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UCAR-10060-80-4

MirrorFusion

Quarterly Report

October through December 1980

University of California

Lawrence Livermore
National Laboratory

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MASTER

UCAR-10060-80-4

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The Cover

In this schematic representation of the improved Tandem Mirror Experiment (TMX Upgrade), now under construction, the flux bundle (plasma) is shown in magenta and the neutral beams in blue. The neutral beams aimed at 45° to the machine axis supply the "sloshing ions" that help create the thermal barrier; the other end-cell beams "pump" away unwanted trapped ions in the barrier. The central-cell beams heat the central-cell ions. The magnet set is similar to that used in the original TMX. However, the central-cell solenoids (shown in dark gray) are the only coils being retained. The transition magnets used in TMX (a C-coil and octupole set) are replaced by a C-coil (orange) and an Ioffe bar (yellow). The baseball set and C-coil in the TMX end plugs are replaced by two C-coils (pale lavender), two solenoids (orange), and a Ioffe bar (gold). Each of these new end-cell magnet sets generates a 2-T mirror field having a 4:1 mirror ratio. The central cell has a magnetic-field strength of 0.3 T.

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Preface

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

The information in each *Quarterly* is presented in the same sequence as in the Field Work Package Proposal and Authorization System (WPAS) submissions prepared for the U.S. Department of Energy; the main sections are applied Plasma Physics, Confinement Systems, Development and Technology, and Mirror Fusion Test Facility (Planning and Projects).

On occasion, we shall include information pertaining to the LLNL role as Lead Laboratory for the Open Systems Mirror Fusion Program. Each of these sections is introduced by an overall statement of the goals and purposes of the groups reporting in it. As appropriate within each section, statements of the goals of individual programs and projects are followed by articles containing summaries of significant recent activity and descriptive test.

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Applied Plasma Physics

Applied Plasma Physics is a major sub-organizational unit of the Magnetic Fusion Energy (MFE) Program. Within this unit are Fusion Plasma Theory, Experimental Plasma Research, and the National MFE Computer Network.

Fusion Plasma Theory encompasses the work of the Fusion Plasma Theory and Computation group and the MFE Computer Center (MFECC) Computational Physics group. The first group has the responsibility for developing theoretical-computational models in the general areas of plasma properties, equilibrium, stability, transport, and atomic physics, specifically for the LLNL mirror experimental program. The MFECC Computational Physics group serves the entire MFE community. Its principal objective is to develop detailed numerical models for investigating plasma phenomena and for simulating present and future magnetic confinement systems, with applications to tokamaks, mirrors, and various alternate concepts.

Under Experimental Plasma Research, we are studying the feasibility of using certain neutron-detection techniques as plasma diagnostics in the next generation of thermonuclear experiments.

The National MFE Computer Network was established in 1974 by the Department of Energy Division of Magnetic Fusion Energy (DMFE). The National MFECC, headquarters of this network, is located at LLNL. The purpose of the National MFECC is to apply large-scale computational technology and computing techniques to the problems of controlled thermonuclear research. At the national center, available to the entire community, are the high-speed Cray-1 computer with one million words of memory and a CDC 7600 central computer with 64,000 words of small semiconductor memory, 500,000 words of large-core memory, and disk storage. Different levels of computer capability are provided at the various remote locations according to research priorities and anticipated computational demand. Various selected universities and other laboratories engaged in MFE research have access to the MFECC at LLNL via the six user service centers (USC's) equipped with PDP-10 computer systems.

FUSION PLASMA THEORY

Self-Consistent, Three-Dimensional Equilibria for Large-Aspect-Ratio Mirror Machines at Moderate Beta

(L. D. Pearlstein, T. B. Kaiser, and W. A. Newcomb)

We have formulated a new scheme for the construction of self-consistent, three-dimensional, guiding-center equilibria for mirror machines with vacuum fields having quadrupole symmetry and arbitrary mirror ratio and flux-surface ellipticity. Equilibria amenable to the new technique are characterized by large aspect ratio, non-axisymmetry, and moderate beta.

We start with the general tensor-pressure magnetostatic equilibrium conditions¹

$$(\nabla P)_\perp = Q\kappa, \quad (1)$$

$$\frac{dP}{dB} = B \frac{d}{dB} \left(\frac{Q}{B} \right), \quad (2)$$

where $P = 1/2 B^2 + p_\perp$, and $Q = B^2 + p_\perp - p_\parallel$. B is the magnetic flux density, κ is the curvature vector, $p_{\perp,\parallel}$ are pressure components perpendicular and parallel to B , and $d/dB \equiv (B \cdot \nabla B)^{-1} B \cdot \nabla$.

We introduce flux coordinates α, β such that $B = B\hat{b} = \nabla \alpha \times \nabla \beta$ and assume the pressure to be of the special form $p_{\perp,\parallel} = p_{\perp,\parallel}(\alpha, B)$. We further assume a large-aspect-ratio system, i.e., one in which lengths in the x, y plane are small (of order λ , say) compared with the axial scale length, and we systematically ignore all terms of relative order λ^2 . One result of this ordering is that $\kappa \sim O(\lambda^2)$, so that Eq. (1) becomes $B^2 + 2p_\perp = B_{vac}^2(z)$, the usual long-thin approximation to perpendicular pressure

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balance. Parallel pressure balance, Eq. (2), relates $p_{\perp}$ to $p_{\parallel}$ by $p_{\perp} = -B^2 d(p_{\parallel}/B)/dB$. Therefore, given $B_{\text{vac}}(z)$ and $p_{\parallel}(\alpha, B)$, it requires only a functional inversion to determine B , $p_{\parallel}$, $p_{\perp}$ as functions of α and z . All are independent of β .

To complete the description of the equilibrium requires a determination of the coordinate transformation $(\alpha, \beta, z) \rightarrow (x, y, z)$, which makes it necessary to determine the flux line geometry $x(\alpha, \beta, z)$, $y(\alpha, \beta, z)$. The equations determining x and y consist of¹

$$\frac{\partial(x, y)}{\partial(\alpha, \beta)} = B^{-1} \quad , \quad (3)$$

which follows from the definition of α, β as flux coordinates, and the parallel current equation that follows from Eq. (1); viz.,

$$\mathcal{H} \frac{\partial Q}{\partial \alpha} = -B \left(\frac{Q}{B^2} \right)' \quad . \quad (4)$$

In Eq. (4), $\mathcal{H}$ is the geodesic curvature ($\mathcal{K} = \mathcal{H} \nabla \alpha + \mathcal{H} \nabla \beta$), a prime denotes differentiation along a field line, $\hat{b} \cdot \nabla = \partial/\partial z|_{\alpha, \beta}$, and i is the parallel current per unit magnetic flux:

$$i = \hat{b} \cdot \nabla \times \hat{b} = B \left[\frac{\partial(x', x)}{\partial(\alpha, \beta)} + \frac{\partial(y', y)}{\partial(\alpha, \beta)} \right] \quad . \quad (5)$$

We solve Eqs. (3) through (5) to leading (first) order in beta. In zeroth order, i.e., in the vacuum field, field lines can be represented by

$$x_{\text{vac}}(z) = \sigma(z) x_0 \quad , \quad y_{\text{vac}}(z) = \tau(z) y_0 \quad , \quad (6)$$

where $\sigma\tau = B(0)/B(z)$ and x_0, y_0 are the coordinates of a field line at the mid-plane ($z = 0$) of the system. Quadrupole symmetry requires $\sigma(z) = \tau(-z)$ and $B(z) = B(-z)$.

The principal flux coordinate σ is identified by imposing the constraint that i vanish at the ends of the system ($z = \pm L$). With Eq. (4), this implies that

$$\int_{-L}^L dz (\partial Q / \partial \alpha) \mathcal{H} / B = 0 \quad ,$$

which is satisfied by symmetry to first order in beta by choosing

$$\begin{aligned} \alpha &= \frac{1}{2} B_{\text{vac}}(0) r_0^2 \equiv \psi \quad , \\ \beta &= \tan^{-1} (y_0/x_0) \equiv \theta \quad , \end{aligned} \quad (7)$$

where $r_0^2 = x_0^2 + y_0^2$.

We linearize Eqs. (3) through (5) by writing

$$x = x_{\text{vac}} + \xi \quad , \quad y = y_{\text{vac}} + \eta \quad , \quad (8)$$

where $\xi, \eta \sim O(\text{beta})$. Then Eq. (3) becomes

$$\tau \frac{\partial \xi}{\partial x_0} + \sigma \frac{\partial \eta}{\partial y_0} = \frac{B_0}{B^3} p_{\perp} \quad (9)$$

if the lateral boundary, at which ψ is fixed, is taken to be at infinity. Since the right side of Eq. (9) is independent of θ , the general solution is

$$\begin{aligned} \xi &= \sigma \left(k x_0 + \frac{\partial \phi}{\partial y_0} \right) \quad , \\ \eta &= \tau \left(k y_0 - \frac{\partial \phi}{\partial x_0} \right) \quad , \end{aligned} \quad (10)$$

where

$$k = (2\psi)^{-1} \int_0^{\psi} d\psi' p_{\perp} / B^2 \quad ,$$

and ϕ is an arbitrary stream function. To specify ϕ , we use the linearized form of Eq. (9), which with Eq. (10) is

$$\tau^2 \frac{\partial^2 \phi'}{\partial x_0^2} + \sigma^2 \frac{\partial^2 \phi'}{\partial y_0^2} = 2 \sin 2\theta \psi \frac{\partial S}{\partial \psi} \quad , \quad (11)$$

where

$$\begin{aligned} S(\psi, z) &= B^{-1} \int_z^L dz' \\ &\times [(\sigma\sigma'' - \tau\tau'') p/B] - (\sigma^2 - \tau^2) k' / 2 \quad , \end{aligned}$$

and the appropriate boundary condition is that $\phi' \rightarrow 0$ as $\psi \rightarrow \infty$.

Since Eq. (11) is an equation for ϕ' , it determines ϕ only up to an arbitrary function of (x_0, y_0) ; i.e.,

$$\phi = \int_0^z dz' \phi'(x_0, y_0, z) + \phi_0(x_0, y_0) \quad (12)$$

We fix ϕ_0 by requiring the parallel current constraint $i(\pm L) = 0$ to be satisfied to $O(\beta^2)$. The resulting equation for ϕ_0 is

$$\frac{\partial^2 \phi_0}{\partial \theta^2} = -\frac{\Sigma}{\Pi} \quad (13)$$

where

$$\Sigma = \int_{-L}^L dz B^{-1}(\partial p / \partial \psi) K \quad ,$$

and K is a known function of (r_0, θ, z) and (σ, τ, ϕ') and the derivatives of the latter functions with respect to (r_0, θ, z) , and

$$\Pi = \int_{-L}^L dz B^{-1}(\partial p / \partial \psi) (\sigma \sigma'' + \tau \tau'') \quad .$$

It is interesting that the flute instability criterion that arises quite generally from the guiding-center energy principle is, in the large-aspect-ratio limit, $\Pi > 0$.¹ Thus we see that at marginal stability ϕ_0 is indeterminate, signaling that the perturbation procedure has broken down, and indicating an apparent bifurcation in the equilibrium. Away from the marginal point, however, the equilibrium is completely determined by Eqs. (11) through (13).

We solve Eq. (11) by separating the elliptic differential operator $\sigma^2 \partial^2 / \partial x_0^2 + \tau^2 \partial^2 / \partial y_0^2$ into its Laplacian and symmetry-breaking components:

$$\left(\frac{\partial^2}{\partial x_0^2} + \frac{\partial^2}{\partial y_0^2} \right) \phi' = \frac{4}{\sigma^2 + \tau^2} \sin 2\theta \psi \frac{\partial s}{\partial \psi} + \epsilon \left(\frac{\partial^2}{\partial x_0^2} - \frac{\partial^2}{\partial y_0^2} \right) \phi' \quad , \quad (14)$$

where $\epsilon \equiv (\sigma^2 - \tau^2) / (\sigma^2 + \tau^2)$. We analyze the integral equation for ϕ' that results from use of the Laplacian Green's function by writing ϕ' as

$$\phi' = \sum_{m=1}^{\infty} \mu(\epsilon)^{m-1} H_m(\psi, z) \sin 2m\theta \quad . \quad (15)$$

We then determine $\mu(\epsilon)$ and $H_m(\psi, z)$ from a recursion relation, and find that the series (15) can be summed. The result is

$$\phi' = \frac{2}{(\sigma + \tau)^2} \frac{1}{\mu} \text{Im} \left(\int_0^\psi d\psi' S(\psi', z) \times \left\{ 1 + 4 \frac{\psi'}{\psi} \frac{\mu \exp(2i\theta)}{[1 - \mu \exp(2i\theta)]^2} \right\}^{-1/2} \right) \quad , \quad (16)$$

where $\mu = -(\sigma - \tau) / (\sigma + \tau)$.

Thus, determination of the equilibrium is reduced to a simple quadrature in ψ , which can be performed analytically for realistic radial pressure profiles, and to quadratures in z that involve only vacuum quantities and that can always be done numerically.

We now consider an instructive particular case. We assume the pressure to be of the form $p_{\parallel} = \omega(\psi) p_{\parallel}(B)$, with

$$\omega(\psi) = \begin{cases} 1 - \psi / \psi_B, & \psi \leq \psi_B \\ 0, & \psi > \psi_B \end{cases} \quad , \quad (17)$$

and choose $\hat{p}_{\parallel}(B)$ to fit the pressure distribution expected in the upgrade to the Tandem Mirror Experiment (TMX Upgrade). Beta ($\equiv 2p_{\perp} / B_{\text{vac}}^2$) is taken

to be 0.16 at the midplane of the central cell and 0.20 at the midplanes of the end cells. Figure 1 shows $B_{\text{vac}}(z)$ (dotted curve), $B(z)|_{\psi=0}$ (solid curve), and beta on-axis (dashed curve). Figure 2 shows a field line in one of the symmetry planes at the plasma boundary ($\psi = \psi_B$), both *in vacuo* (dotted curve) and with the plasma present (solid curve). Notice that the effect of finite plasma pressure is to pull the field line toward the axis, thereby decreasing the ellipticity of the flux surface. This effect is more clearly seen in Figs. 3(a-d), where cross sections perpendicular to the magnetic axis of constant-pressure surfaces are shown at several axial positions. Vacuum flux surfaces are shown by dotted lines, and the surfaces into which they are deformed by induced plasma currents are shown by solid lines. The outermost curves correspond to the plasma boundary, $\psi = \psi_B$.

Figure 3(a) is at the central-cell midplane, $z = 0$. It qualitatively confirms the finding of Stupakov² that parallel plasma currents can significantly deform the constant-pressure surfaces relative to flux surfaces in the vacuum field. The amplitude of the deformation that we find, however, is opposite in sign to that found by Stupakov. The explanation of this difference lies in

the axial boundary conditions used in the two calculations. Whereas Stupakov sets the parallel current to zero at the ends of the central cell, we apply that condition at the ends of the entire system. How this affects the constant-pressure surfaces can be seen by considering the radial displacement of a ψ -contour at $z = 0$, which depends on both $k(\psi, z)$ and $\phi(\psi, \theta, z)$. By definition [see Eq. (12)], $\phi(z = 0) = \phi_0$. The exact form of the contour displacement is

$$\Delta r_0 = kr_0 + \frac{1}{r_0} \frac{\partial \phi_0}{\partial \theta}, \quad (18)$$

i.e., an axisymmetric component kr_0 , and an angular-dependent piece $r_0^{-1} \partial \phi_0 / \partial \theta$. Reference to Eq. (13) shows that the sign of $\partial \phi_0 / \partial \theta$ depends on that of Π , the flute-instability criterion, which is itself independent of θ . By limiting consideration to just the central cell, Stupakov obtained a positive value for Π (by itself, the central cell is flute-unstable). By including the entire machine, on the other hand, we obtain $\Pi < 0$ (the entire system is stable to flute modes by design), which reverses the sign of the nonaxisymmetric component of Δr_0 relative to Stupakov's result.

FIG. 1. Magnetic flux density $B(z)$ on-axis, both *in vacuo* (dotted curve) and with plasma present (solid curve). Also shown is the plasma beta on-axis (dashed curve).

FIG. 2. Field line on plasma boundary in symmetry plane $\theta = 0$, *in vacuo* (dotted curve) and with plasma present (solid curve).

FIG. 3. Constant-pressure-surface cross sections perpendicular to the magnetic axis *in vacuo* (dotted curve) and at finite beta (solid curve). Contours are shown at four axial locations.

Although *any* departure from circularity at the midplane (regardless of its algebraic sign) is important from the point of view of transport, the difference between our result and Stupakov's is important for another reason, *viz.*, its implications for flux-surface distortions in the transition regions, where the vacuum surfaces are highly elliptical. We find that this ellipticity is decreased at finite beta,

contrary to the prediction of Stupakov. Our result is illustrated in Fig. 3(b), in which we plot flux contours at the inside mirror peak, $z = 408$ cm. The axes have been scaled to make the vacuum contours appear circular. The reduction in the maximum excursion of flux surfaces from the magnetic axis is clearly beneficial for the central-cell radial confinement of field lines with increasing beta, and

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therefore alleviates the engineering problem of optimal coil design.

In Figs. 3(c,d), we show flux contours at the midplane of the end cell, $z = 569$ cm, and outside mirror peak, $z = 707$ cm, respectively. At the end-cell midplane, the nearly circular vacuum flux surfaces assume a pronounced ellipticity at finite beta for small r , and a squared-off shape at the plasma boundary. At the outboard mirror, the already highly elliptical vacuum contours become even more so with finite confined pressure. Since there is no plasma at this point, however, the effect is benign.

Our new formulation of the equilibrium problem has the clear advantage that, being essentially analytic, it generates solutions that are easily and rapidly computed. Thus, it is ideally suited for generating equilibria to be used as starting points for calculations of magnetohydrodynamic (MHD) stability. Indeed, the equilibrium shown in Figs. 1 through 3, characterized by $\beta_c = 0.16$, $\beta_p = 0.20$, was determined to be marginally stable to ballooning modes by a new code for solving the ballooning eigenvalue problem that we are currently developing.

Destruction of Superadiabaticity by Classical Pitch-Angle Collisions (B. I. Cohen, R. H. Cohen, and T. D. Rognlien)

We find that classical Coulomb pitch-angle collisions can diffuse the gyro-phase of ions resonant with ion-cyclotron loss-cone modes. This allows ions that would otherwise be superadiabatic to diffuse. However, the ensuing transport is very weak and cannot account for ions observed with energies significantly greater than the injected energy in 2XIIB.

Loss-cone instabilities theoretically studied and experimentally observed in many different mirror devices, e.g., 2XIIB and PR-6, continue to play an important role in tandem mirrors, where ion-cyclotron noise originating in the plugs evidently propagates into the central cell and degrades ion confinement there. The quasi-linear theory of the drift-cyclotron loss-cone (DCLC) instability has demonstrated the importance of heating ions to

energies well in excess of injection energies in limiting the amplitudes of the saturated waves and hence the ensuing velocity-space transport. However, the microscopic theory³⁻⁶ of superadiabaticity and stochasticity has so far been unable to identify a mechanism accounting for the observed ion heating and justifying application of quasi-linear theory. Here we summarize the results of analytical and numerical studies in which we determine that classical Coulomb pitch-angle collisions between ions destroy superadiabaticity and allow the ion-cyclotron wave to drive resonant plateau diffusion.⁷

The methods used here were introduced in Refs. 6 and 7, with the impetus for this calculation being derived from conversations with Shaing and Callen,⁸ who observed that the ion gyro-phase diffusion rate due to classical pitch-angle collisions is geometrically enhanced over the Spitzer ion-ion collision rate ν_{ii} . We find the mean-square deviation of the gyro-phase angle accrued over a time t to be

$$\langle \Delta\psi^2 \rangle \approx \frac{L_m^2}{a^2} \frac{W_{\parallel}}{W_{\perp}} \frac{\nu_{ii}}{\omega_b} \left(\frac{\omega_b t}{2} \right)^3 \quad (19)$$

for small $W_{\parallel}/W_{\perp}$, where ψ is the gyro-phase angle, $a \equiv v_{\perp}/\Omega_0$ is the ion gyro radius, L_m is the axial magnetic scale length, ω_b is the bounce frequency, and $W_{\parallel}/W_{\perp}$ is the ratio of the parallel to perpendicular ion energies. In one bounce time ($t = \tau_b \equiv 2\pi/\omega_b$), $\Delta\psi^2$ is much larger than ν_{ii}/τ_b , due to the geometrical enhancement factor L_m^2/a^2 , provided that $W_{\parallel}/W_{\perp}$ is not too small. For 2XIIB parameters,⁹

$$\langle \Delta\psi^2 \rangle / \tau_b \approx O(10^2) \nu_{ii}$$

What influence will pitch-angle collisions then have on a gyrophase sensitive process like DCLC-driven velocity transport?

The resonant interaction of a single ion-cyclotron wave with an ion in an axisymmetric simple mirror field is described by the Hamiltonian⁶

$$K = (p_x - p_0)^2 G + q\Phi_0 J_{\ell}(ka) J_p(\ell J/4\mu) \cos \chi \quad (20)$$

near the resonant perpendicular energy p_0 , where

$\ell p_\chi = \mu$ the magnetic moment,

$$J = (\Omega_0 W_{\parallel} / \omega_b W_{\perp}) \mu$$

is the longitudinal action,

$$G \equiv -(\omega - \ell \Omega_0 + 6p\omega_b + 5k v_d) / 4p_0,$$

ω is the mode frequency, ω_b is the axial bounce frequency, Ω_0 is the central cyclotron frequency, Φ_0 is the mode amplitude, and

$$\chi \equiv \ell \bar{\psi} - 2p\phi - kY - \omega t. \quad (21)$$

In Eq. (21), ψ is the bounce-averaged gyrophase angle, ϕ is the bounce phase, and Y is the ion guiding-center position. Resonances are diagrammed in Fig. 4 and are determined by the condition

$$d\chi/dt = \ell \bar{\Omega} - 2p\omega_b - k v_d - \omega = 0, \quad (22)$$

where $\bar{\Omega} = \Omega_0(1 + W_{\parallel}/2W_{\perp})$. Ions with energies above the stochasticity boundary in Fig. 4 are

FIG. 4. Plots of finite-width resonances in the $W_{\parallel}$ $W_{\perp}$ plane (where W is ion energy), showing three points at which adjacent resonances touch. (Solid dots are points on the stochasticity boundary.) The resonances are labeled by values of the bounce-harmonic number p . The cyclotron-harmonic number ℓ is unity. Parametric values are mode frequency $\omega = \Omega_0 = 2.8 \times 10^7 \text{ s}^{-1}$, axial scale length $L_m = 60 \text{ cm}$, radial scale length of the magnetic field $R_g = 30 \text{ cm}$, $q\phi_0 = 100 \text{ eV}$, $k = 1 \text{ cm}^{-1}$, and M = the mass of the deuteron (from Ref. 6).

FIG. 5. Solid line shows the resonance curve for $\chi = 0$ in ion-energy space having a finite width because of a wave in the drift-cyclotron loss cone (DCLC). The stippled area enclosed by dashed lines represents the resonance width. Also diagrammed are the unit normal $\hat{n}$ perpendicular to the resonance curve, the direction along which pitch-angle diffusion $\mathcal{D}_{ii}$ occurs [where $\mathcal{D}_{ii} = 1/\sqrt{2}(\hat{e}_{\perp} - \hat{e}_{\parallel})$] and $\Delta \bar{W}^s$ indicates the magnitude and direction of the resonance oscillation.

superadiabatic and execute resonant oscillations described by the Hamiltonian in Eq. (20).⁶

Pitch-angle diffusion occurs at constant energy, $dW = dW_{\perp} + dW_{\parallel} = 0$, with rate

$$\frac{\langle \Delta W_{\parallel}^2 \rangle}{\Delta t} = \frac{\langle \Delta W_{\perp}^2 \rangle}{\Delta t} = \frac{4W_{\parallel}W_{\perp}}{\tau_{ii}}, \quad (23)$$

where $\tau_{ii} \equiv \nu_{ii}^{-1}$. Resonant plateau transport prevails when collisions diffuse an ion across the resonance region, i.e., separatrix ($\Delta W_{\parallel}^s, \Delta W_{\perp}^s \propto \Phi_0^{1/2}$), in less than half the resonance oscillation (trapping) period. This is diagrammed in Fig. 5. Of particular interest to us here are the ions interacting with the $\ell = 1$ and $p \leq 0$ resonances in the superadiabatic region of Fig. 4. We find that ion-ion collisions are sufficiently rapid to produce resonant plateau transport for the $p = -2$ bounce harmonic. However, ions interacting with the $p = -1$ and 0 resonances complete their resonant (banana) oscillation before they collisionally diffuse. The

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banana transport for $p = -1$ and 0 can be significant compared to the plateau regime transport for $p = -2$ because of the relatively larger step-size involved.⁷ However, because we are primarily concerned with a possible mechanism for producing high-energy ions $W_{\perp} > .20 \text{ keV} \gg W_{\parallel}$, we shall focus attention only on the $p = -2$ resonance, which is closest to this energy range (see Fig. 4).

The resonant plateau diffusion coefficient should be less than the layer diffusion coefficient given by $\mathcal{D}_{\ell} = \Delta W_{\perp}^2 / \tau$, where from Eq. (20) we have calculated

$$\Delta W_{\perp} = \dot{W}\tau \approx \ell \Omega_0 \dot{p}_x \tau = q \Phi_0 J_{\ell} J_p \ell \Omega_0 \tau, \quad (24)$$

and τ is the time to collisionally diffuse across the plateau resonance layer. In fact, the true diffusion rate is substantially less because the diffusing ions do not remain in the resonant layer. Thus, a resonant ion diffuses in energy an amount equal to its energy $W_{\perp}$ at a rate less than

$$\nu_{\ell} \equiv \mathcal{D}_{\ell} / W_{\perp}^2 \approx \frac{1}{2} (q \Phi_0 / W_{\perp})^2 (J_{\ell} J_p)^2 \times (\ell \Omega_0)^{4/3} (W_{\perp} \tau_{ii} / W_{\parallel})^{1/3}. \quad (25)$$

For $\ell = 1$, $p = -2$, $q \Phi_0 = 100 \text{ eV}$, $W_{\perp} = 13 \text{ keV}$, $\tau_{ii} = 0.023 \text{ s}$, and $J_{\ell} = 0.1$ appropriate to 2XIIB⁹ gives $\nu_{\ell} = 2 \text{ s}^{-1}$, which is much smaller than the neutral-beam charge-exchange replacement rate $\nu_{cx} \approx 3 \times 10^3 \text{ s}^{-1}$. Thus, resonant plateau transport is inconsequential in a 2XIIB environment, and energetic ions observed in 2XIIB cannot be explained by this mechanism. These conclusions have been corroborated by Monte Carlo simulations that included both pitch-angle collisions and a DCLC radio-frequency (rf) electric field. In an early paper, Momota and Takizuka recognized the possible importance of pitch-angle collisions in randomizing the gyrophase.¹⁰

Further analytical and numerical calculations have indicated that decorrelating the wave-particle phase to model the bursting or bandwidth of DCLC waves observed in the experiment is a much more potent mechanism in producing energetic ions.

Implicit Large-Time-Step

Particle Simulation

(A. B. Langdon, A. Friedman, and B. I. Cohen)

We have made several advances in the quest for more efficient simulation of low-frequency plasma phenomena.

Our most adaptable and reliable tools for studying kinetic plasma behavior are the "particle" codes; however, the stability of these codes has previously required resolution of the electron plasma period in the time integration, even when the phenomenon under study took place on the much-longer time scale. Analogous limitations on the time step in problems, such as heat-flow and chemical-rate equations, are overcome through the use of *implicit* time integration schemes. In particle codes, although implicit methods have been analyzed theoretically,¹¹ their application has been inhibited by the very large number of nonlinear equations to be solved simultaneously, a quantity about equal to the number of particle coordinates plus the number of zone quantities (electric and magnetic fields).

We have begun to experiment with two methods for solving these equations in two steps. In both methods, equations are first set up for the fields. Although these equations involve information from the particles, the number of equations to solve simultaneously is only the number of field quantities, defined on the zones. Since the number of zones is much less than the number of particles, and the resulting matrix equations are sparse and well-conditioned, their solution is convenient with known methods. Once the fields are known, the particle coordinates can be readily solved for serially, one particle at a time. Here, we will discuss simulations including only the electrostatic field.

First we consider finite-differenced equations of motion for the particles that have the necessary stability at large time step ($w_p \Delta t \gg 11$ where w_p is the plasma frequency) and are accurate for the low-frequency phenomena to be studied. In Ref. 12, a centered expression for the time derivative is employed. In Ref. 13, the derivatives are biased using a

scheme such as

$$v_{n+1} - v_n = \frac{3}{4}a_{n+1} + \frac{1}{4}a_{n-1} \Delta t, \quad (26a)$$

$$x_{n+1} - x_n = \frac{3}{4}v_{n+1} + \frac{1}{4}v_{n-1} \Delta t. \quad (26b)$$

This scheme damps unwanted high-frequency oscillations, whereas low frequencies are very weakly damped, as desired: $(\text{Im } \omega)/\omega = \mathcal{O}(\omega \Delta t)$.¹² Such schemes are members of a class whose application to plasma simulation has been analyzed in detail in Ref. 11 and in our present work. We have devised a different class of schemes, whose simplest member is

$$2(v_{n+1/2} - v_{n-1/2}) - (v_{n-1/2} - v_{n-3/2}) = a_{n+1} \Delta t, \quad (27a)$$

$$x_{n+1} - x_n = v_{n+1/2} \Delta t. \quad (27b)$$

This scheme has the same order of accuracy as Eq. (26), while requiring less storage of time levels. The presence of the acceleration at only the $n+1$ time level increases the damping of high-frequency oscillations. The optimum design of these difference equations is the first issue in practical implementation of large time-step methods.

In all implicit schemes, the new positions x_{n+1} depend on the accelerations a_{n+1} due to the electric field E_{n+1} . But this field is not yet known, because it depends on the density ρ_{n+1} of particle positions $\{x_{n+1}\}$. The solution of these coupled particle and field equations is the other major implementation issue.

In the first method that has been tried, the fields at the new time level are predicted by solving coupled field and fluid equations in which the pressure tensor is approximately evaluated from particle velocities known at the earlier time. After the fields are known, the particles are advanced to the new time level; if desired, an improved pressure tensor is then calculated and the process iterated. This approach has been described in detail in Refs. 12 and 13.

It is also practicable to predict the future electric field E_{n+1} quite directly by means of a lineariza-

tion of the particle-field equations. The position x_{n+1} of a particle at time level t_{n+1} , as given by an implicit time integration scheme, can be written as

$$x_{n+1} = \beta \Delta t^2 a_{n+1} + x_{n+1}^{(0)}, \quad (28)$$

where $0 < \beta \lesssim 1$ and $x_{n+1}^{(0)}$ is the position obtained from the equation of motion with the acceleration a_{n+1} neglected. Since $x_{n+1}^{(0)}$ depends only on positions and accelerations at times t_n and earlier, it is known. In its simplest form, the BAAL algorithm is derived by linearization of the particle positions relative to $x_{n+1}^{(0)}$.

One can regard the actual position x_{n+1} as $x_{n+1}^{(0)}$ plus a displacement $\delta x = \beta \Delta t^2 a_{n+1}$. We form the charge density $\rho_{n+1}^{(0)}$ from $\{x_{n+1}^{(0)}\}$; the actual charge distribution is then $\rho_{n+1}^{(0)}$, plus the change $\delta \rho$ brought about by the displacing particles by the amount $\delta x = x_{n+1} - x_{n+1}^{(0)}$. Linearized, this increment to ρ is¹¹

$$\delta \rho = - \nabla \cdot [\rho_{n+1}^{(0)}(x) \delta x(x)]. \quad (29)$$

To the same order of approximation, the displacement $\delta x(x)$ of all particles with $x_{n+1}^{(0)} \approx x$ is obtained with a_{n+1} evaluated at x ; i.e.,

$$\delta x(x) \approx \beta \Delta t^2 (q/m) E_{n+1}(x). \quad (30)$$

We then have

$$\delta \rho(x) = - \nabla \cdot [\chi(x) \underline{E}_{n+1}(x)], \quad (31)$$

where the effective susceptibility is

$$\chi(x) = \beta [\rho_{n+1}^{(0)}(x) q/m] \Delta t^2 = \beta \omega_p^2(x) \Delta t^2. \quad (32)$$

Note that χ depends only on the particle positions $\{x_{n+1}^{(0)}\}$ and not at all on velocity information as required in the moment-equations methods.

With these two source contributions, the Poisson equation becomes, in rationalized cgs units:

$$\nabla \cdot \underline{E}_{n+1} = \rho_{n+1}^{(0)} - \nabla \cdot (\chi \underline{E}_{n+1}), \quad (33)$$

or

$$-\nabla \cdot [1 + \chi] \underline{E}_{n+1} = \rho_{n+1}^{(0)}. \quad (34)$$

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This elliptic equation is solved by standard methods. The field $-\nabla\phi_{n+1}$ and Eq. (30) are then used to calculate the positions $\{x_{n+1}\}$. This algorithm is reminiscent of the method for solution for the vector potential $\tilde{A}$ in some magneto-inductive plasma simulations codes.¹⁴⁻¹⁶

Should it be necessary, we have shown how to refine the approximations used above by linearization about a more accurate prediction of x_{n+1} than $x_{n+1}^{(0)}$, iteration, and by a more accurate evaluation of δx .

In our spatial-difference representation of these equations, Eq. (29) becomes the gradient of a zonal ρ with respect to particle position, and δx in Eq. (30) depends on the electric field in two zones, using the usual interpolation. In this way, we are assured that the density ρ_{n+1} of final particle positions $\{x_{n+1}\}$ satisfies the code's representation of the Poisson equation, $-\nabla^2\phi_{n+1} = \rho_{n+1}$, so that desirable features built into the time-differencing scheme will be realized in practice.

We are delineating the limitations of these methods and learning how to surmount them. For example, it is observed that an unphysical cooling of

the electrons occurs when uncentered equations of motion are used. Our analysis provides guidance for designing algorithms that retain the desirable dissipation of high-frequency oscillations while minimizing this unwanted cooling. This side effect is related to the damping of low-frequency oscillations; both are smaller in the schemes described here with third-order damping than in lower-order algorithms.¹²

Both the moment-equation formulation of Ref. 13 and the BAAL approach have been verified in application to ion-acoustic oscillations, two-stream instability, and corona expansion into vacuum. (In these applications, results have already been obtained by methods with known reliability but less efficiency.) The moment-equation method is being applied to electron transport;¹² and an orbit-averaged¹⁷ version has been proven stable analytically and in computer experiments.¹⁸ An electromagnetic, orbit-averaged, moment-implicit code has been formulated for applications to equilibrium transport and to the low-frequency stability of magnetic fusion devices.

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

Two confinement systems are now in operation at LLNL: the Beta II (formerly 2XIIB), and the Tandem Mirror Experiment (TMX).

- Beta II is a simple-cell mirror machine. In 1979, work was begun on development of a magnetized, coaxial plasma gun to be used for the startup phase of a field-reversed mirror. The closed field lines of the field-reversed mirror should result in improved plasma confinement compared to that in the standard mirror with open lines.

- In 1976, we proposed a new idea: the tandem-mirror concept. A tandem mirror reactor would contain a long solenoidal magnet terminated at both ends by conventional mirror cells. These cells would act as "end plugs" to prevent plasma leakage out the ends of the solenoid. TMX has been constructed to test the principles of this concept. At the end of September 1980, TMX was shut down to permit the construction of an improved tandem mirror, TMX Upgrade. The construction is scheduled for completion by November 1981.

MAGNETIC MIRROR SYSTEM EXPERIMENTS

BETA II

Beta II is the name given to the reconfigured 2XIIB facility after power supplies and other equipment were transferred to the Tandem Mirror Experiment (TMX). Beta II began operation in the Summer of 1979. In the first experiments, a magnetized, coaxial plasma gun is being used to generate a field-reversed target plasma for neutral-beam heating and confinement studies.

Summary

(*W. C. Turner, G. C. Goldenbaum,*
E. H. A. Granneman,[†] C. W. Hartman,
D. S. Prono, J. Taska, and A. C. Smith, Jr.***)

At the end of the last quarter, research on the use of the Beta II plasma gun culminated in the formation of a compact, toroidal plasma in a flux-conserving copper shell.¹⁹ Since then, we have performed additional experiments in which we examined the effect that modifications in the shape of the flux conserver had on the tilting instability. These experiments, coupled with results from three-dimensional calculations of magnetohydrodynamic (MHD) instability, have confirmed that the present oblate shape of the flux conserver is nearly optimal for avoiding the tilting instability. Therefore, although we expect some continued progress in the formation of compact toroidal plasmas, we have now shifted the emphasis of our research toward understanding the factors that control the lifetime of the decaying magnetic fields in the plasma and towards increasing that lifetime.

At present, the magnetic field decays in about 100 μ s to 1/e of the peak value, or in about 200 μ s from the peak value to zero (see Fig. 9 in Ref. 19). In order to contemplate heating the torus with neutral beams (5 to 10 MW incident), we want to increase this lifetime to about 1 ms. To this end, we

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have added diagnostics and modified hardware. Early data from four of the new diagnostics—the Langmuir probe, the vacuum ultraviolet (VUV) spectrometer, the vacuum photodiode, and the bolometer—are described in subsequent articles. The hardware modifications consist of

- Installation of a pinching coil at the muzzle of the plasma gun to force reconnection of the poloidal flux surfaces (peak field about 8 kG; time to peak current about 1.5 μ s);
- Installation of a glow-discharge cleaning apparatus to clean the gun electrodes and flux conserver;
- Activation of liquid-nitrogen cooled cryopanel and Ti getters to improve the base vacuum pressure; and
- Installation of a new, higher-voltage capacitor bank (60 kV, 115 μ F) for the gun discharge (the old bank was 40 kV, 232 μ F).

With these modifications, we hope to reduce the plasma density from $2 \times 10^{15} \text{ cm}^{-3}$ to about $2 \times 10^{14} \text{ cm}^{-3}$, thereby reducing losses due to radiation and classical thermal conduction. The pinching coil and forced reconnection should reduce electron thermal conduction losses during formation. Improving the vacuum conditions should reduce power loss due to impurity radiation. With the additional diagnostics, we hope to be able to distinguish whether the dominant plasma energy loss process is due to plasma transport or radiation.

Langmuir Probe Measurements of Electron Energy Distribution in Beta II

(D. S. Prono)

When we combine Langmuir probe measurements with data from pressure probes and He-Ne interferometer, we find that the electron energy distribution in the Beta II field-reversed plasma is bi-Maxwellian.

In our ongoing experimental work, we are attempting to diagnose the properties of the compact-torus, field-reversed plasma produced by the Beta II plasma gun. To help investigate the electron energy distribution, we use Langmuir probes (the double floating-probe type). Figure 6 shows typical

FIG. 6. Characteristics of the double Langmuir probe response obtained during investigation of the Beta II plasma. The dashed line is the predicted response for a 10-eV, 10^{15} cm^{-3} , simple-Maxwellian distribution. The solid lines show actual I-V characteristics at various times during the decay of a field-reversed plasma.

current-voltage (I-V) characteristics of the probe's response. Because these double probes sample only the high-energy tail of the electron distribution,²⁰ they are sensitive only to features of that part of the energy distribution. Therefore, to obtain the entire distribution, we combine data from diagnostics sensitive to the rest, or bulk, or the electron distribution (pressure probe and He-Ne interferometer) with data from the Langmuir probe. The results indicate a bi-Maxwellian distribution. The density of the electron population is $2 \times 10^{15} \text{ cm}^{-3}$. Of this population, about 98% has electron temperature $T_e \approx 10 \text{ eV}$; the remaining 2% of the population comprises a thermal tail with $T_e \lesssim 250 \text{ eV}$.*

The reduced data in Fig. 7 show how various characteristics of the tail vary with time. Over a given interval, the bulk density and electron temperature remain approximately constant, but the

*An identical interpretation has been given to results from the similar CTX experiment at Los Alamos.²¹

FIG. 7. Variation with time of the temperature and density of the thermal-tail electrons in the bi-Maxwellian distribution of a field-reversed plasma in Beta II. These data were obtained from the characteristics of a double Langmuir probe response.

magnetic fields characteristically decay with an e-fold time $\lesssim 100 \mu\text{s}$.

The partitioning of current between the bulk and the tail of the electron-energy distribution may have an important influence on plasma heating and magnetic-field lifetime. Therefore, we are now concentrating on determining this partitioning. To date, we have found that the particles comprising the thermal tail are highly directional and are aligned with the parallel current and magnetic-field vectors (because the compact-torus plasma is nearly force-free, $\mathbf{J} \times \mathbf{B} = 0$). Our observations result from measurements taken when a small, insulating paddle was positioned so as to shield the probe tip in various ways. Only when the paddle was positioned so that it intercepted the current-field vectors was there an influence on the response characteristics of the probe. Then, the I-V response was consistent with a 10^{15} cm^{-3} , 10-eV, single-Maxwellian distribution (i.e., the probe saw only the cold, bulk plasma).

We have not yet measured the current density carried by the directional, high-energy electrons in the tail of the energy distribution. However, if the drift velocity resembles the measured thermal velocity, these directed, thermal-tail electrons could carry substantially all the current embedded in the plasma.

Measurements of Vacuum Ultraviolet Spectral Lines and Radiation Emission in the Beta II Flux Conservator.

(G. C. Goldenbaum)

Measurements made using a VUV spectrometer showed no metallic-ion lines emitted by the plasma in the Beta II flux conservator. The dominant impurities are carbon and oxygen.

We have recently installed diagnostic equipment to analyze the VUV spectrum emitted by the plasma in the Beta II flux conservator, a VUV spectrometer to obtain time-integrated photographs of the VUV spectrum, and a vacuum photodiode to obtain time-resolved and wavelength-integrated measurements of the radiation emission.

The photographs of the VUV spectrum were made during typical operating conditions (gun-bank voltage = $\pm 20 \text{ kV}$, inner-solenoid voltage = 2 kV) along a diagonal chord through the center of the flux conservator. We used a 0.5-m, f/50, grazing-incidence, VUV spectrometer. About 20 shots were required to produce a useful spectrum: Fig. 8 shows a densitometer trace of this spectrum. The shortest-wavelength lines observed were the CIV resonance lines at $312.4 \text{ \AA}$. This line guarantees the presence of 40-eV electrons. No CV radiation was seen however, indicating that there was not a significant number of long-lived electrons with energy sufficient to excite the CV resonance line at 308 eV. An oxygen VI line originating from a level 83 eV above the ground state was also observed. No higher ionization stages were seen. All identifiable lines were attributed to deuterium, carbon, oxygen, nitrogen, or silicon: no metallic-ion lines were identified. The brightest lines were the CIV doublet at 1548.2 and $1550.8 \text{ \AA}$.

We constructed and used a vacuum photodiode to measure the radiation emission in the VUV spectrum. The instrument viewed the plasma along a major diameter through the midplane of the flux conservator. The diagram in Fig. 9 shows the detector and its orientation with respect to the flux conservator. Typically, a large spike in radiation emission

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FIG. 8. Densitometer trace of the vacuum ultraviolet spectrum: (a) intensity from 100 Å to 1400 Å; and (b) intensity from 1500 Å to 3200 Å.

FIG. 9. Schematic representation of the vacuum photodiode used to measure the radiation emitted in the vacuum ultraviolet spectrum from the Beta II flux conserver.

appeared soon ($t \leq 10 \mu\text{s}$) after the plasma gun had been fired, followed first by a rapid decrease for about $5 \mu\text{s}$ and then by a slower decrease with a decay time of about $50 \mu\text{s}$. Assuming an average photon energy of 12 eV and an average photoemission yield of 10% (a tungsten cathode was used), we calculate that the peak power density was 957 W/cm^3 and that the density of the radiated energy was 20 mJ/cm^3 . Furthermore, if we assume that the entire volume inside the flux conserver radiated uniformly, the peak power and the total energy radiated were 169 MW and 3.6 kJ, respectively.

Bolometer Measurements of Energy Loss from the Beta II Plasma

(C. W. Hartman)

Bolometer measurements show that the energy radiated from the Beta II plasma is a substantial fraction of the total magnetic-field energy and accounts for some, but possibly not all, of the energy lost during the decay of the plasma.

To obtain information about radiation loss from the Beta II compact-torus plasma, we installed a bolometer on the flux conserver. By observing the temperature rise of a thin Cu foil in the bolometer, we can measure the energy incident on the foil during the formation and decay of the plasma. Simultaneously, by observing the photoelectric

current between two bolometer electrodes, we can measure the instantaneous flux of photons radiated to the bolometer. The measurements are conducted behind a collimating array of long, thin tubes transverse to which a 0.6-kG magnetic field is applied. This arrangement inhibits direct charged-particle bombardment of the foil and restricts the field of view to a cone centered on a diameter at the midplane of the flux conserver and having a "spot" size of about 20 cm diameter at the opposite wall of the flux conserver. To interpret the bolometer measurements, we assume that only photons strike the Cu foil and that the instantaneous power received is proportional to the photoelectric current.

The life history of a compact-torus plasma in Beta II has two phases: initial formation with rapidly varying conditions during the first $50 \mu\text{s}$ after the plasma gun has been fired, and a relatively quiescent decay. The initial phase is characterized by a large photodiode current; the second by a slow decay over 100 to $200 \mu\text{s}$.

During the decay phase, magnetic probes indicate that the plasma has assumed an approximately force-free equilibrium for which the magnetic-field energy ψ_{poloidal} is readily found:

$$\psi_{\text{poloidal}} \sim r_1^2 \left(p_1 \frac{r_1}{R} \right) \cos \pi \frac{z}{Z}, r_\theta^B \sim \psi_{\text{poloidal}}, \quad (35)$$

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where r is the radial distance from the symmetry axis, J_1 is the first-order Bessel function, p_1 is the first zero of $J_1 = 3.83$, R is the radius of the flux conserver, z is the axial distance from the midplane of the flux conserver, Z is the length of the flux conserver, and B_θ is the toroidal field component. The energy radiated during the decay is obtained by subtracting the initial, transient photon flux from the bolometer signal and then comparing the result with the magnetic energy at the beginning of the decay.

Relating the total energy radiated Q_{rad} to the detected energy Q_{det} gives

$$Q_{\text{rad}} = \frac{A_d}{A_t} \frac{DZ\ell^2}{Na^4} g Q_{\text{det}} \quad (36)$$

where D is the diameter of the flux conserver, N and ℓ are the number and length of the collimating tubes, respectively, and A_t and A_d are the total integrated area of the photodiode signal and its area during decay, respectively. The geometrical factor g is determined by the spatial distribution of the radiated power P_r in the flux conserver. For uniform P_r , $g = 1$; $P_r \approx \cos \pi z/Z$, $g \approx 1/2$.

Table 1 lists the bolometer measurements for several selected shots for uniform P_r . We estimated the magnetic-field energy using the force-free model

[Eq. (35)] and measured B_z on axis at the midplane of the flux conserver. As can be seen from Table 1, the radiated energy is a substantial fraction of the total magnetic field energy and accounts for some, but possibly not all, of the energy lost during the decay of the plasma.

TANDEM MIRROR EXPERIMENT (TMX)

The Tandem Mirror Experiment (TMX)^{22,23} is testing a new principle for improved confinement in mirror systems. The basic idea is to reduce the plasma loss rate by electrostatically plugging the ends of a solenoidal central-confinement region using the high positive ambipolar potential generated in minimum- B end plugs. Each end plug is driven by the injection of neutral beams from 12 source modules, in a manner similar to that which was used in the 2X11B experiment. Results from this experiment have been reported in previous *Quarterly Reports*.

At the end of September 1980, TMX was shut down to permit construction of an improved tandem mirror, TMX Upgrade.²⁴ The new experiment (see schematic on the cover of this *Quarterly*) will

TABLE 1. Bolometer measurements of Beta II energy loss, $g = 1$.

Date; shot No.	Time of beginning of the decay, t_s (μ s)	Magnetic energy at t_s , U_m (kJ)	Energy lost during the decay, Q_{rad} (kJ)	Q_{rad}/U_m (%)	Comments
11/4/80					
No. 8	50	6.0	1.8	30	All probes in
No. 9	50	4.5	1.0	22	All probes in
11/6/80					
No. 4	50	6	2.4	40	
No. 5	50	10.7	3.3	31	
No. 6	50	6	4.3	72	
10/23/80					
No. 10	50	6	3.3	55	Only on-axis probe in
11/18/80					
No. 14	75	4.2	1.0	24	

test the concept of thermal barriers and includes improvements resulting from the understandings obtained from TMX. Analysis of the TMX data is ongoing during the shutdown period and will continue to be reported in these *Quarterly Reports*.

Measurements of the Radial Potential Profile in TMX

(D. P. Grubb, D. L. Correll, J. H. Foote, R. K. Goodman, and G. A. Hallock)

We have measured the radial profile of the confining electrostatic potential in TMX. In the core of the plasma, the experimental measurements agree with theoretical predictions.

A movable, electrostatic end-loss analyzer (ELA) has been used to map the radial profiles of the end-loss ion current density J , the mean energy, of the end-loss ions W_{el} , and the plasma potential ϕ_p of the west end plug on TMX.²⁵ For these measurements, the ELA was stepped across the plasma fan near the west end wall. By moving the ELA between data shots, we were able to study a dozen different radial positions during a sequence of 50 constant-condition data shots. During this same sequence of shots, the heavy ion beam probe (HIBP)²⁶ scanned across the radial profile of the central-cell plasma so that the plasma potential (ϕ_e) was studied at four distinct radial positions. By subtracting the measured, ϕ_p from the measured ϕ_e , we obtained the confining electrostatic potential ϕ_c . The results of this analysis are shown in Fig. 10(a,b).

Also shown in Fig. 10(b) are theoretically predicted curves for ϕ_c . For a simple tandem mirror such as TMX, theory predicts that

$$\phi_c = T_e \ln(n_p/n_c) \quad , \quad (37)$$

where T_e is the electron temperature, and n_p and n_c are the densities of the plug and central-cell plasmas, respectively. The radial profile of the electron temperature in the east plug of TMX was measured by Thomson scattering techniques. We then estimated the temperature of the west plug electrons according to $\phi_p/T_{ep} = \text{constant}$ (Table 2). The radial-density profiles of the plasmas in the west plug and central cell were determined from the

FIG. 10. Radial potential profiles in TMX: (a) measured values of the potential in the plug ϕ_p and in the central cell ϕ_e , and (b) measured values of confining potential ϕ_c , where $\phi_c = \phi_e - \phi_p$, compared with the calculated values of ϕ_c , where ϕ_c is obtained from Eq. (37) (solid line) and Eq. (38) (dashed line).

attenuation of the neutral beams injected into those regions.

This analysis neglects the fact that the electron temperature measured in the east plug of TMX was almost twice as large as the electron temperature measured in the central cell (87 eV versus 49 eV). One possible explanation for this phenomenon is that a thermal barrier exists between the east plug and the central cell.²⁷ In the presence of a thermal barrier, the confining potential is given by

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TABLE 2. Plasma parameters used in calculation of ϕ_c in TMX (where r = central-cell radius).

Eq. No.	Parameter	Value	Notes
(37)	$T_e = T_{ep}$	$77[1 - (r/38.6)^2]$	a
	n_p	$1.7 \times 10^{13} [1 - (r/38.6)]^{1/2}$	
	n_c	$3.5 \times 10^{12} [0.77 + 0.91 (r/38.6)^2] [1 - (r/38.6)^2]^{1/2}$	
(38)	T_{ep}	Same as for Eq. (37)	
	n_p		
	n_c		
	T_{ec}	$49[1 - (r/38.6)^2]$	b
	n_b^*	$1.75 \times 10^{12} [0.77 + 0.91 (r/38.6)^2] [1 - (r/38.6)]^{1/2}$	c

^aCalculated according to ϕ_p/T_{ep} = constant and assuming same radial profile as that measured in east plug.

^bProfile assumed to be the same as measured in east plug.

^cProfile assumed to be the same as that of the central-cell density.

$$\phi_c = T_{ep} \ln [n_p/n_b^* (T_{ec}/T_{ep})^{1/2}] - T_{ec} \ln (n_c/n_b^*) \quad (38)$$

In this expression, T_{ep} is the temperature of the plug electron, T_{ec} is the temperature of the central-cell electrons, and n_b^* is the density of the passing electrons in the thermal barrier.²⁸

Our measurements of the axial density profile did not reveal the presence of a density depression that would explain the observed differences in the electron temperature. However, a value of $n_b^*/n_c = 0.5$ (Table 2) is sufficient to bring the measured plasma parameters described by Eq. (38) into agreement with the measured values of $\phi_c(r)$ shown in Fig. 10(a). A density depression of this order could be difficult to detect experimentally or it may have been located in a region where we did not make a measurement.

The experimental measurements do not indicate whether Eq. (37) or (38) more correctly describes the electrostatic potential well in TMX. Either equation describes the measured potential for $r \leq 15$ cm. Beyond 15 cm, the measured confining potential is less than that predicted, and for $r > 20$ cm. The potential difference, $\phi_p - \phi_e$, is less than zero (negative). The negative values of ϕ_c for $r > 20$ cm appear to be in conflict with the measured

values of $(n\tau)_c (= n_c^2 CL/j)$ at these radii, which shows that the confinement is better than simple mirror confinement. We are presently trying to resolve this inconsistency and to examine the data to see if there is a relationship between the low value of the confining potential at large radii and the non-ambipolar radial flux of ions that was measured at these radii.²⁹

The TOARBUC Orbit-Averaged Code

(A. H. Futch and M. A. Campbell)

We have developed a finite-orbit, Fokker-Planck model to study plasma confinement in tandem mirrors. Important finite-orbit effects require an orbit-averaged code in order to accurately describe the radial and axial losses.

Code Description. We have modified the radial Fokker-Planck code to treat buildup in the tandem-mirror plug and central cell with a self-consistent model. The new code, TOARBUC (Tandem Orbit-Averaged Radial-Buildup Code), is based on the finite-orbit (radial) Fokker-Planck model developed to study conventional mirrors. We modified the code to allow the plasma parameters in the plug and central cell of a tandem mirror to be calculated during alternate iterations. First, the parameters for the plug ions are generated at each time step, then those of the central-cell ions; last, the code determines the

self-consistent potentials and the transfer of electron particles and energy between the two regions.

The central cell is treated as having separate electron and ion confining potentials, with the ion potential having the sign opposite to that in a conventional mirror. In addition, a two-electron-temperature treatment derived by Cohen³⁰ was included in the present model to allow electron temperatures in the plug and central cell to be different, as observed experimentally.

In several important aspects, the TOARBUC code differs from a particle-buildup code such as TAMBAR that is used to determine the density of the plasma ions. Table 3 lists several differences between TOARBUC and TAMBAR.³¹ (Many other differences exist; we do not attempt completeness here.) In an orbit-averaged code such as TOARBUC, the particle deposition and energy-exchange loss rates are calculated by averaging around an orbit. In a particle (or fluid) code, the particle orbit is unknown, and approximate diffusion coefficients are used to model spatial transport. The importance of orbit effects depends upon the spatial gradients of parameters such as the plasma density, thermal gas density, etc. when compared with the radius of the orbit.

Comparison of TOARBUC Calculations with Experimental Data. Figure 11 and Table 4 show analyzed data from a TMX run for September 24,

1980, compared with results from TOARBUC code calculations. Both measurements and calculations are for the plasma core ($r = 0$), except for the temperature of the central-cell ions E_{ic} , which is obtained from diamagnetic loop measurements and represents an average of E_{ic} over the plasma volume. The TOARBUC input parameters for Fig. 11 are given in Table 5. Full- and half-energy neutral beams were injected into the plug. The TOARBUC code results are shown for two cases. For Case I, only classical processes are included in the central-cell calculations. Comparison of Case I with the measurements shows the calculated density on the central cell to be high by a factor of 2 to 3 and the central-cell ion energy to be too low by a similar factor.

A large radial diffusion coefficient (such as observed experimentally) will lower the central-cell density, but will not affect the ion energy in the central cell. Rognlien and Matsuda³³ have shown that velocity-space diffusion results in both degradation of the ion-confinement time and particle heating. Velocity-space diffusion is included in Case II of the TOARBUC calculations [Fig. 11(b)] by increasing the quasi-linear fluctuations until approximately 100 kW of rf power is added to the central-cell ions by the fluctuating field. Radial transport was included by a separate term

TABLE 3. Basic differences between the orbit-averaged code TOARBUC and the particle-buildup code TAMBAR.

TOARBUC	TAMBAR
Rate equations used for calculating atomic physics includes secondary neutrals (Stallard model). ³²	Three-dimensional Monte Carlo calculation of neutral reactions.
Orbit averaged.	Finite-orbit effects generally neglected except for beam deposition.
Distribution function: plug—calculated; central cell—calculated.	Distribution function: plug—assumed; central cell—assumed.
Ion end loss: all Coulomb processes: quasi-linear stream requirements (ϕ_{rf} parameter that may be set = 0 for classical processes only).	Ion end loss: Spitzer drag with decreased plug lifetime to satisfy quasi-linear requirements.
Ion energy—calculated.	Ion energy—assumed = E_{inj} .

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FIG. 11. Comparisons of line-density measurements in the TMX end plugs and central cell with results from TOARBUC calculations for (a) TOARBUC Case I with no rf power, and (b) TOARBUC Case II with 100 kW of rf power. The radial transport coefficient has the value 0 for Case I and $1 \times 10^6 \text{ cm}^3/\text{s}$ for Case II. Additional results are summarized in Table 4.

$$\frac{1}{r} \frac{\partial}{\partial r} \left(k \frac{\partial D}{\partial r} \right), \quad (39)$$

where D is the guiding-center distribution function and k is taken to have the constant value of $1 \times 10^6 \text{ cm}^3/\text{s}$.

Case II agrees well with most measured parameters. From the TMX data, the ratio of the electron temperature in the plug to that in the central cell $T_{ep}/T_{ec} = 1.77$, whereas the calculated value is 1.35. Experiment has consistently given a

larger T_e ratio than theory. Previous code results gave somewhat higher T_e than those observed in either the plug or the central cell. We have identified and included in TOARBUC two additional processes that bring agreement between measured and calculated T_{ep} . One result from the discovery that energetic neutral beams include about 2% oxygen as an impurity. As it becomes ionized, this oxygen impurity is a source of cold electrons. Although the power loss by impurity radiation is small, each cold electron results in the loss of a hot

TABLE 4. Comparison of TMX experimental results with results from TOARBUC calculations.

Parameter ($r = 0$)	Low-rf shots on 9/28/79	Many shots on 9/24/80	TOARBUC
Plug electron temperature, T_{ep} (eV)	160	80	98
Sum of central-cell electron and ion temperatures, $T_{ec} + T_{ic}$ (eV)	93	80	110
Central-cell electron temperature, T_{ec} (eV)	—	41	84
End-loss current, j ($A \cdot cm^{-2}$)	0.25	0.21	0.11
Plug potential, ϕ_p (V)	510	510	485
Central-cell potential, ϕ_e (V)	—	400	348
Central-cell plasma density, n_c ($10^{12} cm^{-3}$)	5.5	2.5	2.7
Plug plasma density, n_p ($10^{12} cm^{-3}$)	16	18	16

electron that carries out energy $\phi_e + T_e$ as it leaves the plasma.³⁴ The cooling effect of oxygen on the electron plasma is now included in the TOARBUC code.

Higher gas pressures will also lower T_e . Recent experimental evidence indicates that higher gas pressure is responsible for lower T_e in TMX; however, the plasma density calculated by TOARBUC did not build up to the observed density with higher gas pressures. This dilemma has been explained by the penetration of neutral gas into the fan regions between the plugs and the central cell. This gas lowers the electron temperature

with minimum effect on the hot ions that are magnetically confined closer to the midplane of the plug. We added the penetration of neutral gas into the fan to TOARBUC by averaging the product n^+n_0 along a field line from the midplane to the magnetic mirror. This results in a higher rate of neutral-gas ionization along field lines through the plasma core and a lower T_e because of the cold electrons being introduced.

Comparison of TAMBAR Calculations with Experimental TMX Data

(R. A. Jong and R. P. Drake)

We used the particle-buildup code to model the plasma buildup in TMX and compared the results to TMX data. We found that, with the three exceptions noted, the code accurately predicted the centerline parameters. However, differences between the calculated and measured line-density profiles suggest that the transport model used in the code should be improved.

TAMBAR is a one-dimensional fluid code that solves for the particle density and temperature as well as for the self-consistent plasma potential in the central cell and end plugs of a tandem mirror (Ref. 35). The code calculates the time dependence and radial profiles of these parameters given the neutral-beam currents and energies, the molecular gas input to this system, and the basic dimensions of the tandem mirror. The plug stability is maintained by monitoring the end loss from the end plug. If the calculated current streaming through the plug is insufficient to maintain stability (Ref. 36), the

TABLE 5. Input parameters for the TOARBUC analysis shown in Fig. 12 and Table 4.

Parameter	TMX 9/24/80	TOARBUC	
		Case 1 rf power = 0	Case 2 rf power = 100 kW
T_{ep} (eV)	87	77	89
T_{ec} (eV)	49	71	66
E_{ip} (keV)	13.1	11.0	11.0
E_{ic} (eV)	75	31	90
j ($A \cdot cm^{-2}$)	0.31	0.37	0.19
ϕ_p (V)	540	460	435
ϕ_e (V)	325	400	332
n_e ($10^{12} cm^{-3}$)	2.7	6.2	3.6
n_p ($10^{13} cm^{-3}$)	1.3	1.5	1.46

^aNomenclature is defined in Table 4.

^bPlug measurements are for the east plug.

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lifetimes of the plug ions are decreased until the end-loss current meets the requirements for stability. Radial transport is assumed to be ambipolar; the diffusion coefficients are calculated as a multiple of the classical values given by Braginskii (Ref. 37). For the calculation reported here, the coefficients were 10 times classical.

We compared centerline parameters and line-density profiles calculated by TAMBAR with data from a TMX experimental run. The results of the comparison are summarized in Table 6 and Fig. 12. The centerline values of the calculated parameters match the measured values except for end-loss current j , the electron temperature in the central cell T_{ec} , and the ion density in the plug n_p . The calculated value of T_{ec} is 70% higher than measured; the calculated n_p is smaller by a factor of 3 to 4. Furthermore, because the calculated value of $(T_{ec} + T_{ic})$ is close to the measured value, the calculated value of T_{ic} must thus be much lower than would be inferred from the measurements.

These discrepancies between the measured and calculated parameters result from the plug-stabilization criterion used in TAMBAR. The method does not account for the heating of the central-cell ions by the rf fluctuations from the plug. Consequently, the calculated T_{ic} should be lower than measured. In addition, because the lifetime of the plug is decreased in order to increase the streaming current from it, the calculated n_p should be

lower than measured. The lower calculated centerline end-loss current is consistent with the calculated low T_{ic} (~ 16 eV).

These DCLC-stabilized results have also been compared to the earlier calculations made with stable plugs. In those runs, the parameter agreement with measured values was not as good. The calculated plug and central-cell densities were more than an order of magnitude higher than those measured, and the electron and ion temperatures were also much higher than measured. Hence, while the current DCLC stabilization model used in TAMBAR does improve the agreement with the measurements, the model should be improved to include the heating of central-cell ions and to provide an increased end-loss contribution from the central cell without as great a change in the lifetime of the plug ions.

The calculated and measured line-density profiles are compared in Fig. 12. The values of the end-plug profiles agree quite well, but the calculated values for the central cell are about twice the measured values. In addition, the calculated line-density profile is slightly hollow, a feature that is not evident in the measured profiles. This suggests that the calculated density profiles are much more hollow than those measured in the experiment, and indicates that the radial-transport model in the code needs improvement. In addition, since significant charge-exchange neutral currents are detected in the

TABLE 6. TAMBAR comparison of TAMBAR calculations of centerline parameters with TMX experimental results.

Parameter	TMX all shots 9/24/80	TAMBAR
Plug electron temperature, T_{ep} (eV)	87	78
$T_{ec} + T_{ic}$ (eV)	100	86
Central-cell electron temperature, T_{ec} (eV)	49	70
End-loss current density, j ($A \cdot cm^{-2}$)	0.18	0.18
Plug plasma potential, ϕ_p (V)	540	488
Central-cell plasma potential, ϕ_e (V)	325	441
Central-cell density, n_c ($10^{12} cm^{-3}$)	2.7	2.3
Plug density, n_p ($10^{12} cm^{-3}$)	13	4.8

FIG. 12. Results of comparison between calculated (TAMBAR) and measured line density profiles in TMX. The lack of correlation suggests needed improvement in the radial-transport model in the code.

elliptical fan region of the plasma between the central cell and the plug, it is possible that a sizable amount of cold gas is deposited in this elliptical fan region even though limiters are present between the central cell and plug. Gas incident in this region would have a higher probability of deposition in the plasma core than would gas incident directly in the cylindrical central cell. Therefore, the inclusion in the code of a slab model of cold-gas deposition corrected for elliptical effects will very likely produce better agreement between the on-axis densities obtained in the experiment and those densities obtained from the simulations. These improvements are now being implemented.

Nonambipolar Radial Transport in TMX

(R. P. Drake, C. V. Karmendy,
E. B. Hooper, and the TMX Group)

We have used our end-wall diagnostics to investigate radial transport in the TMX central cell. For the experiment described here, we found that the

observed nonambipolar radial transport is in rough agreement with the predicted transport due to resonant-neoclassical diffusion. However, the uncertainties are large.

Four elements contribute to our knowledge of radial transport (Fig. 13):

- First, Faraday cups and gridded end-loss analyzers (ELA's) at the ends of TMX repel the electrons approaching them and measure the flux of ions striking the end wall. Thus, we measure the spatial profile of the ion end losses.

- Second, we detect the net electrical current flowing to the end wall. This electrical current is negative, showing that the electron flux reaching the end wall is larger than the ion flux. We believe that central-cell ions flow to the limiter in the central cell to maintain charge neutrality, but we did not measure the fluxes reaching the limiter.

- The two important particle sources in TMX are the third and fourth elements contributing to our knowledge of radial transport. Neutral beams fuel the end plugs, and a gas feed fuels the central cell. We can model these processes using computer codes and the observed plasma parameters to determine the sources of particles in TMX.

The results of one radial transport experiment are shown in Fig. 14. Figure 14(a) shows the electric current measured flowing to the end wall; Fig. 14(b) shows a comparison of theory and experiment. The fact that a negative electric current is detected at the end wall implies that some nonambipolar mechanism is transporting ions but not electrons across the magnetic field. The electric current increases as a function of radius and falls to zero at the radius of the limiter, as expected. The observed negative current is $40 \pm 20 \text{ A}$ per end within a 30-cm radius, compared to the ion end losses of about 50 A per end.

Resonant-neoclassical transport should cause a negative electric current to flow to the end wall. This transport arises because the quadrupole magnetic fields at the ends of the TMX central cell have an azimuthal component that causes radial motion of the central-cell ions. The ions drift in azimuth because of the electric field in the plasma as they bounce back and forth in the central cell. Some

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FIG. 13. Schematic of radial transport experiment. Neutral beams fuel end cells; puffer valve fuels central cell. Limiters (shown in cutaway) confine gas near the central-cell midplane. End-wall diagnostics include Faraday-cup array, net-current detector array, and end-loss analyzers (ELA's).

ions drift so as to resonate with the magnetic field structure, and a large radial transport of these ions results. The radial transport of electrons by this process is small, so the electrons flow to the end wall to maintain charge neutrality.

The predicted radial ion flux is shown as a function of electric field in Fig. 14(b). The flux increases as the electric field increases because more ions become resonant. The radial fluxes allowed by the data shown in Fig. 14(a), and the electric fields allowed by the measured plasma potential profile, determine the box labeled "TMX Data" in Fig. 14(b). The data and the theory overlap, but there is a significant uncertainty, and the actual radial flux could be several times the resonant-neoclassical flux.

Summary of TMX Operations at High and Low Electron Temperatures

(D. L. Correll, R. G. Goodman, W. E. Nexsen, and W. L. Pickles)

The temperature of the plug electrons in TMX, measured by Thomson scattering techniques to be in excess of 200 eV on several occasions during both 1979 and 1980, had a daily average in 1980 lower than that during the 1979 operation. Better static and dynamic vacuum conditions have been shown to correlate with the higher temperature of the plug electrons.

During the last three months of TMX operation, July through September 1980, we were able to show effects on electron temperature T_e from excursions in the machine pressure on time scales much longer than an experimental shot (static vacuum) and from increases in neutral-gas densities during the experimental shot (dynamic vacuum). For several weeks, we recorded the temperature of the plug electrons and the static vacuum conditions versus experimental shot number. We found that if two conditions were met, the subsequent experimental run would begin with lower than average electron temperatures and would require more than

FIG. 14. Experimental (a) and theoretical (b) results for non-ambipolar transport in the TMX central cell. The calculations in (b) are at radius $r = 28.5$ cm and for three values of central-cell ion temperature T_{ic} . The measured negative electric current shows the presence of non-ambipolar transport; the theoretical predictions are in rough agreement with the data.

the usual number of cleanup shots to return to average electron confinement. These two conditions were: (1) the magnet cases of the baseball coils, which are the "first wall," became the coolest surface in the experiment, and (2) the static vacuum had been seriously degraded since the previous days running. Condition (1) was easily met because the temperature of the coil case was determined by radiation losses and therefore had a long thermal constant. Condition (2) could be met because of failures of the vacuum system or poor vacuum maintenance techniques.

To help quantify this relationship between T_e and vacuum conditions, we used the signal from the secondary electron emission detectors (SED's) located at the midplane of each end plug to estimate the density of the neutral gas surrounding the plasma. Charge-exchange atoms that strike the

detector cone on an SED released secondary electrons. (Ultraviolet light also releases secondary electrons, but tests on 2XIIB had indicated that the charge-exchange component dominated.) The charge-exchange current incident on the detector was proportional to the product of neutral-atom density, ion density, and angular distribution function in the direction of the detector. These detectors viewed 90° to the magnetic axis and have a large acceptance angle. During neutral-beam injection, the neutral-gas density was primarily due to the energetic, neutral-beam atoms. Then, the SED signal was proportional to the product of neutral-beam current and ion density. When the neutral beams were turned off, the neutral-gas density was due to background gas impinging on the plasma surface. The signal was then proportional to the background gas density n_{gas} . To determine the

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charge-exchange current due to background gas, we normalized the SED signal to its value during beam injection.

We measured T_e versus n_{gas} , the density of the neutral gas impinging on the plasma, under three different vacuum conditions. First, in Fig. 15(a), we look at data from August 19 and 21, 1980, where Conditions (1) and (2), which can drastically alter T_e , occurred after the experimental run of the 19th. Next, in Fig. 15(b), we plot data from September 17, 1979, where the gas feed to the central cell was varied from 600 to 6000 A equivalent of neutral atomic deuterium (see Ref. 38). Finally, in Fig. 15(c) data are shown for September 29, 1980; at the beginning of the day, relatively good electron temperatures were observed; however, during the run a vacuum feedthrough was damaged, then repaired, and later the coil case of the west inner C-coil magnet developed a leak. What is common to all three examples is that the value of T_e declines as n_{gas} increases. In fact, the general dependency of T_e on n_{gas} seems to be independent of whether the source of gas is from known leaks [Fig. 15(c)], variations in central cell fueling [Fig. 15(b)], or poor "first wall" preparation and conditioning [Fig. 15(a)]. Figure 16 shows T_e ranging from over 200 eV down to 50 eV as the indirect measurement of n_{gas} increases by a relative factor of 2. The data span almost the full operation period of TMX, and the observed consistency gives strong credence to the hypothesis that the main variation in T_e was due to the effects of background gas pressure.

The specific mechanism by which the background gas lowers T_e is not well understood. We are modeling charge-exchange losses in the plasma fan regions, where neutrals can more readily be deposited within the plasma core, as a possible way T_e can be affected by n_{gas} . Secondary emission coefficients of cold electrons at the machine end walls are also sensitive to neutral pressure levels through the production of cold plasma at the end walls. Recent measurements of the electron temperature in the central cell indicate the possibility of a thermal barrier between the plugs and the central

FIG. 15. Measurements of T_e in TMX under different vacuum conditions: (a) shots from before and after Conditions (1) and (2)—see text—occurred, (b) shots for which the gas feed to the central cell was greatly varied, and (c) shots during which there were vacuum leaks. In all cases, T_e decreased as the n_{gas} increased.

cell, which in turn could also be sensitive to the cold plasma generated by neutral gas. We are studying the magnitude of these effects.

FIG. 16. The new Superconducting Magnet Laboratory under construction. An existing 2-m-diam Dewar plus a new 4-m-diam Dewar will be housed in the pit. A 25-ton overhead crane is being installed and will eventually be upgraded to a 50-ton crane. The control room for this 50-ft by 100-ft building will be located in a 3-trailer complex (freed by the construction of the MFE Office Building) that will be relocated just outside the west end of the building.

Development and Technology

The Development and Technology Program is aimed at developing the technology required for carrying out the magnetic fusion reactor program. The three areas into which the program is divided are component development, materials and radiation effects, and reactor systems and applications.

Component Development

- **Superconducting Magnets:** The mirror program is the only fusion program in the United States that has used superconducting magnets for major confinement experiments, and the largest confinement experiment presently under construction in this country using superconducting magnets is the tandem Mirror Fusion Test Facility (MFTF-B) at Lawrence Livermore National Laboratory (LLNL). The magnet program developed and tested the conductor for MFTF-B. We are now developing, with industry's cooperation, practical high-field materials, e.g., multifilament niobium tin (Nb_3Sn), that will be needed for future experiments. A key feature of this program is the High-Field Test Facility (HFTF) (now under construction) in which the first large multifilament Nb_3Sn coils will be evaluated.

- **Neutral Atom Beams:** A major program for producing neutral beams for plasma heating and fueling is being conducted at Lawrence Berkeley Laboratory (LBL), which also operates several high-power test facilities. Neutral beams based on negative-ion sources, which maintain good efficiency at very high energy, are critical to future mirror facilities. The coordination of the negative-ion program is an LLNL responsibility.

- **End-Plasma Technology:** Technology pertaining to the end regions of tandem mirrors is an important and unique aspect of tandem mirror reactors (TMR's). A coordinated program underway in this area involves direct conversion of plasma exhaust energy to electricity, vacuum pumping, heat removal, and a study of the end region.

Materials and Radiation Effects

The Rotating Target Neutron Source (RTNS-II) is a unique source of 14-MeV neutrons developed and operated by LLNL as a national facility for the irradiation of fusion materials. Many laboratories and universities participate in RTNS-II irradiation programs.

The LLNL irradiation program is aimed at characterizing the damage produced by fusion neutrons and correlating this damage with that produced by other irradiation environments.

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

Reactor Systems and Applications

- **Advanced Mirror Systems:** Design studies of mirror reactors form a basis for evaluating mirror concepts and for guiding our long-range program. Emphasis is on comparing magnetic-field geometries for an eventual TMR and for a facility to follow MFTF-B called Tandem Mirror Next Step (TMNS).

- **Fusion-Fission Hybrids:** A study with major involvement by industry and other laboratories is underway to evaluate a fusion-reactor/blanket combination optimized to produce fissile fuel for light-water reactors (LWR's).

- **Chemical Fuels:** The practicality of fusion reactors, particularly TMR's, as a heat source for producing chemical fuels is the subject of a study. Activity is concentrated on the use of thermochemical processes for producing hydrogen.

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

MAGNETIC SYSTEMS

SUPERCONDUCTING MAGNET DEVELOPMENT

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

The technology of superconductors and superconducting magnets is of vital importance to the building of present-day plasma physics facilities and to the planning and study of future experimental mirror machines and reactors. We have developed a niobium-titanium (Nb-Ti) conductor for the Mirror Fusion Test Facility (MFTF) winding and are now developing niobium-tin (Nb₃Sn) conductors for future mirror devices. Our main emphasis is on proceeding as quickly as possible with the construction of the High-Field Test Facility (HFTF).

High-Field Test Facility (HFTF)

Nb-Ti Coil System. Construction, assembly, and testing of the Nb-Ti backing system for the HFTF has now been completed. We tested the complete system to its full design rating of 8 T at 1200 A during September and October: no problems were encountered. The new digital data-acquisition and analysis equipment was operated during these tests: all equipment behaved as expected.

During November, we used the whole Nb-Ti coil system to produce a background magnetic field for stability measurements carried out on a prototype pulse-field conductor for Los Alamos.

Nb₃Sn Coil System. The design and fabrication of the new facilities required for winding the Nb₃Sn coils for the HFTF are now almost complete. There will be two identical coils, each combining 10 double pancakes. A pair of pancakes will be wound with a continuous length of conductor, with the winding commencing at the center of the conductor length. The main items of equipment now being assembled include the winding machine complete with axial and radial clamps, a conductor supply spool and its associated suspension system, a separate windup spool, and a tensioning machine and the associated equipment for controlling it. We

now expect practice winding with dummy conductor to start during February.

Nb₃Sn Conductor. All the Nb-bronze composite core has been drawn to final strand size and is ready for the cabling operation. This material is sufficient to make 19 of the 20 lengths required for the HFTF Nb₃Sn coils. In addition, two lengths of 18-strand HFTF core have been fabricated and are ready for the reaction heat treatment. The equivalent of two lengths of 54-strand core is being held as cable until the problem of low critical current is resolved (see below).

The production of HFTF conductor has been halted at this stage (i.e., at final strand size) for most of this quarter. Critical currents measured on samples prepared by hand all exceeded the specification of 7500 A at 12 T. However, measurements on samples prepared by machine-processing long lengths have shown serious degradation in critical current I_c , sometimes by as much as 50%. The machine-processing steps include initial cabling and twisting, intermediate cabling, final cabling, tube insertion and welding, die reduction, intermediate annealing, and turksheading. A matrix of test samples is being measured in order to identify the source of the degradation. Thus far, samples without twisted strands are significantly better, and we have therefore adopted a longer twist pitch. However, I_c values are still 15 to 20% below those expected from results on hand-fabricated samples. We are seeking the cause of this degradation.

A trial length of HFTF conductor with a copper core was fabricated last quarter and shipped to LLNL for practice winding. One more trial length will be processed and delivered for practice winding by the end of January. The cladding, plating, and embossing lines are now operating satisfactorily.

Power Supplies and Controls. Acceptance tests have now been carried out on the 20-kA power supply, and delivery is scheduled for January 1981.

Four-m-Diam Cryostat. Completion of the specification for the 4-m-diam cryostat has taken longer than we expected, and the revised date for its delivery to LLNL is now January 1981.

Development and Technology

Superconducting Magnet Laboratory

Construction of the new Superconducting Magnet Laboratory is proceeding on schedule. The pit (see Fig. 16), designed to house the new 4-m-diam cryostat and the existing 2-m-diam cryostat, is complete. The building framework, the support

system for the crane, and the pipework for the services to the new building have been installed, and the main cable trenches on either side of the pit are ready for concrete pouring. We expect the building to be ready for occupancy by the end of next quarter.

PLASMA ENGINEERING

PLASMA DIRECT CONVERSION

(W. L. Barr)

Results of tests of three plasma direct converters agree well with predicted values and lend confidence to our direct converter designs for fusion reactors.

We have stopped tests of three plasma direct converters, and have begun preparing a report on the test results. The first two tests were done at high power density (up to 70 W/cm^2) in steady state to simulate the predicted conditions on a reactor ($\sim 100 \text{ W/cm}^2$). A single-stage unit and a two-stage unit of the Venetian-blind type were tested at up to 100 kV and 5 kW for a total of about 80 h. The results agree with theoretical predictions. Losses in efficiency are due mainly to the production of cold plasma and the trapping of cold ions in the potential well produced by the electron-suppressor grid. The losses are amplified by the emission of secondary electrons. In scaling up in energy from previous experiments, the new effects that become important are the ionization of background gas and the release

of secondary electrons at surfaces. In the third test, a single-stage unit was mounted on the end wall of the TMX device, where it intercepted some of the end-loss plasma. Of the 138 W incident on the direct converter, 79 W were recovered and 12 W were used to power the suppressor grid. The net efficiency was therefore 48%, in good agreement with predictions for a single-stage unit and the TMX plasma parameters.

These test results lend confidence to our direct converter designs for fusion reactors. Typical efficiencies predicted for plasma direct converters on tandem mirror reactors are 50% for single-stage units and 60 to 70% for two-stage, Venetian-blind units. The remaining areas of concern include the general problem imposed by high-voltage breakdown in a large direct converter with many joules of stored energy. There is also some concern about the effect of fast neutrals produced by ions striking the ribbons in a Venetian blind at grazing incidence.

FUSION REACTOR MATERIALS

RTNS-II OPERATIONS

(C. M. Logan, M. W. Guinan, D. W. Heikkinen, and N. P. Panayotou*)

We are conducting an experiment designed to expose over 900 specimens to fluences of interest to the "next step" design.

Early fusion devices will subject first-wall structural materials to a yearly neutron dose equivalent to a 14-MeV neutron fluence of about 3×10^{20} neutrons/cm² while operating at temperatures in the range 50 to 350°C. Observations of the damage induced by fission-reactor-spectrum neutrons show a tendency to saturate at dose levels equivalent to about 3×10^{19} 14-MeV neutrons/cm². If we assume that high-energy, neutron-induced damage produced at temperatures around 100°C

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exhibits similar saturation behavior, RTNS-II can be used to provide timely input to the design of the "next step" devices by achieving fluences of 1 to 3×10^{19} neutrons/cm². At present source strength and operating schedule, RTNS-II can attain a fluence of 1×10^{19} in a 6- to 8-month period.

Experimenters from Hanford Engineering Development Laboratory (HEDL) have initiated an experiment to obtain these data. Specimens of ferritic and stainless-steel alloys are being irradiated at two temperatures and to peak dose levels of 1×10^{19} with an eventual goal of 3×10^{19} neutrons/cm², $E \approx 14$ MeV. The dual-temperature vacuum furnace built for this experiment is designed for maximum utilization of the RTNS-II neutron field. Efficient, foil-type thermal barriers provide good thermal isolation with minimum thickness. An on-line turbomolecular pump maintains the vacuum. All monitoring and control are accomplished from the facility control room. To insure against neutron-induced decalibration, two different kinds of thermocouples are utilized.

Because of the expected duration of this experiment, we cannot use our "standard" ^{93}Nb (n,2n) $^{92\text{m}}\text{Nb}$ dosimetry. Instead, we have included iron foil and wires for this purpose. The ^{54}Fe (n,p) ^{54}Mn reaction half-life (312 days) is just right for this experiment, but the cross section is not as constant between 14 and 15 MeV as the Nb cross section. This means that the activation cross section in the RTNS-II neutron field is position-sensitive.

In earlier measurements, we established the ratio of ^{54}Mn production in iron to $^{92\text{m}}\text{Nb}$ in niobium as a function of position near the RTNS-II source. The effective iron activation cross section varies about 10% among the usual sample positions. Using the measured ratios, we can correct for this effect. Final dosimetry results will be accurate to $\pm 5\%$.

Conventional mechanical-test specimens cannot be used at RTNS-II because of their physical size. We are using two basic specimen configurations. One of these, a newly developed microtensile specimen which yields bulk tensile properties, is shown in Fig. 17 alongside a conventional tensile specimen. A total of 120 such specimens is included in this experiment. The other basic specimen configuration is a 3-mm-diam disk. Over 800 of these disk specimens will be used for transmission electron microscopy (TEM) and microhardness measurements.

The temperatures selected for this experiment, about 380°C and 80°C, are within the range of "next step" designs and will provide a measure of the temperature sensitivity of the saturation of high-energy neutron damage.

A companion experiment in a softer neutron spectrum is being conducted by HEDL and LLNL at Los Alamos in the Omega West Reactor. This experiment had to be moved to Omega West upon the recent demise of the LLNL's Liquid Pool Type Reactor (LPTR).

FIG. 17. Side-by-side comparison of a conventional tensile-test specimen with the much smaller RTNS-II tensile-test specimen. The gauge section of the larger specimen is 0.5 in. in diameter and 2 in. long.

Mirror Fusion Test Facility

The Mirror Fusion Test Facility (MFTF), now being constructed, will bridge the gap between present-day small mirror experiments and future fusion-reactor activity based on magnetic mirrors, e.g., an experimental fusion reactor planned for operation by 1990. In MFTF, we shall investigate advanced engineering problems such as those associated with superconducting magnets (MFTF uses a superconducting magnet of yin-yang design that will be capable of continuous operation), neutral-beam injectors, plasma-wall interactions, the disposal of neutral particles and ions escaping from the plasma chamber, and high-speed vacuum-pumping techniques.

In October 1980, a revision of the scope of MFTF was approved. This revision will convert the facility to a large tandem-mirror configuration, which is now the main-line approach to mirror fusion reactors. Our plan is to proceed directly to the tandem configuration, called MFTF-B, without first operating MFTF in the single-cell mode. By using the equipment now under construction for MFTF, we can complete construction of the MFTF-B facility by January 1985.

The geometry of MFTF-B is shown schematically in Fig. 18. Several operating modes are envisioned. The primary mode, the thermal-barrier mode, utilizes the yin-yang cell solely to anchor the plasma against MHD instabilities. The confining potential for the central-cell ions is created in the A-cell. This is done by creating an anisotropic ion distribution (sloshing ions) and applying electron cyclotron resonance heating (ECRH) to create a warm, electrostatically confined electron distribution. In addition, a potential minimum, or thermal barrier, is created in the A-cell. This is done by using ECRH to form a hot, magnetically confined electron distribution. Additional, simple-tandem operating modes, similar to TMX, are also possible. In these modes, there is no thermal barrier, and the ion-confining potentials are created in the yin-yang cells.

FIG. 18. Machine regions in MFTF-B.

TECHNICAL SUPPORT

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

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

SUMMARY

(G. D. Porter)

During this reporting period, the MFTF Technical Support Group continued to study the physics issues of MFTF-B that have a direct effect on the design of the facility. A brief review of each problem considered during this quarter is included here. More details follow in subsequent sections.

- We have used the code TANDEM to study the sensitivity of the expected plasma parameters to the neutral-beam currents in the central and yin-yang cells and to the gas current in the central cell. We found that the central-cell plasma pressure β_c was relatively insensitive, varying only between 0.15 and 0.17. The ion temperature T_{ic} could be varied between 10 and 20 keV while the plasma density varies between 1 and $2 \times 10^{13} \text{ cm}^{-3}$. Future studies will determine the sensitivity of the plasma to inputs to the A-cell.

- We have continued the development of the one-dimensional plasma-buildup code TAMBAR. When we used the code to simulate some TMX experiments, we found that even a crude attempt to model the effects of the drift-cyclotron loss-cones (DCLC) instability in the plug dramatically improved the agreement between calculated results and experiment. We expected that further improvement will be obtained with a model that includes radio-frequency (rf) heating of the central-cell ions. Although the calculated radial profiles in the plug are in reasonable agreement with the experimental

values, the central-cell profiles are not. This indicates a need in the code for a more sophisticated radial-transport model.

- We studied several issues related to ECRH heating of the A-cell. The results of one-dimensional ray-tracing studies indicate reasonable illumination of the resonance zones ($\omega = \Omega_{ce}$) by both the ordinary and extraordinary modes. The antenna for these studies were placed well outside the plasma. Our review of the ECRH power requirements, including the effect of cold-electron deposition by gas and neutral beams, and synchrotron radiation, and we find that slightly higher power is required than was initially estimated in the MFTF-B Proposal.³⁹

- We have continued to study the possibility of using neutral-flux spectroscopy for phase-space measurements in the A-cell. We find that the contributions to the signal by sloshing and passing ions are well separated in energy space. This permits a clear identification of these two species.

Finally, we have completed a detailed study of the diagnostic requirements for MFTF-B. We have compiled a list of those instruments necessary to meet the physics and technology goals of MFTF-B. A smaller instrument list identified instruments required for initial operation of the facility.

TANDEM—A TIME-DEPENDENT CODE FOR TANDEM MIRRORS WITH THERMAL BARRIERS

(R. S. Devoto)

We have written TANDEM, a code for the computation of mean plasma properties in tandem mirrors with outboard thermal barriers, and are using it to study parameter variations in MFTF-B and in potential tandem-mirror reactors.

The introduction of outboard thermal barriers (A-cells) in tandem mirrors⁴⁰ has added a number of controllable inputs (e.g., ECRH power to the barrier and warm-electron and pump-beam currents) from which to select the type of input and the input-time variations that will allow the attainment of the desired final plasma state.

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To help in choosing, we have written TANDEM, a time-dependent, zero-dimensional (or volume-averaged) code that solves for plasma properties. It is based on an earlier code^{41,42} that was used extensively for studies of "standard" tandem mirrors without thermal barriers.

Time-dependent equations are written for density and mean energy of the species in several easily distinguished regions (Fig. 19): central-cell electrons and ions, hot yin-yang ions (there are also passing central-cell ions in this region), hot sloshing ions [between (a) and (a') of Fig. 19], hot barrier electrons [near (b)] and warm electrons [at (a)]. The potentials shown in Fig. 19 are obtained from requirements of charge neutrality ($\Delta\phi_{pc}$, $\Delta\phi_{pb}$, and ϕ_b) or from an electron conservation equation ($\delta\phi_a$ and ϕ_e).

Three ways to inject sloshing ions are possible in the A-cell: at (a) (Fig. 19) with an injection angle 90° to the field lines; at the inboard bounce point (a'), again at 90° to the field lines; and at (b) with an injection angle $<90^\circ$. For MFTF-B, injection at (a') is used, and injection at (b) is used for TMX-Upgrade; reactor studies to date have considered only injection at (a). The high-energy pump beam (HEPB) is by necessity aimed at (b) with a small angle, but the low-energy pump beam (LEPB) could be directed either somewhat inboard of (a) or, with higher beam energy and perhaps at $<90^\circ$, at (a'). Injection at (a) was chosen for MFTF-B; however, it has the disadvantage of supplying a large number of electrons, which would lower the attainable central-cell ion-confining potential ϕ_c . The latter is found from

$$\phi_c = \delta\phi_a - \phi_b + \Delta\phi_{pc} \quad (40)$$

with $\delta\phi_a$ computed from

$$\delta\phi_a = T_{ew} \ln \left[N_{CW} \frac{1 + J_{AB}}{1 + J_{AB} N_{CW}} \right] \quad (41)$$

In Eq. (41),

$$N_{CW} = \frac{n_{ew}(a)}{n_{ec}(b)} \left(\frac{T_{ec}}{T_{ew}} \right)^\nu, \quad \nu = \frac{1}{2} \rightarrow \frac{3}{2}, \quad (42)$$

FIG. 19. Profile of the magnetic field and electrostatic potential for the thermal-barrier mode in MFTF-B. The machine regions are the same as those defined in Fig. 18. The magnetic field in the central cell is defined as B_c and that in the yin-yang cell as B_p . The magnetic-field maxima are identified with a subscript m. Thus, B_{mc} is the field maximum between the central cell and the yin-yang cell, B_{mb} is the maximum between the yin-yang cell and the A-cell, and B_{ma} is the maximum on the outbound side of the A-cell. The central-cell potential is denoted as ϕ_e , while the confining potential for the central-cell ions is ϕ_c . The potential increase from the central cell to the midplane of the yin-yang cell is $\Delta\phi_{pc}$, and the potential decrease from the midplane of the yin-yang cell to the magnetic-field maximum between the yin-yang cell and the A-cell is $\Delta\phi_{pb}$. Finally, the barrier potential (point b) is determined by $\delta\phi_a$, the potential difference between the potential maximum at point (a) and the minimum at point (b), and by ϕ_b , the potential difference between the midplane of the A-cell and point (b).

where the first term is the ratio of warm electron density to the passing electron density at (b) and the second term is the ratio of the central-cell and warm electron temperatures. The term J_{AB} in Eq. (41) is directly proportional to the external source of cold electrons (i.e., electrons from pump beams, sloshing ion beams, or external gas penetration).

For a "good" tandem mirror, $N_{CW}J_{AB} \gg 1$; therefore,

$$\delta\phi_a \approx T_{ew} \ln \left[\frac{1 + J_{AB}}{J_{AB}} \right], \quad (43)$$

and it is clearly desirable to reduce sources of cold electrons at (a). Thus, sloshing-ion beam injection at (a') or (b) and LEPB injection near (a') are desirable. Location of the sloshing-ion beam at (b) has the further advantage of supplying pumping of deeply trapped ions, thereby reducing the required HEPB current.

Currently, the TANDEM code allows for sloshing-ion injection at (a) or (b) and LEPB at (a), but it will soon be extended to include the other possibilities. Thus, we shall be able to compare parameters for reactors under different injector arrangements. The present version has been used for extensive parameter studies of MFTF-B⁴³ and is being tested for application to TMX Upgrade, which employs injection at (b) with no LEPB.

PARAMETER RANGES IN THE MFTF-B CENTRAL CELL

(R. A. Jong)

Using TANDEM, a volume-averaged code for studying tandem mirror systems, we are determining the range in plasma parameters and confinement times that can be attained in MFTF-B: thus far, we have found that increases in gas feed to the central cell or in neutral beams injected into either the yin-yang or the central cell degrade the confinement of central-cell plasma.

The TANDEM code⁴⁴ uses the formalism developed by Logan⁴⁰ to solve for the electron and ion densities and temperatures in the central-cell,

yin-yang, barrier, and A-cell regions as well as the plasma potential in each region. In this initial study, we varied the neutral-beam current to the yin-yang and central cells as well as the cold-gas feed to the central cell. Neutral-beam and power inputs to the A-cell were constant for the work reported here. In this article, we discuss variations in central-cell plasma pressure, ion temperature, ion density, and potential (β_c , T_{ic} , n_{ic} , and ϕ_c , respectively). The dependence of electron temperatures is also shown. Figures 20 through 22 show the results of the study.

Figure 20 (a through d) shows the effects on various parameters of an increase in gas feed to the central cell. For an 8.3-A neutral-beam input to the central cell (solid lines in Fig. 20), we observe the following: β_c decreases with increasing gas feed (a) because of the rapidly decreasing ion temperature and density (b). The gas cools the central-cell ions, and the density decreases because the Pastukhov confinement time is degraded. The Pastukhov lifetime τ_p is proportional to

$$\tau_p \propto T_{ic}^{1/2} \exp(\phi_c/T_{ic}) \quad (44)$$

Since ϕ_c/T_{ic} is relatively constant, as shown in Fig. 20(d), τ_p decreases as $T_{ic}^{1/2}$, and the ion confinement is poorer in the central cell. Therefore, n_{ic} decreases with increased gas current to the central cell, Fig. 20(b).

If the neutral-beam input is increased to 15 A (dashed lines in Fig. 20), we observe the following: β_c improves slightly (a). Because of increased input to the central cell, there is a large increase in T_{ic} and a decrease in n_{ic} because the potential confinement is poorer in the presence of the higher ion temperature; i.e., τ_p decreases because the increase resulting from the higher T_{ic} is more than compensated for by the decrease in $\exp(\phi_c/T_{ic})$. The dependence of the central-cell and A-cell electron temperatures is shown in Fig. 20.

Figure 21 (a through d) shows the effects of an increase in the neutral beam injected into the central cell for no gas feed (solid line) and for a 10-A gas feed (dashed line). We find a slight increase in β_c as the neutral beam injected into the central cell is

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FIG. 20. Central-cell plasma parameters in MFTF-B vs central-cell gas feed for two values of neutral-beam injection into the central cell.

varied from 0 to 20 A, regardless of gas feed. As shown clearly in Fig. 21(b), the primary effect of increasing the neutral beam to the central cell is to increase the ion temperature there. This large increase in T_{ic} decreases ϕ_c/T_{ic} [Fig. 21(d)], so that again the confining potential of the ions is degraded and the ion density decreases. The dependence of the central-cell and A-cell electron temperatures is shown in Fig. 21(c).

In Fig. 22 (a through d), we see the effect of varying the neutral beams to the yin-yang cell for two values of the central-cell beam current. For an 8.3-A central-cell beam current (solid line), β_c is relatively insensitive to increases in the yin-yang beam current, but it does start to fall for larger beam currents to the central cell. As the yin-yang beam is increased, T_{ic} remains relatively constant, not rising until the yin-yang beams exceed 10 to 12 A. It is this increase in T_{ic} that ruins the confine-

ment [Fig. 22(d)], causing a sharp decrease in n_{ic} [Fig. 22(b)] and hence a decrease in β_c .

The confinement for the 15-A central-cell beam (dashed line) is spoiled even more than for the 8.3-A case because the increases in T_{ic} are more pronounced: hence the density drop shown in Fig. 22(b) is very large. Our calculations indicate that the largest β_c values can be achieved with moderate yin-yang beam currents (≈ 8 A), with about 4 A being absorbed in the yin-yang plasma [Fig. 22(a)].

The preceding calculations suggest that large β values in the central cell cannot be achieved by varying the central-cell gas feed or the neutral beams injected into either the central cell or the yin-yang cell. The β_c that can be achieved lies in the range $0.15 \lesssim \beta_c \lesssim 0.17$ with $n_{ic} \approx 1.7 \times 10^{-13} \text{ cm}^{-3}$ and T_{ic} in the 10- to 20-keV range. Increases in the injected beams and gas currents have the greatest effect on the T_{ic} and generally degrade ϕ_c .

FIG. 21. Central-cell plasma parameters in MFTF-B vs neutral-beam injection into the central cell for two values of gas feed into the central cell.

ECRH HEATING IN MFTF-B

(J. W. Shearer and D. A. Lappa)

We obtained the first ray-tracing code results for the MFTF-B electron cyclotron resonance heating (ECRH) application and find good penetration to resonance zones. In addition, we revised our estimates for the power requirements for ECRH heating of the electron populations of the MFTF-B thermal-barrier (A-cell) region and found a slight increase in the required ECRH power.

We used the ray-tracing-code techniques developed during the previous quarter,⁴⁵ and applied them to determining the ray path of the ECRH waves in the plasma-fan geometry of the thermal-barrier (A-cell) (Fig. 23). The source of the rays was chosen at a plausible antenna position, well outside the plasma, and at a point where the

magnetic field is greater than the resonant field value. This location provides accessibility for both the ordinary and extraordinary wave polarizations, and the "slab" geometry of the plasma fan permits a rather close approach of the antenna (a favorable solid angle).

We reported our initial ray tracing results in October⁴⁶; they were for the plane of Fig. 23, that is, the narrow cross section of the plasma fan. Figure 24 displays two examples of these calculations; they show some extraordinary rays for 28-GHz fundamental resonance heating near the thermal-barrier minimum. For the zero plasma beta case [Fig. 24(a)], one finds that, because of the effects of refraction and total internal reflection, these rays reach the resonance surface near the edge of the plasma. For the finite-plasma beta case, the geometry is more favorable for resonance absorption deep inside the plasma.

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FIG. 22. Central-cell plasma parameters in MFTF-B vs neutral-beam injection into the yin-yang cell for two values of neutral-beam injection into the central cell.

FIG. 23. Axial cross section through the narrow dimension of the plasma fan in the MFTF-B thermal-barrier cell, showing conditions for microwave heating of the plasma: (a) the predicted on-axis electron-density distribution, and (b) the relative locations of the plasma, coils, magnetic field lines, and point of ECRH input.

FIG. 24. Predicted ECRH-ray paths of the 28-GHz extraordinary waves in the plasma in the MFTF-B thermal-barrier cell (a) for the vacuum-field case ($\beta = 0$), and (b) for the field contour modified by a finite- β plasma model. The ray-calculation code was stopped at the $B = 1$ T contour (cold-plasma resonance).

All these ray-tracing results, however, must be used with caution; the cold-plasma assumptions used in the present code are only a first-order model for the hot plasmas anticipated in MFTF-B. Nevertheless, in a qualitative way we interpret these results to show the sensitivity of the microwave-plasma interaction to plasma parameters. Also, in these plasmas, the extraordinary waves experience rather large increases in the refractive index especially near the resonance surface. However, for these densities, the ordinary waves experience only modest decreases in this index and their rays appear almost straight. We found qualitatively similar

results for 56-GHz fundamental resonance heating at 2 T near the potential-barrier peak. In future work, we intend to investigate rays in three dimensions, out of the plane of Fig. 23.

We have made more detailed estimates for the required ECRH-absorbed power. The original estimates⁴⁰ included the effect of the addition of cold electrons by ionization of the sloshing-ion pump beam. Since that time, however, that beam has been moved from $z = 25$ m to $z = 22.3$ m (see Fig. 23), where the ECRH-heated hot-electron population is negligible. However, we have added estimates for the cold-electron contributions from the low-energy pump beam (LEPB), and the high-energy pump beam (HEPB), charge-exchange neutrals from the background gas, and synchrotron radiation losses.⁴⁵ Table 7 shows these revised estimates; they imply that good coupling efficiency must be achieved to the plasma.

TABLE 7. Revised ECRH power requirements for MFTF-B.

Parameter	Power ^a (kW)	
	At 1-T thermal barrier	At 2-T potential peak
Collisional losses	293	280
Synchrotron losses	133	—
Electron ionization from pump beams	—	284
Background gas	—	143
Total:	426	707

^a Values are for each end plug.

NEUTRAL-FLUX SPECTROSCOPY STUDY FOR MFTF-B

(J. E. Osher¹)

Our preliminary calculations show that a set of neutral-flux spectrometers could be used successfully

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to obtain neutral-flux energy and angular distributions in MFTF-B plasmas.

The primary diagnostic for measuring the phase-space details of the plasma ions in the various regions of MFTF-B is a set of neutral-flux spectrometers (NFS). The energetic neutral flux measured by a well-collimated NFS arises primarily from charge-exchange interactions between the trapped plasma ions and the injected neutral beams, and therefore accurately reflects the local angular and energy distributions of the plasma ions.

Our NFS study involves modeling the expected plasma and neutral-beam configurations in each of the plasma regions (A-cells, yin-yang cells, and central cell) of MFTF-B to allow calculating the expected neutral-flux energy and angular distributions. A continuing part of this study also involves selecting a suitable set of port locations on the walls of the MFTF-B vacuum chamber and end domes for NFS installation, and also specifying the physical requirements for the NFS instrumentation to adequately measure the details of the phase-space density from the predicted neutral fluxes.

For simplicity and cost effectiveness, we are considering a combination of two types of NFS instruments; namely, a fairly complete array of simple, collimated surface-barrier detectors capable of pulse-height analysis, and a few more elaborate parallel E- and B-field analyzers that can resolve ion species and measure a wider range of ion energies.

To date, the major portion of our NFS study has concerned the A-cell (thermal-barrier) region of MFTF-B, since this region involves the most important ion-physics issues and requires resolution of several ion species that are spatially mixed but widely separated in energy. In particular, the formation of an outside barrier in each of the MFTF-B A-cells requires buildup of a tailored, sloshing-ion distribution, local removal of ions in certain regions of phase space by neutral-beam pumping, and spatially selective use of ECRH. The base case for the present level of neutral-flux calculations from the A-cell barrier region involves use of simple, axially dependent analytic models for:

- The magnetic field—fitted to EFFI code calculations, i.e., models of general form

$$B(z) = \sum \frac{B_i}{1 + b_i(z - z_i)^2} \quad (45)$$

- An electrostatic potential—fitted to the form given in Ref. 39;

- Injection of sloshing ions by neutral beam having 80-, 40-, and 27-keV components injected at $z = 22.3$ m.

- Neutral-beam pumping by an axial, high-energy pump beam (80-, 40-, and 27-keV) and a low-energy pump beam (~ 2 keV) injected transversely near the maximum of the plug potential;

- Passing-ion flow from the central cell of approximately 15-keV Maxwellian;

- First-order corrections for neutral-beam dimensions, changes in the volume of the tube, and off-axis bendings of the magnetic field lines.

Our calculated results for NFS viewing near the barrier minimum show that the 80-keV component of the sloshing-ion group would be well separated for viewing angles between 40° and 50° to the axis, and that the passing-ion group would be well separated for viewing angles of 30° to 15° to the axis. The neutral flux levels would range up to about 1 mA/cm^2 (equivalent), which is easily compatible with needed collimation and with counting rates to $\gtrsim 3 \times 10^4/\text{s}$ by pulse-height electronics. The histogram in Fig. 25 shows the expected relative energy distribution for the base case. Similar (but much simpler) neutral-flux calculations for the central-cell and yin-yang regions show angular spreads dependent upon the degree of ion relaxation, with typically higher flux rates and no question of resolving ion-energy groups for usable viewing angles of about 45° to 90° to the axis.

“BASIC” SET OF DIAGNOSTICS FOR MFTF-B

(G. W. Leppelmeier)

Inasmuch as diagnostics for plasmas are an open-ended prospect, we have developed a progressive plan for implementing diagnostics on MFTF-B that will provide the instruments we need, when we need them. To do this, we have determined a set of

measurements that fulfill the physics goals of MFTF-B, and have identified a set of instruments, the "basic set," that will obtain those measurements. We are now analyzing the basic set to determine the detailed instrument requirements and physics design.

FIG. 25. Expected relative energy distribution derived from neutral-flux spectrography (NFS) measurements made near the barrier minimum in the MFTF-B A-cell at five selected NFS viewing angles.

The physics objectives of MFTF-B are to:

- Demonstrate the improvement in Q (in the range of $0.1 \leq Q \leq 1$) with increasing potential well depth.

- Explore radial transport in the central cell and determine its influence on confinement.

- Explore microinstabilities in the end plugs and means of controlling them.

- Explore the β -limits imposed by MHD stability.

In addition, the diagnostics system must support physics and engineering studies in the characterization of plasma confinement by tandem-mirror machines.

The goals of MFTF-B can be met by studying various physics issues. The overall issue of concern is confinement, which can be studied by measuring plasma densities, potentials, temperatures, volumes, and particle and power flow. Of particular importance here is plasma buildup, the critical process of creating a plasma and bringing it to a hot, dense equilibrium state. Buildup will be characterized by spatial profile measurements of density and temperature.

Particular issues relate to individual regions of the machine. (For purposes of the discussion here, "barrier" refers to the region of minimum potential and the "plug" refers to the region of maximum potential. Both are contained in the region generally referred to as the A-cell.)

In the central cell, the principal issues are fusion power—studied by measuring ion densities and temperature, and fusion rate—and confinement, which is studied by measuring potential profiles, losses from radial transport, rf heating, and charge-exchange flux.

The primary function of the yin-yang region is to provide an MHD anchor. Therefore, the principal issues are MHD stability, β -limits, plasma heating, and microstability. The measurements involved are rf emission, plasma energy, particle and power flow, and end losses.

The function of the A-cell is twofold:

- To create the particular anisotropic profiles of plasma density, temperature, and particle energy

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that will generate the large electrostatic potential for plasma confinement (the plug), and

- To create the dip in the potential (the thermal barrier) that will keep the central-cell electrons from cooling the hot electrons of the plug.

Thus, the primary issues pertaining to the A-cell are the formation and operation of the barrier and plug, and microstability. The measurements required include ion trapping, ion density and energy profiles, electron heating and losses, effectiveness of halo shielding of the plasma from gas, pumping of trapped ions, rf emission, and end losses.

The end region provides the largest losses and also the greatest amount of cold plasma and gas impinging on the plasma regions. Hence, here we must concentrate on measuring the amount and character of end-loss flux (e.g., ion spectra), and the processes by which gas and cold plasma can cool the A-cell plasma.

So far, measurements and issues have been discussed in relation to the physics goals. To obtain

those measurements, we must adopt a set of diagnostics. Therefore, at this point let us change our orientation to that of examining the types of instrumentation foreseen for MFTF, and where these instruments will be applied. Table 8 summarizes the following discussion.

Neutral-Flux Spectroscopy

The energy spectrum of neutrals leaving the plasma—usually the result of charge-exchange interactions between plasma ions and injected neutral-beam current or neutral background gas—has long been a means of characterizing the mean energy of the plasma ions. In MFTF, ion energies will range from a few keV (in the central cell in the simple tandem mode) to 100-plus keV (thermalized ions from 80-keV sources in the yin-yang cell). We expect that covering such a wide range of energies in so many regions will be most effectively done by using solid-state detectors for high-energy ions (≥ 20 keV) and parallel **E**- and **B**-field analyzers for lower energies.

TABLE 8. Distribution of instruments on MFTF.

Instrument	Central cell	Transition region	Yin-yang cells	Barrier	Plug	End fan
Bolometry	X	X	X	X		
Background gas pressure	X		X	X		X
Diamagnetic sensors	X	X	X	X		
Doppler-shift spectroscopy	X		X	X		
Electron cyclotron emission	X		X	X		
End-loss analysis					X	X
Electro-magnetic fluctuations	X	X	X	X		
Interferometry	X	X	X	X	X	X
Microwave scattering	X		X	X		
Neutral-beam transmission	X				X	
Neutral-flux spectroscopy	X		X	X		
Neutron counting	X		X			
Neutron spectroscopy	X		X			
Photon imaging	X		X	X		X
Plasma potential diagnostic	X					
Probes						X
Secondary-emission detectors				X		
Thomson scattering	X		X			
uv/x-ray spectroscopy (impurities)	X			X		
X-ray spectroscopy (T_e)	X		X	X	X	X

In addition to measuring mean ion energy in the various regions of the machine, neutral-flux spectrometers placed at specific angles to the z-axis will yield information about the slowing-down processes in the yin-yang cell and barrier, the electrostatic potential at the sloshing-ion injection point, and the trapping and pumping rates of slow ions in the barrier region.⁴⁷

Doppler-Shift Spectroscopy

One of the most critical parameters is electrostatic potential: the increase in plasma confinement by a tandem-mirror configuration arises directly from the difference in electrostatic potential between the central cell and the "plug" (defined here as the potential maximum). Moreover, the enhanced operation of the thermal-barrier-enhanced tandem-mirror configuration is due to a tailored dip in the electrostatic potential, called the barrier. One of MFTF's specific tasks is to correlate plasma confinement with the depth and shape of the electrostatic potential.

In fulfillment of this task, we are generating a conceptual design of an instrument that would measure the electrostatic potential by measuring the Doppler shift of a characteristic He^+ line. This line would arise from He ions injected in the neutral A-cell region and along the axis of the machine. This injection could be either by seeding the high-energy pump beam, the sloshing-ion source, or by means of a dedicated injector. If the initial promise of this scheme continues, we shall undertake a development effort.

Plasma-Potential Diagnostics

Initial examination of the technique of using a Th^+ beam injected transversely to the magnetic field to measure radial potential profile in the central cell, as was done on TMX, indicates that it is possible, but perhaps technically (and fiscally) very demanding. Nonetheless, to see exactly what would be required, we are carrying out a more detailed study of the actual configuration of such an instrument.

End-Loss Analysis

The ions streaming out the open field lines at the end of the machine carry several important pieces of information. Perhaps the most important is that a radial profile of the electrostatic potential can be obtained because the ions will have a minimum energy equal to the highest of the electrostatic potentials in the plug, along the magnetic field line intercepting the detector. Moreover, the energy distribution of such ions carries information about the processes by which the ion arrived in the loss cone with enough energy to get over the potential barrier. Finally, the radial distribution of ion current, when compared with the (calculated) injection profile, will yield estimates of radial-transport rates.

Ultraviolet and X-Ray Spectroscopy

As the electron temperatures in mirror machines rise, photon spectroscopy becomes more and more crucial. The use of ultraviolet (uv) spectrometers to identify and monitor impurities, begun on 2XIIB and TMX, will be expanded. Because of the increased confinement time in the central cell, and the delicate operation of the thermal barrier, impurities will be critical. The range of wavelengths will vary from near-uv, on the edges of the plasma and during early phases of plasma buildup, to soft x rays when the mean electron energies reach the 10- to 100-keV range. Spectrometers to observe impurities will be required in the central cell and in the A-cell barriers.

Thomson scattering has been the standard for electron-temperature measurement for over a decade because it yields an absolute point temperature measurement and a density measurement. Unfortunately, as the temperature rises, the spectrum broadens, which decreases the signal-to-noise ratio. That fact, plus the limited number of temporal and spatial points available, has made x-ray spectroscopy, as a means of measuring electron temperatures, attractive in spite of the limitation imposed by having to devise a temperature from a spectrum resulting from a signal that is a line-of-sight integral. X-ray spectroscopy will be used for

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electron-temperature measurement in the central cell, the yin-yang cells, the barriers, and the plugs.

Thomson Scattering

Thomson scattering, in spite of its limitations, will be used in the central cell and in one yin-yang cell. It will be necessary at the lower electron temperatures (100 to 1000 eV) characteristic of operating in the simple-tandem mode and two-component modes when x-ray spectroscopy will be obscured by spectral lines and low signals. It will also be useful at medium electron temperatures as an absolute calibration of other electron-temperature measurements.

Bolometers

In both the debug/startup phase and in the full physics experiment phase, we must know where the power is going and where it is coming out. Bolometers will be used in all regions of the machine to follow the power flow during a shot.

Background Gas Pressure

Cold gas crossing the plasma edge has a major effect in cooling the plasma. The diffusion of gas into the plasma, and the generation of gas from walls and other surfaces, will be monitored by pressure-measuring devices that can be oriented to look at flux in a particular direction, that will operate in the presence of the large magnetic fields, and that have a reasonably rapid time response. These devices will be installed in all regions of the machine.

Diamagnetic and Electrostatic Sensors

Plasma pressure will be measured in all regions of the machine by measuring the diamagnetic flux. In addition, fluctuations due to instabilities will be monitored with magnetic and electrostatic probes.

Interferometry and Forward Scattering

Density profile measurements in the central cell, the yin-yang cells, the barriers, and the plugs, are required to reduce temperature and potential data, to calculate power absorptions, etc. In addition, single line-density measurements are required at a number of points to verify the plasma model.

Most of the density profile measurements will be obtained with arrays of microwave and far-infrared interferometers.

In addition, some of the interferometer channels will observe low-order (spatial) density fluctuations by looking for signal modulations at ion-cyclotron frequencies and their harmonics.

Electron-Cyclotron Emission

The emission of microwave-frequency radiation at electron-cyclotron frequencies and their harmonics can be used to infer an electron-temperature profile. This will be used in the central cell and yin-yang cells, but with many more time and space points than are feasible with Thomson scattering.

Neutral-Beam Transmission

The neutral-beam transmission (NBT) diagnostic complements interferometry in measuring line density in the central cell and the plugs. In the case of the latter, the source will be the 2-keV low-energy pump beam, and the detectors will be placed opposite the source. In the central cell, the NBT diagnostic will have its own source, in order to avoid the difficulties of designing a detector to withstand the high power from an 80-keV source for 30 s.

Neutron Counting

To determine fusion efficiency and to provide a qualitative machine performance index, we shall measure the rate of neutron production in the central cell, the yin-yang, and the A-cell regions.

Neutron Spectroscopy

At high ion energies and high line densities, the interpretation of the charge-exchange flux spectra is seriously complicated by the secondary charge-exchange interactions of neutrals leaving the plasma. Therefore, a fast, high-resolution, pulse-height-analysis neutron spectrometer has been under development at LLNL, and will be included on MFTF-B to measure the mean ion energy in the central cell and in the yin-yang cells.

Electrostatic Probes

The operation of the plug is sensitive to the nature of the cold plasma and gas in the end-fan

region. There will be an array of Langmuir-type probes in this region to measure the cold-plasma temperature and local potential.

Secondary-Emission Detectors

These are relatively simple, hardy detectors, which simply indicate the existence of a flux of particles and/or photons. They will be used during the startup phase of the machine's operation to indicate whether or not a sloshing-ion population has been established.

Photon Imaging

Photon imaging is another simple, qualitative diagnostic to be used for gross checking of alignment of magnets, sources, etc. It consists of a pair of video cameras in each region of the machine, whose output will be displayed (and recorded) in the MFTF control room.

"STARTUP" SET OF DIAGNOSTICS INSTRUMENTS FOR MFTF-B

(G. W. Leppelmeier)

The startup set of instruments will provide early clues to the operation of MFTF-B.

To make effective use of manpower, financial, and technical resources in planning the MFTF-B diagnostics system, we must identify which parts of the system must be in place and functioning at the beginning of operation, and which parts can, or should, be delayed. Therefore, we have identified a "startup set" of instruments, with characteristics and requirements corresponding to a more limited role than the "basic set." This startup set has the purpose of aiding in the transition from engineering acceptance, when all the MFTF pieces and parts are in place but have not yet worked together, to the time when true physics experiments begin. Such a transition is necessary because much of the interplay between various MFTF subsystems occurs only when an attempt is made to create and sustain a plasma, and therefore only then will it be possible to debug system operation.

Thus, the nature of the startup set is different from the basic set. Its purpose is not to make precise and extensive physical measurements, but simply to

provide clues to the machine's behavior. Is there a plasma in the central cell (yin-yang, A-cell, etc.)? Is it large or small? Is it cold or hot? Is there a barrier? Do things get much better or much worse when something is changed? In other words, the startup set answers simple, qualitative questions. In some cases, the startup-set instrument is a reduced-channel version of the basic-set instrument. In others, it is a simpler instrument.

In the sections which follow, we shall explain startup-set instrumentation region by region. With the exception of one neutral-flux spectrometer, all instrumentation is duplicated end-for-end. Table 9 lists the instruments in the startup set and their locations.

Central Cell

The following summarizes startup diagnostics measurements on the central cell:

- A bulk measurement of plasma density, and a measure of plasma radius will be obtained with a seven-channel interferometer, probably in the far infrared.
- A bulk measurement of central-cell electron temperature will be obtained with a single-position Si(Li) detector, using pulse-height analysis.
- General size and shape of the plasma will be monitored with orthogonal-view TV cameras, with the signals displayed directly in the control room.
- Diamagnetic sensors will be used to obtain an estimate of the bulk ion temperature.
- Data from six end-loss analyzers (three on each end) will be used to estimate the confinement parameter $n\tau$.
- Particle input to the plasma will be estimated from gas-feed instrumentation and from modeling calculations.
- Power input will be estimated from the measure of density and plasma radius and from neutral-beam instrumentation.

Transition Regions

In each transition region, instabilities will be monitored with diamagnetic sensors, and the bulk density will be monitored with a single microwave channel.

TABLE 9. Startup instrument set for MFTF diagnostics.

Instrument	Location				
	East end	East plug	East barrier	East yin-yang	East transition
Neutral-flux spectroscopy	—	—	1 instrument	1 instrument	—
Microwave interferometry	1 channel	1 channel	2 channels	—	1 channel
Neutral-beam transmission	—	7 channels	—	—	—
Neutron counters	—	—	—	1 instrument	—
Diamagnetic sensors	—	—	—	1 array	1 array
rf noise	—	1 array	—	1 array	—
End-loss ion spectroscopy	1 instrument	—	—	—	—
Background gas pressure	—	—	2 detectors	4 detectors	—
Laser interferometry	—	—	—	1 channel	—
X-ray spectroscopy	—	1 instrument	1 instrument	—	—
Photon imaging (3 instruments)	—	—	2 locations	2 locations	—
Secondary emission detectors	—	—	1 array	—	—
uv spectroscopy	—	—	1 instrument	—	—
Machine instrumentation:					
Neutral beam	—	—	X	X	—
ERCH	—	X	X	—	—
Gas feed	—	—	—	—	—
Pump beam	X	—	—	—	—

TABLE 9. (Continued)

Instrument	Location					
	Central cell	West transition	West yin-yang	West barrier	West plug	West end
Neutral-flux spectroscopy	—	—	1 instrument	—	—	—
Microwave interferometry	—	1 channel	—	2 channels	1 channel	1 channel
Neutral-beam transmission	—	—	—	—	7 channels	—
Neutron counters	—	—	1 instrument	—	—	—
Diamagnetic sensors	3 arrays	1 array	1 array	—	—	—
rf noise	—	—	1 array	—	1 array	—
End-loss ion spectroscopy	—	—	—	—	—	5 instruments
Background gas pressure	—	—	4 detectors	2 detectors	—	—
Laser interferometry	7 channels	—	1 channel	—	—	—
X-ray spectroscopy	1 instrument	—	—	1 instrument	1 instrument	—
Photon imaging (3 instruments)	2 locations	—	2 locations	2 locations	—	—
Secondary emission detectors	—	—	—	1 array	—	—
uv spectroscopy	—	—	—	1 instrument	—	—
Machine instrumentation:						
Neutral beam	X	—	X	X	—	—
ERCH	—	—	—	X	X	—
Gas feed	X	—	—	—	—	—
Pump beam	—	—	—	—	—	X

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Yin-Yang Cells

The following summarizes startup diagnostics measurements in the yin-yang cells:

- The central line density will be measured with a single interferometer channel. The plasma radius will be estimated by tracing field lines from the central cell, and used with the line-density measurement to estimate density.

- The ion temperature will be measured with a solid-state detector. This measurement will be used to estimate the plasma fusion cross section (σv), which will be used with the measured fusion rate to estimate the volume of the hot plasma. This in turn will be used to estimate the overall index of performance Q .

- MHD and microstability will be monitored with an array of electrostatic and magnetic sensors. Diamagnetic sensors will also be used to estimate plasma pressure.

- Background-gas pressure sensors will be used near the edge of the plasma to estimate the gas flow to the plasma edge, in order to understand radial energy losses and to estimate one term in the particle balance. Particle and power input data will be obtained from neutral-beam instrumentation.

A-Cell, Barrier, and Plug Regions

The following summarizes startup diagnostics in the A-cell, barrier, and plug regions:

- The major questions of startup for the A-cell, barrier, and plug regions concern formation of the desired potential profile. The on-axis line density will be measured with an interferometer channel in the barriers, and with neutral-beam attenuation arrays in the plugs. On-axis, electron temperature T_e will be measured in each of the plug and barrier regions with x-ray spectrometers. The plug potential will be measured at three points on each

end with end-loss ion spectrometers. There will be no direct measurement of the barrier potential, but determination of whether or not a barrier exists will be inferred from comparisons of density and temperature measurements in the yin-yang cells, barriers, and plugs.

- The relative populations of sloshing ions and trapped cold or warm ions will be estimated with a solid-state, neutral-flux spectrometer and with an array of secondary emission detectors. The latter will simply measure the angle of maximum flux from the barrier potential minimum. If the angular distribution is broad, the trapped-ion population is relatively high. The angle of maximum flux will yield a crude estimate of the potential drop from injection point of the sloshing ions.

- The plasma density at the edge (halo) will be measured in both plug and barrier with interferometers. Background gas pressure measurement will be used to estimate the gas feed to the halo, and a uv spectrometer will be used to see how much and what kind of impurities collect in the barrier.

- An array of electromagnetic sensors will monitor rf noise in each barrier.

- Magnetic field alignment will be observed with orthogonal video cameras.

- Instrumentation on ECRH equipment and neutral-beam sources will provide particle and power input data.

End Regions

The end domes will contain end-loss ion spectrometers, already mentioned in connection with the plug potentials. These will also be used to estimate end-loss current.

The bulk density of the end-fan regions will be measured with an interferometer path through the thick dimension of the fan.

DESIGN AND CONSTRUCTION

GENERAL PROGRESS

*(F. P. Dixon, V. N. Karpenko, and
T. A. Kozman)*

Introduction

On October 1, 1980, we made the transition from MFTF Project, a single magnetic mirror facility, to MFTF-B Project, a large, tandem mirror fusion test facility. The MFTF-B device is a 65-m-long vessel containing 22 superconducting magnets designed to confine hot plasma within magnetic field lines and high potential barriers so that the charged particles in the plasma may fuse with a resultant release of energy. The fuel for MFTF-B is deuterium gas. Heating and refueling are provided by neutral-beam injectors at deuterium atom energies up to 80 kV.

The MFTF-B is a significant upgrade of the original MFTF capabilities; it will provide up to an order of magnitude improvement in the confinement parameter (plasma density times lifetime). This improved capability will lead directly from smaller-scale experiments to a sound experimental basis for future mirror fusion reactors capable of supplying heat and electric power.

The first major Department of Energy (DOE) review of plans for the MFTF-B Project was held at LLNL in early November. An assessment of funding profiles and schedules led to approval of the plans but to deferral of the completion date proposed by LLNL (September 1984) to December 1984. The earlier completion date would have required increased funding during FY 1981 and FY 1982. The new completion date resulted in a significant rescheduling of activities. The MFTF-B Project is now moving ahead toward December 1984 delivery within the authorized cost of \$226.1 million for the construction of MFTF-B, including the original \$94.2 million authorized for the MFTF facility. The revised MFTF activities to be completed through Technology Demonstration (Tech. Demo.) testing were 84.8% completed by the end of December 1980.

During this quarter, we published the basic documentation for MFTF-B, including System Requirements, the Configuration-Management Plan, cost/schedule baselines, and other project control tools. We began preliminary design on the new or modified components for MFTF-B, while continuing integration and testing on the original systems and facilities of MFTF. Significant progress was made in all hardware and software systems implementation, and tests of major components, subsystems, and systems were successfully accomplished. The first steps were taken toward the full Tech. Demo. of MFTF ability to meet the MFTF-B design objectives and operational requirements. We began leak tests of the vacuum vessel and completed subsystem testing for several systems.

The current status of the major MFTF Project elements and of some MFTF-B activities is presented in the following paragraphs.

Magnet System

On the east yin-yang magnet (originally the single cell of the MFTF), closeout welding was slowed because of a 6-week-long strike by the boilermakers union. Since the strike settlement and restart of work on November 17, the welding closeout progress on both coil cases has been faster than expected, and we now expect completion of the yin-yang magnet assembly in April 1981. All case closure welds have been ultrasonically inspected for weld defects; very few voids have been found. The need for only minor repairs indicates that, in spite of work stoppage and startup with some newly qualified welders, the quality of workmanship has remained high. Figure 26 shows the first coil case with the initial transition structure welded to the side of the C-coil case.

Other work on the yin-yang coils has included fabricating the miscellaneous components for magnet installation and testing later in the year. The first set of magnet current leads has been fabricated and assembled, and cryogenic testing has begun. We have received major components for the two

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FIG. 26. MFTF magnet coil case with the transition structure attached. The east yin-yang magnet for MFTF-B will be assembled from two of these C-coil units. The transition structure will join the ends of one case (upper left) to the center of the other at the interface in the middle, where the four circular holes are seen. The superconducting C-coil is located inside the case; the stiffening ribs are placed on the outside. The ends of each coil case thus act as a C-clamp on the other, preventing the 5775-A current forces in each conductor from spreading the C-coils.

magnet power supplies, with the exception of the cabling. These components include the power supplies, fast-dump resistors, programmable controllers, and slow-dump resistors. We have received and inspected the first of the A286 stainless-steel forgings for the magnet-support rods, and sent them out for final machining and assembly. All the piping for the magnet guard vacuum and liquid-helium (LHe) systems has been received, as have all the liquid-nitrogen (LN) panels, which serve as thermal radiation shields for the magnet. Work is continuing on procedures for the assembly and installation for these panels, which will begin after we complete the assembly of the yin-yang magnet.

For the west yin-yang magnet (the second end plug for the tandem-mirror solenoid of MFTF-B), we have scheduled activities and started the long-lead procurements. Awards were made to Supercon and Airco for fabrication of the approximately 180,000 ft of Nb-Ti in copper matrix that makes up the superconducting core. Bids were received and analyzed for coil interlayer insulation materials, botton-on-a-string interturn insulation, stabilizer-copper wrapping line startup steps, stabilizer-copper sheathing, and for fabrication of the magnet case (including procurement of 304 LN stainless steel). All these procurements were within the budget estimate, and contracts should be awarded early next quarter.

Work on the A-cell, transition, and solenoid coils was centered around the magnet design and fabrication contract. From among four excellent proposals, we selected the one submitted by General Dynamics/Convair Division. This is the largest single procurement (over \$31 million) ever let by LLNL, and was within 5% of the budget estimate. Work on the preliminary designs of these coils and procurement of a second large coil winder (for the A-cell coil) is scheduled for early next quarter. The large-magnet contract work will be done under a cost-plus-incentive-fee (CPIF) contract with a target value of \$31,324,063 calling for construction and installation of two A-cell magnets of one C-coil each, two transition region magnets, and fourteen 5-m-diam solenoid magnets. All magnets have Nb-Ti superconductor in a copper matrix that will be operated at a LHe temperature of about 4.5 K.

Vacuum Vessel

The leak-detection, repair, and pressure test of the 18-m-long, 10.8-m-diam, stainless-steel vacuum vessel for the east end proceeded; a vacuum pressure of 5×10^{-6} Torr was achieved at the end of December. Helium leak detection led to adjustment of the east-dome Flexseal, repair of an upper neutral-beam dome weld, and replacement of several O-ring seals on the vessel's ports. We are continuing to work with helium-filled gas bags placed on selected regions of the vessel exterior to isolate the smaller leaks and to achieve the initial objectives of 10^{-6} Torr. The tests using external diffusion pumps will then be discontinued, and the cryopanel will be installed in the vessel. Then, the external vacuum system and cryopanel will be used to verify that the vacuum vessel supports a base vacuum pressure of 10^{-8} Torr.

The neutral-beam injectors are attached to the vessel with bellows that allow aiming movements of ± 4 degrees. The first nylon-reinforced bellows was qualified mechanically with 20 cycles of repeated pumpdown to 1.5 atm overpressure at the maximum angle of flexure. The bellows will hold a vacuum around the injector magnetic shield and permit movement by means of the gimbals and actuators attached between the neutral-beam domes and each injector.

The design of the MFTF-B vessel progressed through alternate concepts and trade-off analyses to allow project management to select a modular central vessel over various monolithic structures. The modular vessel is to be made in cylindrical sections and will provide simplified maintenance, greater flexibility in assembly procedures, reduced solenoid magnet costs, and more schedule flexibility of installation alternatives during initial assembly.

Studies of glow-discharge cleaning indicated that this procedure offers possible advantages over gettering techniques, if surface cleanliness and thermal properties can be maintained. We are planning an experiment to determine the effects of glow-discharge cleaning (if any) on the surface finish of the cryopanel. We shall measure the thermal properties of the cryopanel after we have used glow-discharge techniques to clean a test vessel containing cryopanel samples.

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We are studying heat loads on the MFTF-B cryopanel (both LN and LHe cooled) caused by ECRH energy absorption and also the transient effects caused by heat loads during plasma startup. These continuing design activities will lead to selection of optimal subsystem design details for the vessel and cryopanel system specifications.

The vacuum vessel in the vault of Building 431 at LLNL is beginning to show visible signs of MFTF hardware integration. In preparation for the fusion chamber system (FCS) acceptance test, cables and piping are being assembled between the external vacuum system, the cryogenic system, and the vessel. Figure 27 shows the racks and pipes on top of the vessel that carry compressed air and

cryogenics to the valves and cryopumps. The ladder-like racks also carry cables between the cryopods on the vessel and the electrical and control interface points outside the vault.

Current plans include completion of the FCS acceptance test around the end of April 1980. Then, the east yin-yang magnet can be installed in the vessel for the next major step in MFTF Technology Demonstration: the operation under vacuum of the superconducting magnet while being cooled by LHe from the cryogenic system.

External Vacuum System

Two of the five high-vacuum cryopumps were repaired and tested; apparently, the LHe interior

FIG. 27. Piping and cable support structures being attached to the MFTF vacuum vessel (barely visible under the pipes and cables). The external vacuum cryopumps and valves are operated by liquid helium and compressed air. The regions outside the vessel are being filled as supporting hardware is placed within the vault and connected by structures, piping, and cables to distribution points or interfaces outside the vault.

pipings had been damaged while in transit from France to LLNL. All five cryopumps are ready for pumpdown of the vacuum vessel in the integrated FCS tests.

Our studies have verified that doubling the MFTF capacity for MFTF-B will provide pumpdown from atmospheric pressure to 10^{-6} Torr within 42 h; that is, the study confirms that the external vacuum system will meet the requirements for the MFTF-B external vacuum system.

Cryogenic System

We completed tests on the major components and assemblies of the LN and LHe cryogenic

FIG. 28. MFTF coldbox with its cover raised to show superinsulation on the interior components. The helium refrigerator/liquefier has multilayer reflective/insulating material wrapped on the cold elements to reduce heat transfer by radiation from the outer walls and cover to the elements confining the LHe and LN. The unit is located in the cryogenic area on the north roof (fourth floor) of Building 431.

systems and qualification of the LN subcooler and transfer lines from the storage Dewar. Also, two helium turbo-expanders were installed in the helium refrigerator coldbox in preparation for helium refrigerator/liquefier tests.

The acceptance of the 150,000-l, LN-storage Dewar was successfully completed at LLNL. The measured boiloff from the installed component averaged 0.17% per day, well below the specifications.

Superinsulation was installed on internal, low-temperature surfaces of the helium refrigerator coldbox after a successful vacuum leak test of the unit. Figure 28 shows the superinsulation inside the refrigerator coldbox before the cover was lowered back in place.

The 25,000-l, LHe-storage Dewar was installed on the fourth floor of Building 431 at LLNL. We completed inflation and leak-checks of the 1274-m³ (45,000 ft³) gas bag for the helium-recovery system. Figure 29 shows the gas bag on the north roof of Building 431 during the inflation test. The gas bag is part of the system that recovers helium gas from the cooled magnet-current leads between the power supplies and the two superconducting coils of the yin-yang magnet, as well as from other components that are not directly in the recycling loop of the helium refrigerator. Gas goes from the bag to the

FIG. 29. The two-layered gas bag for the He-recovery system, shown inflated during acceptance testing. The tests verified the performance of the bag. The bag is located on the north roof of Building 431 (fourth floor). The outer, nylon-reinforced plastic bag holds the inner plastic bag that contains the He gas. When fully inflated, the gas bag is 34-m long.

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helium purifier and then back into the helium refrigerator process for liquefaction. If a sudden boiloff should occur (e.g., sudden vacuum loss in the entire vessel), the bag would hold 50% of the helium gas contained in MFTF. Of course, when the rest of the MFTF-B magnets and vessel components/cryopanel are added to the original MFTF systems, a smaller proportion of total cooling helium will be contained by this particular unit.

The helium-recovery gas bag is made of double-layered material. The outside is nylon-reinforced plastic, which acts as a weather cover to prevent sunlight and other environmental agents from degrading the inner plastic bag. The outside bag also contains pressure and accommodates wind stresses. To provide enough stiffening for adequate wind resistance, the bag is subjected to an overpressure of 494 Pa (0.07 psi) above the outside atmosphere. The inside plastic bag has a high resistance to helium leakage in order to prevent excessive loss of helium from the closed systems during normal operation.

For MFTF-B, the helium refrigeration system will be augmented by one 6,600-W or two 3,300-W units for refrigeration/liquefaction that will be capable of providing the LHe at 4.5 K to the additional helium cryopanel, external vacuum cryopumps, and 20 superconducting magnets.

Sustaining Neutral-Beam Power Supply System (SNBPSS)

The 80-kV source modules for the sustaining neutral-beam injectors are powered by the SNBPSS units. Power comes from a dedicated 230-kV, 250-MW power line and substation on site at LLNL that was placed in operation during this quarter. The substation will provide power for 23 80-kV injectors, the ECRH system, and other pulsed-power systems on a duty cycle up to 10% (one 30-s pulse every 5 minutes) during experimental operations.

The next use of power from the substation will be to fully power the SNBPSS units for individual and dual acceptance tests. Also, a power supply unit will operate neutral-beam sources on the High-

Voltage Test Stand (HVTS) to provide acceptance testing of source module production units before they are integrated with the vacuum vessel.

In December, the first accel dc power supply (ADCPS), a subsystem of SNBPSS unit No. 12, was tested at full power; it achieved both full voltage and full current. Figure 30 shows the completed ADCPS on site at LLNL. There are 24 of these units to the east of Building 431, where the vessel and other power supply subsystems are housed.

Another element of the SNBPSS, the pulsed-power module (PPM), has been undergoing tests at the contractor's facility. The PPM hot deck (at 80 kV above ground) was tested up to 40 kV, 40 A, for 200 μ s using a 5- μ F capacitor bank as the power source. Subsystem tests of the arc, filament, and suppressor power supplies were completed. Excessive ripple, experienced by the filament power supply in earlier tests, was reduced to about 2%. Inductive coupling between the isolation transformer and the diode bridge was found to be the major cause. Cropping and adjusting the leads reduced the mutual inductance, and ripple was reduced accordingly.

Control and Diagnostics System

All seven of the MFTF control consoles were assembled at LLNL, and training for operation of the HVTS from the supervisory control and diagnostic system (SCDS) consoles was started. Several software improvements have resulted from simulated operation of the SCDS.

We began tests of software for device monitoring using hardware and software of the local control and instrumentation system (LCIS) that connects the SCDS to each of the control or monitoring points of MFTF subsystems or diagnostics.

We completed the software necessary for controlling and monitoring the external vacuum and cryogenic systems. Data on the control configuration valve (positions, set points, etc.) of components and monitoring data have been successfully transferred between supervisory (SCDS) and local (LCIS) elements. The CDS is progressing on

FIG. 30. One of the MFTF accel dc power supply units installed on site at LLNL. The completed installation takes 13.8-kV ac power and converts it to over 80-kV dc to power a pulse power modulator in Building 431. This is part of an 80-kV neutral-beam injector power supply for sustained plasma heating and deuterium refueling.

schedule to support acceptance of individual and integrated systems and Technology Demonstration tests.

In November, we completed the installation of the trays for the fiber-optic cables and began installing the cables. Connection of the optical links between the CAMAC* modules of the device locations and the local microcomputers in the MFTF Control Building 439 was completed as the cables were installed in November and December.

The hardware and software efforts for the SCDS are discussed later in more detail.⁴⁸

*CAMAC = Computer automated measurement and control.

Electron-Cyclotron-Resonance Heating (ECRH) System

The conceptual design for the ECRH system was reviewed in December. Via waveguides and transmitters (antennae) inside the vessel, the system provides power to heat the potential-barrier electrons in MFTF-B with energy from gyrotron rf generators. Sufficient confidence was established to proceed with preliminary design of the system.

Particular emphasis will be given to power balance, plasma coupling, two-frequency heating, stray rf effects, and superconducting versus conventional magnets for the gyrotron magnetic fields. The MFTF-B magnetic fields where the ECRH energy

Mirror Fusion Test Facility

FIG. 31. Nearly completed Magnetic Fusion Energy Office Building at LLNL. The exterior is nearly completed, and interior finishing is underway. Completion is expected in March; the building will be occupied in May. Many MFE scientists, engineers, and support personnel, formerly widely dispersed in temporary buildings, will then be housed in one central location. The larger wing (on the far left) contains the MFE library, and the cylindrical structure houses a 168-seat auditorium. The main lobby entrance is on the far side of the auditorium.

will be absorbed are in narrow-field values nominally at 1 T and 2 T. Two frequency ranges, one around 28 GHz and another from 56 to 60 GHz, appear to best meet our present requirements for heating plasma electrons. Two, or maybe even three, different gyrotron frequencies may prove best in each field range. This will be investigated in the two-frequency ECRH studies for both the low- and high-frequency resonance ranges for the 1-T and 2-T nominal fields, respectively.

Conventional Facilities

The modifications to Building 431 that are required to house and support the original MFTF systems are nearly complete. Work has started on the site utilities to support additions for MFTF-B. The door in the west end of the building is being enlarged, and a large cover is being provided for weather protection in preparation for moving the first yin-yang magnet into the west end of the building. This is the last major task necessary to complete the original construction activities for MFTF.

The new office building construction is nearly completed. The exterior finishing has been completed, and the interior work is nearly done. Figure 31 shows a view toward the southeast, with the auditorium and the larger office wing on the left. The main entry, located between these two features, opens into the three-story structure in the central

part of the picture. The smaller office wing is on the right. This building will house MFE scientists, engineers, and support personnel, and replaces temporary quarters now dispersed throughout the area.

MFTF SUPERVISORY CONTROL AND DIAGNOSTICS SYSTEM

(R. H. Wyman)

The top-down system design approach that we have used for the SCDS has allowed the construction of a modular system that permits partial implementation for initial testing of components; integration then proceeds as multiple systems become available. Based on present plans and progress, it is now evident that the SCDS will meet all performance requirements for the MFTF systems Technology Demonstration Tests and the concluding Technology Demonstration integrated systems test in 1981.

Hardware Status

The original hardware order for the nine computer systems, the central processor units (CPU's), disks, terminals, memory, etc., has been complete for over 2 years. We are now expanding the memory and, except for delays in delivery of some memory units from the vendor, have all hardware in hand at LLNL. The seven consoles of the control system are

now ready for use, and the additional equipment required to handle the increased data load from MFTF-B will be ordered in FY 1982 for delivery late in that year.

Software Status

The components of the software system can be roughly divided into six groups:

- IPCS—The inter-processor communications system (IPSC), which handles all communications between the nine computers.
- Data base—The common data-storage and retrieval system for SCDS.
- Console—The system for managing displays and control panels, which are the primary man-machine interface in MFTF.
- Injector EAS—The beam-injector execute/action system (EAS) for controlling the plasma and neutral-beam injector systems.
- FCS and facility EAS—The system for controlling the fusion chamber system (FCS), magnet, etc.
- General functions EAS—The system for handling startup and shutdown of SCDS, activity journals, timing, etc.

The IPCS has been running for over a year. It contains approximately 60,000 lines of code and has been very successful—it is being used regularly by all the other systems. Additionally, several utilities have been completed, one for allowing users from terminals to copy files from one machine to another (an obvious application), and another which allows users to debug simultaneously (from one terminal) codes running on several machines. This latter utility is very important since most of the operations in SCDS involve multiple codes on several machines operating in a coordinated way.

The data-base system is approximately 40% complete. The basic functions of read and write have been working for several months, and a significant number of modules of the three EAS's use the data base on a regular basis. This system employs a relational data base which is distributed over the system. Data are typically stored on disk nearest the point of most frequent use. Further, the data are "paged" so that a user employing a particular relation will have that portion which he is currently accessing in core memory. The system manages the

space for the pages so that when a new piece of data must be moved to core, an "old" page having low usage is removed.

The parts of the data-base system currently incomplete are in the area of interface elaborations. Hence, present use is limited to read/write/create. One feature of the system has been implemented, though, because of its critical importance to SCDS: that feature is the "notify" function. We have dynamic displays of data which must be updated as changes occur. To do this periodically involves much redundant traffic through IPCS. Hence, upon user request a flag is put on certain relations. This flag, the notification flag, will cause the updating code for the display to be activated anytime the relation is written, thus causing changes to be started only when required. This feature has been working since early December 1980.

The console system is nearly complete. This code, which contains approximately 20,000 lines, takes operator instructions on touch-sensitive panels and converts them into messages sent through the IPCS to the EAS's. It also manages the files of control panels.

Another function of the console system group is the revision of the graphic editor. The graphic editor allows a user to "draw" a control panel on the color TV screen. The output of the editor is a file that is used by the console system to identify which "pushbuttons" are at what location on the touch panel. The editor was originally written for the color-graphic hardware in the prototype console and is being revised to take advantage of the features of the production hardware.

Much of the software for the sustaining neutral beam system EAS is in test, and many of the displays have been implemented. Operators are currently being trained and are using SCDS in this training to gain familiarity with its control scheme. Set-point information can, for example, be entered by the operator into the data base. Checkout down to the power-supply interface is continuing; connection to the control unit is expected to occur in early 1981.

We have not begun work on the startup-beam system or the plasma-injection system, and none is contemplated for this fiscal year since there will be no hardware to control until 1983.

Mirror Fusion Test Facility

The FCS EAS is in much the same state as the neutral-beam EAS. Much of the system is in test in anticipation of connection to the vendor's equipment in January. Displays have been designed and implemented, but there has been no complete test of the integrated FCS elements.

The general-functions EAS has a number of system-wide functions to perform. SCDS startup and shutdown have been operational for a year and

a half. Modules for control of the central timing clock have been debugged, but the interface to the clock itself is still in checkout.

The journal system allows construction of a log of operator actions and machine events. The software for this system has been designed, partially implemented, and debugged. We expect that an elementary system will be available for use in January.

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