure 1 shows the results for neutral-beam injection.

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Fig. 1. Comparison of measured and calculated temporal evolution of plasma density at the midplane for 2XIIIB experiment. Computed curve is from the coupled HYBRID-II and PHLOW codes. The sudden increase in plasma density is due to the arrival of gas-box plasma.

Fig. 1. Comparison of neutral densities obtained from analysis and the Monte Carlo code. We injected a neutral beam of 18 keV into a plasma with a parabolic radial profile and density $3 \times 10^{13} \text{ cm}^{-3}$. The analytical result and the Monte Carlo result represented by the symbol "X", for the case ignoring secondary charge-exchange collisions, show good agreement. The symbol "X" represents the Monte Carlo result, including all multiple charge-exchange collisions.

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Adiabatic Invariants by Lie Transforms

We applied the modern technique of Lie transforms to a description of adiabatic invariants, their behavior around resonances, and their breakdown at large amplitudes of the perturbing forces. The essential results are in a few simple formulas.^{1,2} Given a Hamiltonian dependent on a small parameter ϵ in the form of a series expansion:

$$h(p, q, \epsilon) = \sum_{n=0}^{\infty} \frac{\epsilon^n}{n!} h_n(p, q), \quad (1)$$

where h_0 represents a soluble problem with periodic orbits, then a further constant of motion, K , can be calculated. This can be given in terms of the Poisson bracket [,]

$$[h, K] = \sum_{n=1}^n \left(\frac{\partial h}{\partial p_n} \frac{\partial K}{\partial q_n} - \frac{\partial h}{\partial q_n} \frac{\partial K}{\partial p_n} \right) \quad (2)$$

and in terms of the averaging and integrating operators, $\bar{\cdot}$, $\wedge$,

$$\bar{h} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T h dt \quad \text{and} \quad (3)$$

$$\dot{h} = \int (h - \bar{h}) dt, \quad (4)$$

where the integrals are taken along the orbits of the lowest order Hamiltonian, h_0 .

The invariant is

$$K = K_0 + \epsilon [K_0, \hat{h}_1] + \epsilon/2^2 [\hat{h}_1, [\hat{h}_1, K_0]] + \epsilon/2^2 [K_0, \hat{h}_2 + [\hat{h}_1, \hat{h}_1] + [\hat{h}_1, \hat{h}_1]] + O(\epsilon^3). \quad (5)$$

For a charged particle in an electromagnetic field there are up to three ways in which the particle may execute periodic motions or experience oscillatory forces. When two or more oscillations resonate, the integrations implicit in Eq. (5) give resonant denominators that can be removed by careful choice of the zero-order invariant, K_0 . The canonical coordinate transformations used to generate series like Eq. (5) are expressed in terms of the Lie-transform generators, W , given by

$$\partial/\partial \epsilon p(P, Q, \epsilon) = [p, W(P, Q, \epsilon)], \quad \partial q/\partial \epsilon = [q, W]. \quad (6)$$

When W is independent of ϵ the transformations and their inverses can be expressed as the operator equations

$$p = e^{[W, \cdot]} p(P, Q, \epsilon), \quad P = e^{\{W(p, q), \cdot\}} p(P, Q, \epsilon). \quad (7)$$

These simple types of Lie transform can be used to investigate the trapped orbits around a particular resonance or to generate the superconvergent series of Kolmogorov. The advantages of the Lie method are that the development of series solutions of mechanics problems can be developed by recursive processes at each order and that the transform generator, W , can be used to transform any function of the phase space variable to or from the averaged variables with equal ease.

The averaged Hamiltonian for the invariant in Eq. (5) is

$$H = h_0 + \epsilon \bar{h}_1 + \epsilon^2/2 (\bar{h}_2 + [\hat{h}_1, \hat{h}_1]) + O(\epsilon^3), \quad (8)$$

and the corresponding transform generator is

$$\epsilon W = \hat{h}_1 + \epsilon/2 (\hat{h}_2 + [\hat{h}_1, \hat{h}_1] + [\hat{h}_1, \hat{h}_1]) + O(\epsilon^2), \quad (9)$$

which transforms a function $F = F_0(P, Q) + \epsilon F_1 + \epsilon^2/2 F_2 + \dots$

10

$$F(p, q) = F_2 + \epsilon(F_1 + [F_0, W]) + \epsilon^2/2(F_2 - [W, (2F_1 - [W, F_0]) - [F_0, W_2]]) + O(\epsilon^3) \quad (10)$$

These are the key formulas and definitions of a powerful mathematical tool that we also implemented on MACSYMA.³

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Tandem Mirror Studies

To study plasma confinement in a tandem mirror system we developed a computational model based on the 2-D multispecies Fokker-Planck code, HYBRID II.¹ The main features of the model are

- Spatial square-well profiles for $B(s)$ and $\phi(s)$.
- v - θ velocity space for magnetically confined ions in the plugs and for both magnetically and electrostatically trapped ions in the central cell.
- Maxwellian electrons with rate equations for determining electron temperature and the self-consistent ambipolar potential.

Results

For deuterium-tritium reactor studies² this model was primarily used to generate a few reference cases. We subsequently used these to calibrate a simple rate-equation model for making extensive parameter surveys.

For deuterium-deuterium (advanced fuels) reactor studies³ we surveyed the Q (fusion power/injection power) of the central cell as a function of the positive-deuterium-ion injection energy and the plug-to-central cell density ratio. Our results appear in Fig. 1. The strong dependence on injection energy was primarily due to the variation of the

Fig. 1. Survey of Q (fusion power produced/input power) for central cell of deuterium-deuterium reactors shows strong dependence on injection energy. Our calculations assumed reinjection of tritium and helium-3; we also accounted for radial alpha diffusion.

deuterium-deuterium fusion cross section.

We also used our code for modeling the Tandem Mirror Experiment (TMX). Our work included regulation of the central-cell gas feed so the escaping plasma just stabilizes the drift-cyclotron loss-cone mode in the plugs. Results are in the TMX proposal.⁴ For neutral-beam injection into the central cell, we determined the form of the anisotropic ion-distribution function and used it in an analysis of the Alfvén ion-cyclotron mode stability.⁵

We investigated the trapping and energy deposition of alpha particles in the central cell of a tandem mirror reactor. Results are in Figs. 2 and 3. Our analytic estimates⁶ did not include the effect of a loss boundary in velocity space. We incorporated these data in the simple rate code used for reactor parameter surveys.

The confinement of electrons and ions by ambipolar potentials in a magnetic mirror was investigated in detail. We compared two analytic theories^{7,8} with results of the 2-D code and a simpler 1-D code. Results appear in a paper to be published in *Nuclear Fusion*.⁷

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Fig. 2. Trapping fraction for alpha particles in the central cell of a tandem mirror reactor shows weak dependence on electron temperature. Ion density, $n_i = 10^{14} \text{ cm}^{-3}$; ion temperature, $T_i = 30 \text{ keV}$; potential barrier, $\phi_c = 90 \text{ keV}$; and mirror ratio, $R_c = 10$.

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Fig. 3. Fractional alpha particle energy deposited in the central cell ions and electrons of a tandem mirror reactor depends on electron temperature. Some of the energy escapes with untrapped alpha particles.

Conversion of Bounce-Average Code to μ -J Space

We partially rewrote the bounce-average Fokker-Planck code to have the adiabatic invariants μ -J as independent phase-space variables replacing the velocity and pitch angle (v - θ). We made this change of independent variables to eliminate a numerical instability for high-beta runs. This instability arose from the field update, which uses the long thin approximation, and from the convective terms used to maintain μ -J invariance. [The mapping of μ -J contours onto v - θ space is shown in Fig. 1. A typical distribution function for conventional mirror-conventional mirror-confined ions is shown in μ -J and v - θ phase-space by Figs. 2 and 3.]

Conversion to μ -J space appeared to have been satisfactorily made; convective terms were eliminated. The annoying numerical instability,

Fig. 2. Contour plot of ion distribution in μ -J space with X's marking the loss-boundary curve each time it crosses a grid line in v - θ space. These points determine the loss boundary in μ -J space.

Fig. 1. The μ -J grid mapped onto v - θ space. The dotted lines represent the constant magnetic moment (μ). The solid lines represent the constant longitudinal invariant (J).

Fig. 3. Same ion distribution as in Fig. 2, but contoured in v - θ space.

however, still remained, driven by the field-update calculations' dependence on past quantities. We are looking for a computationally feasible remedy.

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Magnetohydrodynamic Equilibrium and Stability of Minimum-B Mirror Traps

If (ψ, α) are normalized flux coordinates ($\nabla\psi \times \nabla\alpha = 2\pi\mathbf{b}$) in a volume containing a mirror-trapped plasma with anisotropic pressure components $p_{\perp, \parallel} = p_{\perp, \parallel}(\psi, B)$, necessary and sufficient conditions for the magnetohydrodynamic stability of equilibrium against perturbations localized within a small tube of force are the nonexistence of solutions of the Euler-Lagrange equation

$$\begin{aligned} & \mathbf{b} \cdot \nabla \{ (h/2\pi B^2) [(\nabla\psi)^2 + 2\mu(\nabla\psi \cdot \nabla\alpha) \\ & + \mu^2(\nabla\alpha)^2] (\mathbf{b} \cdot \nabla\hat{\phi}) \} + (\mathbf{T}/B) [\mu^2(\kappa \times \mathbf{b} \cdot \nabla\alpha) \\ & + \mu(\kappa \times \mathbf{b} \cdot \psi)] \hat{\phi} = \theta \hat{\phi} \quad (1) \end{aligned}$$

Here $\mathbf{b}$ is the unit vector along a line of force; $h(\psi, B)$ and $\mathbf{T}(\psi, B)$ are functions defined in terms of the pressures $p_{\perp}$ and $p_{\parallel}$ ($\mathbf{T}$ is proportional to $\partial p_{\perp, \parallel} / \partial \psi$) such that h , $\partial h / \partial B$, and $\mathbf{T}$ are all positive for a well-designed and well-injected mirror trap; $\kappa = \mathbf{b} \cdot \nabla \mathbf{b}$ is the field-line curvature; and the mode-number ratio μ is an arbitrary constant related to the transverse structure of the flux-localized perturbation. The nonnegative scalar θ is always stabilizing; its two prescribed values distinguish the necessary and sufficient conditions. In the large-aspect-ratio (small-curvature) limit, $\theta \hat{\phi}$ vanishes

compared with the term proportional to $\hat{\phi}$ on the left of Eq. (1). The two conditions then coalesce.

At finite plasma pressure the difficulty of applying Eq. (1) lies in the determination of the true flux coordinates, (ψ, α) .

With large aspect ratio in the straight-axis mirror trap, the introduction of cylindrical (r, θ, z) coordinates permits the introduction of a single function $P(\psi, \theta, z)$. This coordinate potential fully defines the finite- β geometry. Both ψ and α can be determined from P . Specifically

$$(1/2)r^2 = P_{\theta}, \quad \alpha = 2\pi B P_{\psi} \quad (2)$$

and

$$B_z + 2\pi p_{\perp}(\psi, B) = B_z^2, \quad (3)$$

where the subscripts θ and ψ denote partial derivatives in mixed (ψ, θ, z) coordinates and $B_z(z)$ is the (known) vacuum induction on axis. In general, $P(\psi, \theta, z)$ satisfies a rather complicated fourth-order nonlinear partial differential equation that requires numerical solution. However, if we go to the limit in which the pressures have an explicit dependence upon ψ only within a boundary layer $\psi < \psi < \psi + \Delta\psi$, then throughout the bulk of the plasma,

$$P = (\psi/2\pi B) \arctan(e^c \tan \theta), \quad \psi < \psi. \quad (4)$$

Here, $c(z)$ is an antisymmetric scalar function of z alone, which is determined self-consistently by the quadrupole component of the vacuum field and the currents flowing along the lines of force in the plasma boundary-layer. Within the boundary layer, the equation for the coordinate potential P is also considerably simplified. In the limit of small plasma pressure, it can be solved analytically. In this case the important result is that the variation of the second flux coordinate through the boundary layer is given by

$$\begin{aligned} \alpha_{\psi} = & -\frac{1}{2}(\sin 2\alpha) \int_0^z dz_1 (\cosh c - \sinh c \cos 2\alpha)^{-1} \\ & \times \int_{z_1}^{\infty} dz_2 (T/B) [(B_{\theta}/B)_{z_2} \sinh c - c_{zz} \cosh c]. \quad (5) \end{aligned}$$

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*Ab Initio** Multiconfiguration/ Self-Consistent Ground-State-Potential Energy Curves

We evaluated the $1\Sigma^+$ ground states of lithium hydride (LiH), sodium hydride (NaH), and cesium hydride (CsH) and the $2\Sigma^+$ ground states of LiH^+ , NaH^+ , and CsH^+ (as well as the $2\Sigma^+$ ground state of CsH^+) over a wide range of internuclear distances. Multiconfiguration/self-consistent-field wave functions were obtained with the optimized-valence configuration approach to the description of chemical bonding. Four configurations for the neutral molecules and seven for the negative ions provided satisfactory descriptions. All the negative-molecular-ion ground states are attractive; all have lower potential energies than the neutral-parent-hydride molecules over the internuclear distances studied. Molecular-electron affinities at the equilibrium internuclear separations were 0.283 eV (LiH), 0.278 eV (NaH), and 0.357 eV (CsH).

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Formation Processes and Secondary-Emission Coefficients for Negative-Deuterium Ion Production on Alkali-Coated Surfaces

Negative-ion formation by deuterium collisions on cesium-coated surfaces was considered in the limiting cases where the resident cesium was either in the purely ionic state or in the purely atomic state.

The secondary-emission coefficient for negative-ion production is a product of the backscattering coefficient, the formation probability, and the survival fraction for negative ions moving away from the surface. We calculated the survival fraction using a method of complex eigenvalues. For optimum cesium coverages, the survival fraction may be near unity for bombarding energies between 10 and 100 eV. Similarly, this is true for formation probability. In this energy range the secondary-emission coefficient is then given approximately by the backscattering coefficient; it is expected to be as large as 30 to 50%.

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Radiation Losses in 2X11B Using the Prono Source

It was proposed to use a 2- μs , 10^5-A source of neutral deuterium and carbon for injection into the 2X11B device. This source was recently developed by Dan Prono. As much as one-third of the beam might consist of neutral carbon. We want to know how serious the radiation loss would be because of trapped carbon. During the injection pulse (and provided the electron temperature was maintained above 100 eV) radiation losses would exceed 100 MW. This would be mainly due to the helium-like C^{4+} ion. Although such losses would be large we would, generally speaking, expect the energy-transfer rates from the trapped ions to the electrons to exceed these loss rates by a large factor.

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Computer Calculations of 2X11B Field-Reversed Mirror Configurations

Introduction. We compared the results from the particle simulation code SUPERLAYER with some recent 2X11B experiments. Our purposes were (a) to determine how well SUPERLAYER performed as a predictive tool to optimize experimental parameter and (b) to verify experimental results.

The code has the following features:

- 2-D (R,Z) Plasma (azimuthal symmetry assumed).
- Self-consistent magnetic (B) fields.
- Charge neutrality.
- Darwin model for fields.
- 3-D neutral beams (with charge exchange and ionization).
- rf turbulent diffusion (based on quasilinear theory).
- No electron dynamics (electron temperature, T_e , an input parameter used in ion-electron drag term).

Results. Four experimental setups were concentrated on: they were characterized by the vacuum B fields, the measured electron temperatures, (T_e), and input neutral-beam current (I_b) and geometry. (See Fig. 1 for the two geometries.) The resultant quantities used for comparison at steady state were the average ion energy (E_i), the peak ion density (n_i), the resultant B at $R = 0$, $Z = 0$ due to the ion currents (ΔB), the peak value of plasma pressure/magnetic pressure β (β_{max}), plasma radius (R_p), the half length in z (L_z). Table I summarizes the results. (The columns labeled Code-limiter will be explained later.)

* From the beginning.

Table 1. Comparison of experimental vs calculated results for four experiments.

B (T)	0.435	0.68	0.68	0.68
T_e (eV)	40	60	130	130
I_b (A)	310	385	500	500
Geometry	tangential	tang.	tang.	head-on

	Code-limiter, $R_L = 7$			Code-limiter, $R_L = 9.5$					
	Expt	Code		Expt	Code		Expt	Code	
E_i/E_b	0.88	0.86	0.82	1	1.02	1	1.1	1	1.04
n_i (10^{14} ions/cm ³)	1-(0.8)	0.9	0.17	0.6-(0.7)	1.5	1.2	4.5	0.9	0.6
$\Delta B/B$	0.9	1	0.21	0.4	0.95	0.6	1.8	0.66	0.3
L_z (cm)	16	7	7.5	16	4.5	16	4.5	6	16
R_p (cm)	6.8	10	7.5	8.6	7	6.5	6.5	6	11.5
β_{max}	2.5	1.9	0.4	0.85	1.6	1.4	2.5	1.15	0.8

The results show the following:

- For $B = 0.435$ T calculation and experiment agreed for n_i and $\Delta B/B$.
- For all other cases calculation gave a larger n_i and $\Delta B/B$.
- For all cases calculation gave smaller plasma half-length L_z (by a factor of 1/2 to 1/4).

Fig. 1. Midplane schematic of beam-plasma geometry.

• We forced the calculated E_i/E_b to agree by adjusting the rf-diffusion coefficient. The rf electric fields implied by this, however, agreed with the experiment.

Some of the code-model limitations that might contribute to the disagreement with the experiments are considered in the following discussion. Before proceeding with that we want to point out that although our calculations do not include electron currents, this should not be a serious effect for these results because the experiments are open-field configurations ($\Delta B/B < 1$), and electron currents only become significant in closed-field regions.

Axisymmetric Magnetic Fields. Our calculations assumed axisymmetric B fields, whereas the experiment had a θ -dependent quadrupole vacuum field. Preliminary results from a paraxial calculation,¹ which includes a quadrupole field, gives $\sim 20\%$ increases in L_z for 2X11B conditions.

We introduced a lengthening effect in the axisymmetric model by amplifying the spread in the initial velocity in the z direction (V_z) for the injected neutral beam. We found, for the case $B = 0.68$ T, $T_e = 60$ eV (where $\theta_{max} = \sin^{-1} [V_{zmax}/V_b]$) that $\theta_{max} = \pm 26^\circ$ gave a plasma half-length $L_z = 13$ cm (Table 2). Note that this 2.9-fold increase in L_z only reduced $\Delta B/B$ by $\sim 30\%$.

Table 2. The effect of increased initial z velocity in the neutral beam.

θ_{max} (deg)	Plasma half-length, L_z (cm)	$\Delta B/B$
± 6	4.5	0.95
± 13	5.5	0.90
± 26	13	0.70

Note: $\theta_{max} = \sin^{-1} (V_{zmax}/V_b)$.

Accelerated Time Scales. We used accelerated time scales (Table 3) to limit the computer running time and the number of simulation particles necessary for a given problem.

Source and sinks (neutral-beam current, electron-ion drag rates, rf diffusion) are accelerated by an arbitrary factor K (typically ≈ 100); however, the ion equations of motion are not accelerated (i.e., the ion-cyclotron period is not accelerated).

To test the effects of these modified time scales requires a longer running, larger capacity program. This is now in progress.

Radio-Frequency Diffusion. In the present model, rf turbulent electric fields are not computed self-consistently. Their effects are represented by a velocity-space diffusion coefficient calculated from quasilinear theory.²

The results show a strong dependence on rf effects. If rf is not included, the disagreement between the calculated solutions and the experimental results increases (except for L_z). This is seen in Figs. 2 through 5, which compare results for the case $B = 0.68$ T, $T_e = 60$ eV. These results support the contention that the present rf model is a step in the right direction (but more improvement is needed).

Radial-Limiter Effects. Experimentally, increased beam current and T_e resulted in a smaller radius plasma. This suggested the possibility that

some external effect (such as cold gas) acted as a radial limiter. To simulate this effect we ran the code with a condition that removed any particle if its radial trajectory exceeded a fixed parameter, R_1 . The results are shown for two cases in the columns in Table I labeled Code-limiter. As is evident, the limiter improves the agreement for the case $B = 0.68$ T, $T_e = 130$ eV; it, however, reduces the agreement for the case $B = 0.435$ T, $T_e = 40$ eV. To make this approach anything more than speculation at this point would require experimental evidence that cold gas was important in the one case and not the other.

Summary. In general (three out of four cases) the calculations over predict the peak ion density and the reversal parameter $\Delta B/B$ and underpredict the axial length. To improve these results we are aiming at improved models for rf turbulence (self-consistent), refinement of present rf-diffusion coefficients, reduction of accelerated time scales, and cold-gas models. Note that the calculational model assumes a stable plasma, and if the experiment has some instabilities present that could play a large part in the discrepancies.

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Table 3. Time-scale comparison (for $n_i = 10^{14}$ ions/cm³, $T_e = 60$ eV $K = 100$).

Quantity	Normal	Accelerated
Electron drag $\left(\frac{v_p}{\omega_{ci}} \right)$	10^{-4}	10^{-2}
Axial bounce in vacuum B $\left(\frac{\omega_{bv}}{\omega_{ci}} \right)$	10^{-1}	10^{-1}
$\frac{\Delta V_{\perp}}{V_{\perp}}$ from rf over time $= \frac{2\pi}{\omega_{ci}}$	0.007	0.07

Notes: v_p = electron-ion drag rate.

ω_{ci} = ion-cyclotron frequency.

ω_{bv} = axial bounce frequency.

$\Delta V_{\perp}/V_{\perp}$ = fractional change in perpendicular velocity.

Fig. 2. The effects of rf on the low-field case, $B = 0.435$ T.

Fig. 3. Particle distribution function with rf ($\psi = 0.01$) and without rf ($\psi = 0$), $\psi = \exp(\Delta\omega/\omega_i)^{-1/2}$, where $e\phi$ = normalized energy in rf field and $\Delta\omega$ = correlation frequency.

Fig. 4. Plasma radial profile with and without rf, where $R_0 = 5$ cm.

Fig. 5. Plasma axial profile with and without rf, where $R_0 = 5$ cm.

Tokamak Microinstability

We completed a two-dimensional study of the nonlinear saturation of the dissipative trapped-ion mode.¹ This low-frequency drift wave is expected to be unstable in tokamak device like the Princeton Large Torus, T-10, and the Tokamak Fusion Test Reactor. We expect the drift wave to make an important contribution to anomalous particle and energy losses in these devices. The saturation scheme investigated involved the tapping of available energy sinks, as described by linear kinetic theory, by means of the nonlinear $\mathbf{E} \times \mathbf{B}$ coupling of unstable modes to stable ones. Two-dimensional effects not considered in previous 1-D mode-coupling theory² played an essential role. One-dimensional nonlinear equilibria were unstable to radial perturbation. We found new equilibria explicitly including 2-D effects. These equilibria could saturate at significantly smaller amplitudes of the electrostatic potential and transport than in the 1-D case. We investigated the stability and accessibility of nonlinear saturated states to ascertain their relevance.

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Computer Simulation of High-Beta Mirror Plasmas

We continued to design and implement new particle simulation algorithms to study low-frequency phenomena in magnetized plasma. We applied these algorithms to the examination of microinstabilities and the buildup of plasma currents to reversal of the magnetic field in a mirror plasma. For particle simulation of high-beta mirror plasmas with no closed magnetic field lines, we demonstrated that the SUPERLAYER-II code provided a satisfactory physics description of the self-consistent magnetic and inductive electric fields and the ion motion. To this simulation model we added an external quadrupole magnetic field, consistent in magnitude with the 2X11B Experiment, as part of a continuing theoretical effort to better understand that experiment.

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In progress is a further extension of SUPERLAYER II in which the quadrupole self-fields are calculated, and in which we included a general, but limited, superposition of Fourier modes to describe azimuthal variation.

There was further progress on the development of physics models and new simulation methods that describe important electron physics features in a high-beta (plasma pressure/magnetic pressure) plasma. We introduced a new family of algorithms for quasineutral, hybrid (particle ions and fluid electrons) simulations.¹ The electrons are described by their momentum equation, with inertial effects ignored:

$$0 = -en_e (\mathbf{E} + \dot{\mathbf{V}}_e \times \mathbf{B}/C) - \mathbf{V} \cdot \nabla_e \mathbf{P}_e - \sum n_{es} n_e (\dot{\mathbf{V}}_e - \dot{\mathbf{V}}_s), \quad (1)$$

The ions are advanced at each time step, using particle equations of motion, Maxwell's equations are solved in the Darwin (nonradiative) approximation and with the assumption of quasineutrality:

$$\nabla \times \mathbf{B} = 4\pi e^{-1} (\mathbf{J}_\parallel - n_e c \dot{\mathbf{V}}_e)_\parallel, \quad (2)$$

$$\nabla \times \mathbf{E}^\perp = -n\mathbf{B}^\perp / c\omega t, \quad (3)$$

$$\nabla \cdot \dot{\mathbf{J}}^\perp(\phi) = 0, \quad (4)$$

and the added relations

$$\dot{\mathbf{E}} = \dot{\mathbf{E}}^\perp - \nabla\phi \text{ and } n_e = \sum_s Z_s n_s, \quad (5)$$

where the t and ℓ superscripts indicate transverse (divergence-free) and longitudinal (curl-free) vector-field components and the sum over s indicates that the possibility of more than one ion species is admitted. We successfully applied these algorithms to the simulation of compressional Alfvén waves (Fig. 1); electrostatic instabilities with some finite-beta effects, e.g., the drift-cyclotron loss-cone mode (Fig. 2); and electromagnetic instabilities, e.g., the Alfvén-ion-cyclotron mode (Fig. 3). We also studied the relaxation of electron return currents by means of the excitation of compression Alfvén waves upon injection of a weak current perpendicular to an externally applied magnetic field in a cold, uniform plasma. Our results are in good agreement with the theory of Berk and Pearlstein.² We

Fig. 1. Theoretical dispersion relation for compressional Alfvén waves with space-time mesh corrections deduced for a canonical-momentum-conserving algorithm. This establishes accuracy and confidence limits in the new algorithms. The dashed line is for $\Delta x = \Delta t = 0$; the solid curve includes the modifications due to finite differencing and is the solution of $\sin^2(\omega\Delta t/2) = (k_{\text{eff}} v_A \Delta t/2)^2$, where $k_{\text{eff}} \equiv \eta^{-1/2} k$ for $\Delta x = 0$ (linearized simulation) and $k_{\text{eff}} \equiv S k$ for $\Delta x \neq 0$ (fully nonlinear). Simulation data are shown in solid symbols for $\Delta x = 0$ and open symbols for $\Delta x \neq 0$.

Fig. 2. Dispersion relation for the drift-cyclotron loss-cone instability (DCLC), $(\omega + i\gamma)/\omega_{ci} \approx k^2 a_i^2/2$, with $\beta_e = 0$, $\beta_i = 1$, $a_i = R = 10$, $\omega_{ci}\Delta t \leq 0.05$, and (a) $\beta_e = 0.1$ or (b) $\beta_e = 1.0$. The data here and in Fig. 3 show successful application of these new codes to important microinstabilities in finite- β mirror plasmas. The solid and dashed curves denote the predictions of analytical theory. The results of linearized simulations using a canonical-momentum-conserving algorithm are indicated by the data points.

Fig. 3. Dispersion relation for the Alfvén-ion-cyclotron (AIC) instability, $(\omega + i\gamma)/\omega_{ci} \approx |k_{||}c|/\omega_{pi}$, for $\beta_{\perp i} = 1$, $\beta_e = 0$, $T_{\perp i}/T_{\parallel i} = 10$, and $\omega_{ci}\Delta t = 0.1$. The solid and dashed curves denote the predictions of analytical theory; the results of linearized simulation using a predictor-corrector scheme appear as data points.

more recently extended these methods to the simulation of field-reversed configurations for which the electrostatic potential on open field lines is determined by end loss and on closed field lines by $\nabla \cdot \mathbf{j} = 0$.

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Laser Interactions with Plasma

We continued our study of some aspects of laser-plasma interactions. In collaboration with Allan N. Kaufman (University of California and Lawrence Berkeley Laboratory) we extended an analysis of the resonant excitation of a large-amplitude plasma wave¹ to include the back-reaction of the plasma wave on the driving force for the specific case of stimulated Raman scattering.² Such scattering is of interest for plasma-heating applications and plasma-laser amplification; it could be deleterious in future laser-pellet fusion and laser-heated solenoid experiments.

The interaction is described by the following coupled-mode equations:

$$du_1/dt = -(i/2) (\omega_{pe}^2/\omega_1) (\tilde{n}/n_0) u_2 \quad (1)$$

and

$$du_2/dt = -(i/2) (\omega_{pe}^2/\omega_2) (\tilde{n}^*/n_0) u_1, \quad (2)$$

where u_1 and u_2 are the slowly varying (complex) amplitudes of the transverse oscillation velocities of two transverse waves with frequencies ω_1 and ω_2 ($\omega_1 > \omega_2$) and $\tilde{n}$ is the amplitude of the associated density perturbation of the beat-wave. These waves resonantly excite a plasma wave through their nonlinear $\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}$ force [derivable from a ponderomotive potential whose amplitude is given by $\tilde{\phi}_0 = (m/e) |u_1 u_2|$ if $\omega_1 - \omega_2 \approx \omega_{pe}$]. We directed particular attention to the effects of electron trapping in the beat-wave. To this end we married the couple-mode

equations to an electrostatic particle simulation code. We did this to perform efficient numerical calculations on the plasma-frequency time scale, in which large-amplitude plasma waves are excited and considerable trapping occurs.

Figures 1 and 2 illustrate typical results. Trapping causes the plasma wave to become heavily damped, and the scattering continues at a reduced, but finite rate. In this example 90% of the energy in the high-frequency wave is depleted over eight bounce periods of the trapped electrons, with a fraction, ω_{pe}/ω_0 , going through the plasma-wave channel into the plasma as kinetic energy. This result is encouraging for plasma heating and laser-amplification applications; it is possibly discouraging for laser fusion where Raman backscatter could lead to large reflectances and hot electrons.

We undertook further research in collaboration with Claire E. Max (Lawrence Livermore Laboratory) to theoretically study the linear evolution in space and time of stimulated Brillouin scattering, induced scattering by ions, and filamentation of laser light in a uniform, underdense plasma. These instabilities could be extremely deleterious

Fig. 1. Shows the efficient conversion of the high-frequency electromagnetic wave into the lower frequency wave and a plasma wave. This figure shows data from a simulation of the resonant response of a Maxwellian electron plasma (thermal speed $v_e = (T/m)^{1/2}$) to a ponderomotive plane-wave driving force, of frequency ω_0 (chosen equal to ω_p) and phase velocity ω_0/k_0 (chosen equal to $3v_e$), induced by the $\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}$ coupling of two opposed electromagnetic waves with oscillation velocity amplitudes u_1 and u_2 (chosen initially equal to $0.2 \omega_0/k_0 = 0.6 v_e$). Initially the linear normal-mode frequency is $\text{Re } \omega_1 = 1.17 \omega_{pe}$ and the linear Landau damping rate is $-\text{Im } \omega_1 = 0.03 \omega_{pe}$. The transverse waves have frequencies $\omega_1 = 5 \omega_{pe}$ and $\omega_2 = \omega_1 - \omega_0 = 4 \omega_{pe}$. Shown as functions of time are the magnitudes of the coupled-mode amplitudes $|u_1|/v_\phi$, $|u_2|/v_\phi$, and $|\tilde{n}|/n_0$ where $v_\phi = \omega_0/k_0$.

Fig. 2. Shows that, of the energy available to the plasma, most of it is deposited into plasma kinetic energy (heating) and not into coherent-wave energy. The spatially averaged longitudinal kinetic and field energy densities, $nmv_z^2/2$ and $(\partial\phi/\partial x)^2/8\pi$, are tracked in time (up to $\omega_p t/2\pi = 40$) for the simulation shown in Fig. 1. The initial thermal fluctuation level for $(\partial\phi/\partial x)^2/8\pi$ is less than $0.25 \times 10^{-2} n_0 T(0)$.

for laser-pellet and laser-solenoid fusion schemes. Large reflectances (50 to 70%) as the result of Brillouin scattering have been experimentally observed. We calculated Green's functions for the pulse-response problem, which clarified the competition of these parametric instabilities; absolute and convective instabilities were distinguished. Unless filamentation is preferentially initialized, stimulated Brillouin scattering dominates filamentation in a uniform plasma with $T_e \gg T_i$; for $T_e \sim T_i$ induced scattering and filamentation are both convective and have competitive growth rates.

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B. I. Cohen

Alfvén Ion-Cyclotron Mode

The theory of the Alfvén Ion-Cyclotron (AIC) mode¹⁻⁴ described in last year's annual report⁵ has since proceeded in several directions.

One mode of operation of the Tandem Mirror Experiment (TMX) involves neutral injection in the central cell.⁶ We have shown that the anisotropy inherent in the magnetically confined hot-ion distribution does not cause absolute instability.⁷ Specifically, the combined electrostatic and magnetic confinement of ions in the central cell is such that high-energy ions experience a loss-cone of semi-angle 18.4° . This satisfied the condition for absolute AIC stability, which is that the cone excised from the high-energy part of the ion-velocity distribution shall have a semi-angle less than 30.9° . This figure is arrived at by considering a two-component model, with a Maxwellian cool component and a loss-cone-Maxwellian hot component chosen to approximate the output of Rensink's Fokker-Planck computations. The effect of the cell's finite width is evaluated by inserting a nonzero $k_\perp$. Convective⁸ growth is shown to require more than 950 cm for seven e-foldings (a thousandfold amplitude increase) when the loss-cone has the 18.4° semi-angle.⁷

A request for computer time and scientific collaboration was received from another group working on the AIC mode. These persons were studying the spatial variation parallel to the magnetic field of the AIC mode in a finite machine. In the course of evaluating their request, we discovered that their second-order differential equation was incorrect and that, in any case, the fourth-order differential equation was required for an adequate description of the unstable eigenfrequency problem. We further found that the correct equation would not yield jump conditions.

Byers⁹ has reported stabilization of the AIC mode by finite length in particle simulations. The simulations in question¹⁰ are one-dimensional (along the magnetic field) and linearized. In equilibrium, $B_0(z)$ is a constant, so there is no detuning of the mode by variation in ω_{ci} . The ions are confined by an effective potential that is parabolic, so there is no dephasing of the mode by variation in the ion-bounce frequency ω_{bi} .

We derived the integro-differential equation describing the spatial variation of the complex amplitude $E(z)$ of the mode field. Rather than solving the complete spatial problem, we set up a simple dispersion relation as follows. We assumed a single spatial-frequency electromagnetic wave and found the response in the form of a (spatially varying) plasma current. The wave and current together were

required to satisfy Maxwell's equations at the plasma midpoint. Dispersion diagrams based on the dispersion relation show resonances at $\omega/\omega_{ci} = \omega_{ci} \pm 2n\omega_{ci}$ as expected¹¹ (Fig. 1).

We obtained a series of dispersion diagrams for plasmas of fixed length and increasing anisotropy. Restricting ourselves to real wavenumbers such that a half-wavelength fits in the plasma length, we found stabilization of the AIC mode occurring at anisotropies of $T_{\perp}/T_{\parallel} \sim 10$ to 20 for short plasmas of length the order of the ion-Larmor radius. Including the ion bounce motion in the dispersion relation could increase the anisotropy allowed at marginal stability by a factor of two. Stabilization at these anisotropies for short plasmas was consistent with the linearized particle simulation of Byers.^{9,10}

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3-D Calculations of Mirror

Equilibria with the Finite-Element

Vector-Potential-Equilibrium Code (VEPEC)

We perfected a new version of the VEPEC¹ code that calculates mirror equilibria rapidly and accurately in the finite-element (cubic spline) formulation of Ampere's law. Presently, for the guiding-center fluid model, it calculates equilibrium configurations for beams (plasma pressure/magnetic pressure) less than the mirror-mode limit after first determining the equilibrium at the mirror-mode threshold. Figure 1 plots the mirror-ratio enhancement factor for the long-thin model.

$$\frac{R_r}{R_v} = (1 - \beta_{\perp})^{-1/2} \quad (1)$$

and its generalization,

$$\frac{R_r}{R_v} = \left[(1 - \beta_{\perp}) - \frac{1}{\beta_{\perp}} \frac{\partial k}{\partial r} \right]_{\omega_{ci}} \left(\beta_{\perp} + \frac{1}{4} (\beta_{\perp} + \beta_{\parallel}) (1 - \beta_{\perp}) \right)^{-1/2} \quad (2)$$

Fig. 1. AIC bounce-mode dispersion relation. Light continuous line is real frequency corresponding to real wavenumber. Heavy line, which is the real part of a complex frequency, denotes instability. Dashed line is infinite-medium dispersion curve. Parameters are $\omega_{ci}/\omega_{ce} = 0.42$; $T_{\perp}/T_{\parallel} = 10$; $\beta_{\perp} = 0.75$; and $L_p = 1.46 \rho_i$. Note the resonance structure as indicated by the dotted lines.

suitable for field lines with small curvature (name'y, the 2X11B Experiment) vs the actual VEPEC results for several different beta values.

Fig. 1. The mirror-ratio enhancement factor (R_e/R_y) is plotted as a function of the perpendicular plasma beta ($\beta_{\perp}$). The two curves are for the simple long-thin formula (upper) and the first-order modified long-thin formula. Vertical lines indicate the mirror-mode threshold (MMT) and the $\beta = 1$ limit.

We further discovered that the onset of the mirror mode (at the machine midplane on axis) always coincides with the onset of bad curvature. Later this effect was analytically proven. The converse is not true—bad curvature does not guarantee the mirror mode.

The present guiding-center model is only applicable to cold plasmas in 2XII-B and not to the prevailing experimental hot plasma. New models for the plasma, which allow large gyroradii and field reversal, are required to make VEPEC equilibria more realistic. When there are new models the modular structure of VEPEC will easily allow their incorporation.

Solution of the nonlinear-vector Poisson's equation

$$\nabla^2 \underline{A} = (4\pi/c) \underline{J}(\underline{A}) \quad (3)$$

is presently carried out by the Douglas-Gunn algorithm² applied to the difference scheme derived from the finite-element expansions. An incomplete Cholesky conjugate-gradient algorithm³ (ICCG) will be used to replace the slower Douglas-Gunn algorithm. Equilibria that now require several minutes (~ 10) for solution will be obtained in less than 1 min on the Lawrence Livermore Laboratory Magnetic Fusion Energy Division's CDC-7600 computer.

The spatial truncation errors in $\underline{A}$ for the solution to Eq. 3 are 4th order in space. A typical finite-difference method would have third-order errors.

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Preliminary Planning for a 3-D Multifluid Magnetohydrodynamic Mirror-Plasma Simulation Code

Programmatic needs and the promise of greater computer power with the acquisition of the CRAY computer suggest that a large-scale 3-D fluid simulation code for mirror plasmas may be a realistic tool for understanding plasma dynamics (as well as steady states) in a mirror plasma.

Short time simulations need to be performed to follow the evolution of various magnetohydrodynamic (MHD) instabilities. Long time simulations are also needed to understand the evolution toward and the maintenance of a steady plasma configuration. Whether one code could operate one code on both timescales is being investigated; if true, savings of unnecessary duplication might be had.

Further incentives to undertake this work have been provided by several recent breakthroughs in numerical analysis. Here we refer to the application of finite-element models to fluid equations¹ and the incomplete Cholesky conjugate-gradient² method. These together form a synergistic relationship that allows fast, accurate solutions of the fluid equations on uneven coarse grids.

Many peculiar features of mirror plasmas (including large anisotropies in flow, pressure, and heat flow) dictate that existing 3-D MHD models based on isotropy will not be satisfactory.

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Authors

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Accurate Single-Particle Orbits in Realistic 3-D Minimum-B Mirror Fields

Three-dimensional cubic spline representations of gridded mirror fields were used to calculate trajectories of particles in the ORBXYZ code.¹ This code is a considerably more accurate generalization of the familiar TIBRO² and TIBROX³ codes.

We undertook two major applications of ORBXYZ. These were calculations of

- Low-beta (plasma pressure/magnetic pressure) plasma shapes and sizes in the vacuum fields for the 2XIIB and Mirror Fusion Test Facility (MFTF) experiments.

- Super-adiabatic phenomena using both gridded realistic fields as well as idealized analytic fields.

For the first application we calculated plasma axial half-lengths for e-folding (13.5 cm and 22 cm, respectively, for 2XIIB and MFTF). These were derived from the alignment of the neutral beams producing the plasmas.

The second project, still underway, has shown that the stochastic variations of the magnetic moment, μ , are often much less than first estimated. Particularly, after a full drift period, we sometimes find μ coming back quite close to its initial value. Simulations of the particle resonance effects thought to be seen in RECE-BERTA at Cornell University (and that might occur in 2XIIB as well) are now being performed with analytic fields. A wealth of diagnostics pertinent to these resonances and to the adiabatic theory is evaluated in the ORBXYZ code, making it particularly well-suited for this study.

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Authors

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Parameter Studies of Axisymmetric Reversed-Field Vlasov Equilibria for the 2XIIB Regime with the CYLEQ Code

The simple double-delta function

$$f = c_1 \delta(E - E_0) \delta(P_c - P_{c0}) \quad (1)$$

was taken to be the Vlasov equilibrium-distribution function for our study. We plotted various measures of field reversal vs many parameters that determine c_1 , E_0 , and P_{c0} in the distribution function. For the dependent parameters we chose

$$R_p = B_{c0}(0,0)/(B_{vac}(0,0) = \text{reversal on axis.}$$

$$V_{cfl} = \text{volume of closed field lines.}$$

$$F_{cfl} = \text{fraction of the plasma volume in } V_{cfl}.$$

$$\beta_{pk} = 8\pi nkE/B_{vac}^2(0,0) = \text{peak beta.}$$

Many possible sets of independent parameters were used. Primarily we studied

$$E = \text{total energy.}$$

$$I_\theta = \text{total poloidal current.}$$

$$r_0 = \text{inner turning radius.}$$

These in turn are related to other parameters of interest, both from a theory and an experimental viewpoint. We used

$$P_c = \text{canonical angular momentum.}$$

$$N = \text{total number of plasma ions.}$$

$$A_r = \text{inverse aspect ratio.}$$

$$L = \text{axial half-length of the plasma.}$$

$$E_{th} = \text{thermal energy at the vortex.}$$

$$\epsilon = \text{eccentricity of the cross-section.}$$

$$c_{dm} = 2\pi \int I_\theta(r,0) dr = \text{midplane current.}$$

$$R_{thk} = R_{pl} - R_0 = \text{radial thickness of the plasma.}$$

Obviously these are not all independent of each other. From hundreds of various equilibria calculated by CYLEQ we plotted elsewhere¹ all the various dependencies indicated above.

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Calculation of 2XIIB Self-Fields from Experimental Data

We developed several models of the plasma current profile for calculating the self-fields in the 2XIIB Experiment. The code CYLEQ was adapted to calculate the self-fields from these models, assuming the plasma current and self-fields to be axisymmetric. Rigidly rotating ion plasmas with both gaussian and radially humped density profiles were used as well as some models where the plasma was differentially rotating. We calculated the normalization of the density and the rotation frequencies so the measured total magnetic moment and line den-

sities were satisfied. Then we performed a parametric search of the axial and radial scale lengths to obtain a best fit to the measured off-axis self-fields.

Profiles were found best fitting the famous April 14th 2X11B runs, which were intended to approach field reversal. Comparing the different density and rotation models we calculated field reversal at $\Delta B/B = 0.9 \pm 0.2$, showing a dependence somewhat independent of the model chosen. Other measurements support the conclusion reached here than the field is almost reversed but still short of producing any closed field lines.

Authors

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2-D Axisymmetric Fluid Simulation of Plasma Production and Flow in Ion Beams

Extensive modifications were made to the multifluid r, z magnetohydrodynamic code PLASFLOW to study the interaction of the ion beam with the background plasma produced by the beam.

The code presently represents three ion or neutral fluids as well as electrons treated in the quasineutral limit. All three components of the magnetic field, electric field, and velocity fields are included. Very general boundary conditions may be imposed by the algorithm, including sheath boundaries. Source and sink terms in the various fluid equations allow the inclusion of chemistry, which was essential in modeling the plasma production.

This code could also be used to study the roles played by the Ohkawa current and the "bootstrap" current in reversed-field mirror configurations.

Authors

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Implementation of Incomplete Cholesky-Conjugate Gradient Method

We significantly reduced the running time of HYBRID-II (a major production code) by converting to the incomplete Cholesky conjugate-gradient (ICCG) algorithm.¹⁻⁴ The amount of reduction was problem-dependent, but the least we observed was a factor of five. With stiff problems, the reduction was three or four orders of magnitude in running time. At the same time the accuracy of results improved markedly. Other codes in our group should benefit similarly from ICCG methods.

ICCG is a method for solving large, sparse, linear

systems of equations. Such systems, in particular, include the difference equations arising from the numerical solution of partial differential equations. This new method, which is iterative, is economical in its storage and arithmetic operations. It can much more effectively get at exact solutions to a given set of difference equations than can alternating direction implicit (ADI) or operator-splitting methods in terms of computer time and accuracy. This is especially true for stiff problems in which the fastest time scale is much shorter than the time scale in which the interesting physics takes place. Direct methods of solving for the set of difference equations are competitive with ICCG only for problems with a modest number of data points.

Prompted by David Kershaw's success with ICCG² in the Lawrence Livermore Laboratory laser-fusion production code, LASNEX, we coded the nonsymmetric version of ICCG into software packages that solve for the nine-banded matrix that arises from a nine-point, 2-D difference operator. We incorporated these packages into the Fokker-Planck code, HYBRID-II.⁴ Our savings in computer running time and the improved accuracy were clear.

Runs with a confining electrostatic potential, applicable to the Tandem Mirror Experiment, are extremely stiff. They greatly benefit from the implicit solution allowed with ICCG.

We used a 3-D, seven-point symmetric version on Poisson's equation. Rapid convergence was obtained, even when the charge density was made a nonlinear function of the potential. We also tested a five-point, nonsymmetric version. Both of these efforts applied to magnetohydrodynamic equilibria.

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3-D Plasma Equilibrium

We applied the McGUS¹⁻³ equilibrium code to several different magnetic geometries. Our primary effort was directed at magnetic geometries from the Fusion Engineering Research Facility (FERF), hybrid-reactor design, Ioffe-coil reactor design, and the Tandem Mirror Experiment (TMX). Each of these designs yielded a distinct magnetic field and correspondingly different equilibria. The central distinguishing feature among the four fields was the variation of curvature along field lines.

The FERG coil set consists of a long yin-yang coil pair, which results in a small radial-well depth and field lines having very little curvature. For the basic design, which has a coil sweep angle of 85°, McGUS yielded an equilibrium at beta (plasma pressure/magnetic pressure) = $(8\pi p_1/B_{vac}^2) = 0.56$. Modified coils with sweep angles of 65° and 75°, while having a diminished field line curvature, gave only slightly reduced beta values.

The hybrid-reactor design consists of two sets of yin-yang coil pairs, nested inside each other. The coils are positioned to provide a nearly spherical confinement region in contrast with the elongated FERG design. Consequently, there is a greater radial-well depth and greatly enhanced field-line curvature. For optimal pressure profiles with various injection lengths, we computed equilibria, with beta between 0.8 and 0.9. The beam injection of the hybrid design was tailored using a Fokker-Planck code. To incorporate the parallel and perpendicular pressure corresponding to the Fokker-Planck calculated distribution, we modified McGUS to accept pressure as a tabulated input in addition to the standard procedure of using an analytical formula. For the hybrid design the use of the Fokker-Planck pressure proved successful in the low-beta regime. Closer to the stability limits, noisiness of the numerical data generated convergence problems that are being examined.

The basic Ioffe field was generated by a system of two loops and four quadrupole-bar currents. For a given device length and loop radius there are two fundamental design decisions remaining. First the bar coil may or may not be split at the end or position where the bar coil meets the loop coil. Second the ratio of bar current to loop current must be specified. For the split-end case with a bar-to-loop current ratio of 2, a Baseball-like field structure is generated. In this case, $r(f)$, the radial distance of a field line from the z axis, is a monotonic function of the distance along the field line, f . In other words, in the region of interest, as f varies, a field line in a symmetry plane either fans out or compresses in toward the z axis. For a general bar-to-loop current

ratio, a fanning field line has an $r(f)$ that increases, decreases, and then increases. The region of decrease occurs when the field line goes under a loop. This nonmonotonic behavior causes a bad curvature region along fanning field lines near the loop coil. The effect of increasing the bar-to-loop current is twofold. First the bad curvature region is accentuated since $r(f)$ increases more rapidly for a fanning field line moving toward a loop: thus $r(f)$ has a more rapid decrease region. Second the saddle point of the magnitude of the magnetic field moves generally in a radially increasing direction. The position of the saddle point proves to be important for the separable pressures used by the McGUS code since it is necessary for the average drift-surface action function $\bar{\Gamma} = |\hat{p}_1|dr/B$ to be monotonic, a general requirement of stable equilibrium.⁴ If the saddle point is too near the axis, $\bar{\Gamma}$ is nonmonotonic in the region where plasma exists. This places a restriction on the plasma radius. To increase the plasma radius the bar-to-loop current ratio must be increased; this action, however, adversely affects stability since it accentuates the bad curvature region. Our compromise for a device with length equal to 2.8 times the loop radius was a plasma radius equal to a quarter-loop radius with a bar-to-loop current of 1.5. We obtained betas between 0.5 and 0.6 with and without split-end coil configurations.

The TMX field geometry is generated mainly by a central group of loop coils and two end-plug coil sets. An end plug consists of a Baseball-like coil and several C-shaped coils. Earlier work has shown that the omnigenity property is maintained in a variety of yin-yang and Baseball coils.⁵ The end plug is of this type. Its field, however, is perturbed in an unsymmetric fashion by the added TMX coils. To determine whether or not particles with different pitch angle drift on the same surface, we used the MAFCO11⁶ code to calculate guiding-center trajectories. In all cases omnigenous drift surfaces were generated. With this assurance we used the McGUS code to construct finite-beta equilibrium. The pressure-weighted stability of the TMX device was then examined by considering the radial behavior of $\bar{\Gamma}$. In the end plug, $\bar{\Gamma}$ was computed in the finite-beta magnetic field: in the central TMX region, $\bar{\Gamma} = |\hat{p}_1|dr/B$ was calculated with the MAFCO76 code.⁷ The stability index was then the radial variation of $\bar{\Gamma} + \alpha I$, where α is the pressure ratio between an end plug and the central cell. On this basis, in the predicted operating regime, TMX was satisfactorily stable to interchanges.

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Exploratory Concepts: Intense Pulsed Ion-Neutral Source (IPINS)

Introduction

Attaining a field-reversed configuration in the 2X11B confinement experiment is a major objective of Lawrence Livermore Laboratory's mirror program. To date, achievement of this goal appears to be thwarted due to insufficient input neutral-beam energy or energy confinement time (see 2X11B section) or both. These experiment limitations cause the contained plasma energy to be less than the energy that would allow field reversal to occur. In the most simple form, 2X11B field reversal would be accomplished by injecting and trapping sufficient beam energy to substitute the magnetic field energy. Thus

$$Q_B W_B \approx \xi \cdot B^2 / 2\mu \cdot \chi \cdot \text{volume of plasma. (1)}$$

where Q_B is the injected beam charge at energy W_B , ξ is the degree of field reversal (> 1), and χ is the swelling factor of the plasma volume. For 2X11B parameters, $Q_B W_B \approx 5 \text{ kJ}$. The purpose of this exploratory concepts program is to determine if a new

technology¹ can develop an Intense Pulsed Ion-Neutral Source (IPINS) capable of furnishing the beam parameters necessary to attain field-reversal requirements for 2X11B.

Approach

Past Livermore experiments² have shown that the new technology of intense-ion diodes was characterized by the following parameters:

- Particle energy $> 100 \text{ keV}$.
- Ion current density $> 2 \text{ kA/cm}^2$.
- Pulse duration $\sim 50 \text{ ns}$.

Since this early work other researchers³ have demonstrated intense-ion diode operation at higher voltages (i.e., 500 or 800 keV) but with similar pulse durations and current densities.

These operational parameters, although interesting, are insufficient for Livermore's objectives in two areas. First, for ion orbits to be contained by the existing confinement experiments magnetic field and to allow for the high-intensity ion beam to be atomically neutralized (to avoid injection problems across the mirror magnetic fields) the ion-beam energy must be lowered to 50 to 100 keV. Lowering W_B means that Q_B must substantially increase; to deliver the necessary Q_B in the customary ion-diode pulse time of 50 ns would require low-impedance generator currents of unwieldy proportions (several 10s of MA). To avoid this difficulty one should extend the intense-ion-flow pulse duration from 50 ns to $> 1 \mu\text{s}$. Thus, FY 1977 activity in this exploratory concept program concentrated on these major objectives:

- Investigate whether intense-ion-diode flows of energies $\geq 100 \text{ keV}$ were possible.
- Determine if atomic neutralization of the extracted high-intensity ion beam could occur.
- Determine if one could extend the time duration of the intense-ion pulse to $\leq 1 \mu\text{s}$.
- If results are encouraging, fabricate an experimental facility whose performance is expected to be within a factor of two of the requirements for 2X11B application.

Accomplishments

We addressed the first three research issues on a small test stand built to determine if ion-diode technology could be so advanced. Accomplishments of the test stand^{4,5} appear below:

- Developed intense-ion-flow diodes of 1.2 μs .
- Generated ion-current intensity of 200 A/cm². Limitations on this current intensity were power-supply designs (high impedance).
- Developed stable diode voltage of 75 kV lasting a full pulse duration.

- Accomplished atomic neutralization of the ion beam by using thin carbon foils. Because of the high ion intensity, customary gas-cell neutralizers were unfeasible.

- Extracted the neutral beam and propagated it 1.2 m to a diagnostic target. Beam divergence was $\pm 3^\circ$.

Because of these encouraging results we completed fabrication of the larger experimental facility (last major objective) at the end of FY 1977. We began efforts to make this facility fully operational. Advancements in power-supply design and improvements in diode construction should improve efficiency and increase our current density by over an order of magnitude. The key issues for FY 1978 research are (a) improving where possible the beam fluence (further increasing diode efficiency) and (b) more importantly, decreasing the beam divergence. If both these research issues proceed favorably then

the experimental facility will be within a factor of two of 2XIB requirements.

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