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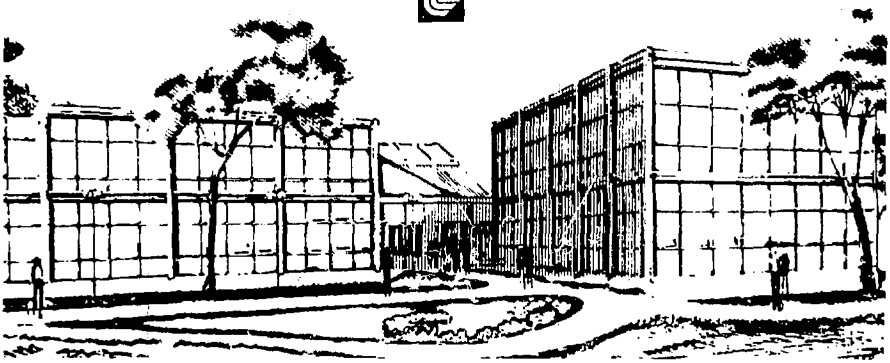

MAGNETIC MIRROR CONFINEMENT OF HIGH-ENERGY, HIGH-DENSITY PLASMA*

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ABSTRACT

This paper summarizes results obtained from and work in progress on those experiments which have contributed significantly toward the confinement in single-cell magnetic mirror systems of plasmas close to thermonuclear conditions. Because the mirror confinement of such high-energy, high-density plasmas has been studied most extensively in the 2XIIB experiment, discussion of 2XIIB results forms a major portion of this paper. In these experiments, injection of low-energy plasma has been shown to suppress microinstabilities to sufficiently low levels that high-beta (1) plasmas could be achieved and sustained by cross-field injection of beams of neutral particles. Plasma confinement was found to improve with ion energy, electron temperature, and plasma size. Based on these results, a larger Mirror Fusion Test Facility (MFTF) was designed to pursue confinement scaling to higher energies and larger plasma dimensions. MFTF design parameters and construction status are briefly reviewed.

Key words: magnetic mirror; open magnetic confinement systems; high-energy plasmas; high-temperature plasmas; high-density plasmas; thermonuclear plasmas; 2XIIB; plasma confinement; fusion; thermonuclear.

INTRODUCTION

Magnetic mirror experiments are aimed at demonstrating principles which can be employed to make practical and economical thermonuclear reactors. There are experiments to study basic mirror physics as well as experiments to investigate concepts employing mirror principles capable of improving power balance over that possible in a basic single mirror. This paper deals with single-cell-mirror experiments. Table 1 lists many of the presently active mirror experiments. Not listed in Table 1 are many other mirror experiments such as those using tandem mirrors, multiple mirrors, and field-reversed mirrors. Several of these experiments will be described in a second paper. This paper will restrict itself mainly to a review of 2XIIB experiments which have been carried out over the past 4 years.

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TABLE 1 Active Single-Cell Mirror Experiments

Ref.	Experiment	Laboratory	Purpose
Simonen and co-workers (1978)	2XIIB/Beta II	LLL	Scaling studies/field reversal
Kanaev (1979)	PR7	Kurchatov	DCLC investigation
Zhiltsov and co-workers (1978)	OGRA 3B/OGRA 4	Kurchatov	Plasma confinement studies
Miyoshi and co-workers (1978)	Gamma	Japan-Tsukuba Nagoya	rf heating
Klinkowstein and Smullin (1978)	Constance I&II	MIT	DCLC stabilization
Mai, Kesner, and Post (1977); Breun and co-workers (1978)	Phaedrus	U. Wisconsin	Ion cyclotron heating
Bekhtenev and Volosov (1977)	87/PSP2	Novosibirsk	Confinement of rotating plasma
Seikles (1978)	PSX	UIRC	DCLC stabilization
Fornaca, Kiwamoto, and Rynn (1979)	Irvine mirror	U. C. Irvine	MHD flute stabilization
Ferron, Dimonte, and Wong (1978)	Large mirror	UCLA	Large mirror ratio experiment

In their basic form, magnetic mirrors confine those particles having sufficient transverse energy by causing them to be reflected in regions of higher magnetic field strength. Those particles with too much parallel velocity then escape through the mirror loss cone. Since the electron scattering rate is much more rapid than that of the ions, electrons tend to be lost more rapidly. As a result, the mirror region charges up to a positive potential which electrostatically confines electrons and expells low-energy ions. Ions are injected deep into the confined region of velocity space by means of neutral-beam injection nearly normal to magnetic field lines. These ions are then confined until they cross the velocity space loss boundary by processes such as those listed in Table 2.

The production of high-energy and high-density plasma in magnetic mirrors required the development of a number of concepts and technologies, as outlined in Fig. 1. The 2XIIB experiment employed these developments to produce a plasma near thermonuclear conditions. Magnetohydrodynamic (MHD) stability was first demonstrated in experiments by Ioffee. Subsequently, most energetic mirror experiments employed minimum-B magnets. Vacuum technology was developed in a number of experiments including OGRA, 2X, Phoenix, and Baseball II, and continues to play an important role in the engineering design of present-day mirror machines. Microinstabilities have been studied in nearly every mirror experiment, but it was PR6, PR7, and 2XIIB that demonstrated stabilization of the drift-cyclotron loss-cone (DCLC) mode and opened the way to the present generation of mirror experiments. Development of neutral-beam heating and fueling of mirror machines was underway for many years, but

TABLE 2 Loss Processes in Magnetic Mirror Machines

Loss process	Method to improve confinement
Ion-ion scattering	High ion temperature
Electron drag	High electron temperature
Wave diffusion:	
Wave scattering	Stable distributions
Enhanced scattering	Machine size
Radial transport:	
MHD	Minimum-B magnets
Wave diffusion	Reduce fluctuation levels
Drift surfaces	Magnet design
Nonadiabatic	Strong and large magnets
Charge exchange	Good vacuum conditions; high ion temperature

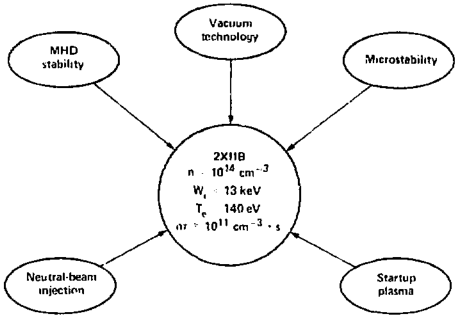

Fig. 1. Major developments required to produce high-energy, high-density mirror plasma.

the high-current beams developed for 2XIIB by Lawrence Berkeley Laboratory (LBL) made possible sustained plasmas near thermonuclear conditions. Such high-current neutral beams are now widely used in the tokamak program. Until the advent of these high-current neutral beams, a considerable amount of research effort was devoted to the production of target plasma suitable for ionization of neutral beams. High neutral-beam currents permit startup with relatively simple target-plasma production methods.

The major portion of this paper reviews 2XIIB experimental results. In 2XIIB we have demonstrated the suppression of microinstabilities to allow neutral-beam buildup of high-beta plasmas. In these experiments, plasma confinement was found to improve with ion energy, electron temperature, and plasma radius. The parameters and construction status of a larger Mirror Fusion Test Facility (MFTF) are described. The MFTF experiment is being built to pursue confinement scaling to higher energies and larger plasma dimensions.

THE 2XIIB EXPERIMENT

The 2XIIB experiment illustrated in Fig. 2 employs a minimum-B yin-yang magnet for plasma confinement. The magnetic field strength is approximately 0.7 T at the center and rises to 1.4 T at the mirrors. Near the center, the magnetic field strength can be approximated by the parabola

$$B(r,z)/B_0 = 1 + (r/55)^2 + (z/75)^2 \quad ,$$

where r and z are in centimetres. This minimum-B magnetic well provides MHD stability to the high-beta plasma.

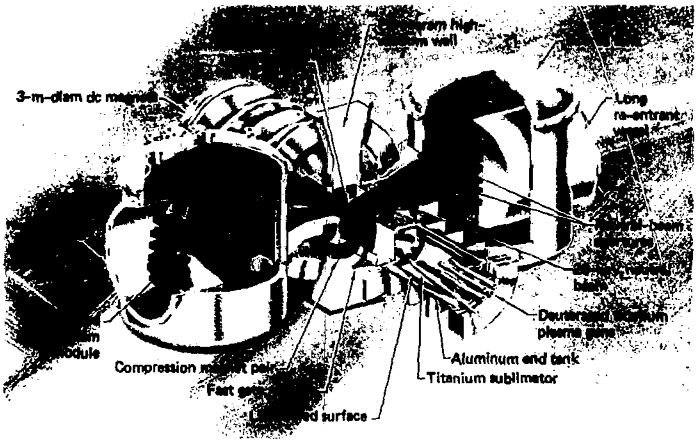

Fig. 2. 2XIIB machine.

The high-vacuum chamber consists of a total volume of 57,000 litres. The 270 m^2 of surface area is coated with several monolayers of fresh titanium before each shot to increase the pumping speed.

The 2XIIB neutral-beam system consists of twelve 20-keV LBL neutral-beam modules, each having a 10-ms pulse duration. In the experiments reported here, we injected up to 7 MW of power. The equivalent atom current reached 500 A.

Plasma startup is initiated by titanium-washer plasma guns. By injecting plasma into the mirror along field lines, these guns provide a target plasma density of $\geq 10^{13} cm^{-3}$ and an initial electron temperature of 30 eV. As described below, startup has also been initiated with a 20-keV, 10-A, 1-ms electron beam to ionize gas introduced near one mirror.

The DCLG mode is stabilized either by allowing the plasma guns to operate for the entire shot duration or by pulsing in a gas-feed system after hot-plasma buildup occurs. Electrons, which have been heated by the hot ions, ionize the gas. This gas is fed in near the mirror throat to minimize charge-exchange loss of the hot ions in the center of the mirror.

An extensive array of diagnostics is employed on 2XIIB, as shown in Fig. 3. About 100 diagnostics channels are recorded after each shot using transient digitizers. These data are then stored and analyzed by means of a computer system.

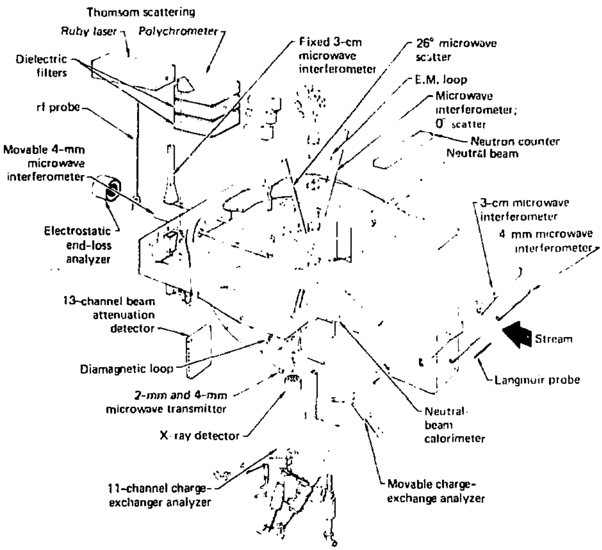

Fig. 3. 2XIIB diagnostics.

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STABILIZATION OF MICROINSTABILITIES

In 2XIIB, there are two strong departures from thermodynamic equilibrium, the radial density gradient and the ambipolar hole in velocity space. If uncontrolled, these two sources of free energy drive ion cyclotron fluctuations to such high levels that neutral-beam injection of energetic ions can not sustain an equilibrium plasma density. The injection of low-energy ions suppresses the level of DCLC fluctuations to a lower level with a marginally stable velocity distribution function. The amount of warm stabilizing plasma required decreases if the plasma radius increases. Figure 4 shows an example of the buildup of ion cyclotron oscillation when the stabilizing plasma stream is turned off during a shot. These fluctuations cause rapid diffusion of ions into the ambipolar hole as plasma turbulence attempts to supply the low-energy ions from the high-energy population injected by neutral beams. Without a stabilizing stream, the beams can no longer sustain the plasma density, so the plasma decays.

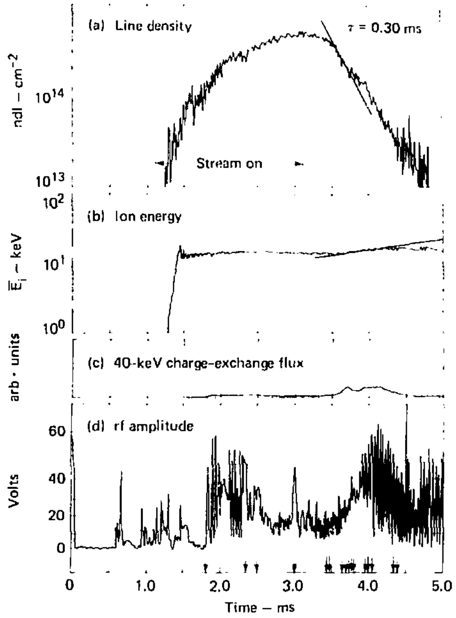

Fig. 4. Measurements show plasma stream stabilizes DCLC instability.

ION CONFINEMENT SCALING LAWS

There are two fundamental Coulomb processes that limit mirror confinement of energetic ions:

- Ion-ion angle scatter

$$n\tau_{ii} = 2 \times 10^{10}\ E_i^{3/2}\ \log_{10}R\ \mathrm{cm}^{-3} \cdot \mathrm{s} \tag{1}$$

where $R = B_{max}/B_{min}$ = mirror ratio, and E_i is in keV.

- Electron cooling or electron drag

$$n\tau_{drag} = 4.4 \times 10^{7}\ T_e^{3/2}\ \mathrm{cm}^{-3} \cdot \mathrm{s} \quad , \tag{2}$$

where T_e is in eV. We have studied these Coulomb scaling laws in 2XIIB. By varying the neutral-beam extraction voltage, we were able to vary the mean ion energy as shown in Fig. 5. Measurements of the particle lifetime by three methods indicated that the hot-ion lifetime increased with ion energy. The dashed curve shows the value expected according to Eq. (1). From measurements of electron temperature, we estimated the effects of electron drag as shown by the solid line. A residual level of ion cyclotron fluctuations diffusion and a small level of charge-exchange losses account for the lower than ideal confinement time. These experiments have been simulated with a one-dimensional quasi-linear computer code (Berk and Stewart, 1977).

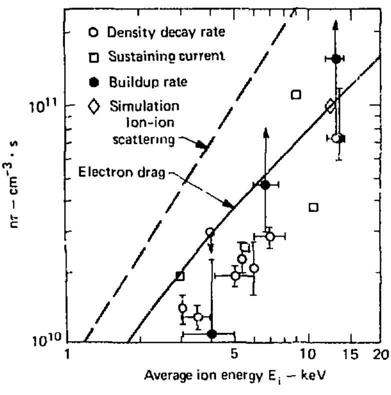

Fig. 5. Particle lifetime $n\tau$ vs ion energy. Dashed curve is ion-ion scattering, Eq. (1). Solid line includes electron drag losses.

Since 2XIIB ion energy confinement is strongly dependent on electron temperature, we have plotted the mean energy confinement paramater versus the central electron temperature in Fig. 6. The ion energy confinement time is

$$\tau_E = \frac{\text{plasma energy}}{\text{trapped beam power}} = \frac{n\bar{E}_i \cdot \text{Vol}}{P_{\text{beam}}\ f_{\text{trapped}}} \quad . \tag{3}$$

We see that the measured $n\tau_E$ increases with electron temperature but falls below the value obtained from Eq. (2). This departur is attributed to the radial electron density and temperature profile, the charge-exchange losses, and the ion cyclotron fluctuations.

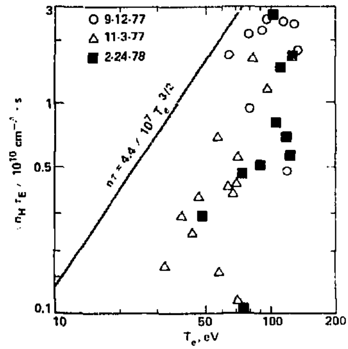

Fig. 6. Ion energy confinement time $n\tau_E$ vs central electron temperature.

For further direct study of the ion cooling rate, we conducted a series of experiments in which the neutral beams were turned off after plasma buildup. In this case, with beams turned off the fluctuation level was very low. We then measured the characteristic ion cooling time τ_E in plasmaa with different electron temperatures. The results, shown in Fig. 7, exhibit the $T_e^{3/2}$ scaling of Eq. (2) and agree reasonably well with the Spitzer coefficient when we account for the plasma radial density profile.

HIGH-BETA (FIELD-REVERSAL) EXPERIMENTS

Closure of magnetic field lines by plasma diamagnetic currents offers the possibility of substantial improvement in plasma confinement relative to open-ended magnetic mirrors. Such magnetic configurations have been created at a number of other laboratories by methods outlined in our second paper (Coensgen, Simonen, and Turner, 1979). Field-reversal experiments in 2XIIB were motivated by the unprecedented high betas achieved in earlier experiments.

Field-reversal experiments were done at two values of vacuum field strength, $B = 0.67$ T (mirror ratio $R = 2.0$) and $B = 0.433$ T ($R = 1.8$), with the neutral beams

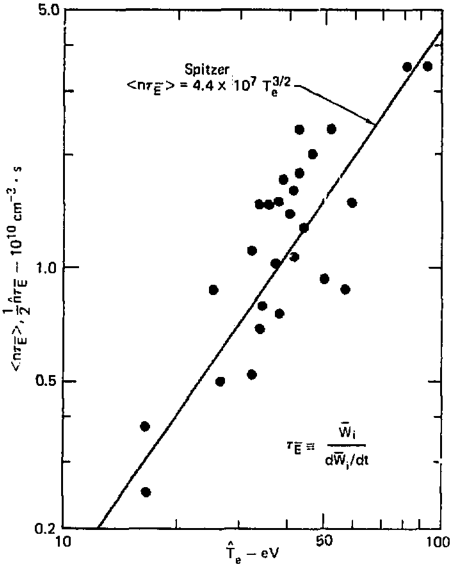

Fig. 7. Low cooling rate vs central electron temperature.

aimed one gyroradius offset from the magnetic axis to enhance the axis-encircling component of the ion diamagnetic current. Scaling of the measured plasma parameters as functions of injected neutral-beam current I_b is shown in Fig. 8 for the two values of vacuum-field strength. Plasma line density increased with injected beam current. The mean plasma radius R_p and axial length L_p, defined as the 1/e point of the line-density profiles, were nearly independent of beam current (R_p = 6.5 cm and L_p = 16 cm).

Electron temperature T_e increased linearly to 140 eV with beam current for the high-field data [see Fig. 8(b)]. The scatter of these T_e measurements for the low-field data was believed to be associated with the changing vacuum environment of the plasma. For both experiments, the mean ion energy was independent of beam current.

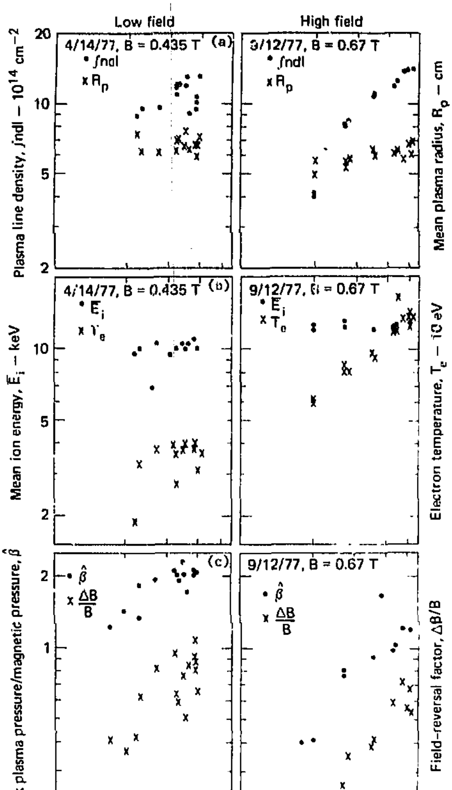

Fig. 8. Plasma parameters for field-reversal experiments for low- and high-magnetic field strengths as a function of incident neutral-beam current: (a) line density and plasma radius, (b) mean ion energy and electron temperature, and (c) peak beta and field-reversal factor $\Delta B/B$.

Figure 8(c) shows the plasma beta on-axis, $\hat{\beta} = 8\pi \hat{n}_i W_i / B^2_{vac}$, and the field-reversal parameter, defined to be the field change on-axis divided by the central vacuum field:

$$\frac{\Delta B}{B_{vac}} = \frac{1}{B_{vac}} \frac{\mu_0}{2} \frac{M}{R_p^2 (R_p^2 + L_p^2)^{1/2}} \quad . \tag{4}$$

The bulk plasma diamagnetic moment M is measured by a plasma-encircling loop. The relationship between the field change on-axis and the externally measured dipole moment is derived for a cylindrical current sheet with radius R_p and half-length L_p and is a good approximation to a rigid rotor with Gaussian current-profile $j = en_0\Omega r \cdot \exp(-r^2/R_p^2 - z^2/L_p^2)$. The rigid rotor rotation frequency is Ω. The scale lengths R_p and L_p, taken from the line-density profiles, were cross-checked for the low-field data with an array of small magnetic-loop probes placed close to the plasma surface to measure the shape of the plasma-current distribution.

Figure 8(c) shows that $\hat{\beta}$ increases with I_b, reaching $\hat{\beta} = 2.3$ for the low field and $\hat{\beta} = 1.2$ for the high field. Since the plasma length is comparable to the diameter, $\hat{\beta} > 1$ does not imply field reversal. The effect of finite length and the resulting magnetic-field line curvature is included in Eq. (4). For the data at $B_{vac} = 0.435$ T, $\Delta B/B_{vac}$ increases approximately linearly with beam current, reaching an average value $\Delta B/B_{vac} = 0.9 \pm 0.2$ at $I_b = 400$ A. The data at $B_{vac} = 0.67$ T increase with beam current, but reach a lower value $\Delta B/B_{vac} = 0.6 \pm 0.1$ at $I_b = 500$ A.

These experimental results have been compared with the SUPERLAYER particle-simulation code (Pearlstein and co-workers, 1978; Simonen and co-workers, 1978). The experimental data for $B_{vac} = 0.435$ T are in reasonable agreement with the code predictions. The high-field data are below the code predictions presumably because these experiments are more strongly dominated by DCLC-mode wave diffusion.

LARGE-RADIUS EXPERIMENTS

To maintain marginal stability of the DCLC mode in 2XIIB, it was necessary to supply a warm streaming plasma as shown in Fig. 4. Energy exchange with the electrons of this unconfined stabilizing plasma reduced T_e and hence the energy-containment time of the mirror-trapped ions. The larger the plasma size R_p compared with the ion Larmor radius a_i, the smaller the fraction of warm to hot plasma necessary for DCLC stability.

Motivated by these theoretical ideas, we increased the radius of the 2XIIB plasma by aiming the neutral beams off axis and relocating the streaming plasma guns to larger radius. In these experiments, we found that the central electron temperature and ion energy confinement parameter increased as shown in Figs. 9 and 10. The large plasmas required only one-fourth the trapped neutral-beam power per unit volume that is needed in the small plasmas to produce the same central electron temperature. Measurements of the current of streaming plasma transmitted through the machine were found to be near the value predicted by the DCLC quasi-linear theory.

An objective of these experiments was to generate large-radius (R_p/a_i) high-beta plasma. In these experiments, we succeeded in producing a 14-cm-radius plasmas with a radius parameter $R_p/a_i = 6$ at a beta of 0.4. This beta was limited by the available neutral-beam current.

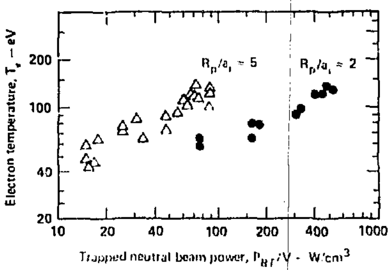

Figure 9. Central electron temperature vs trapped neutral-beam power. For a fixed neutral-beam power, the electron temperature was twice as large at R_p = 15 cm as at R_p = 5 cm.

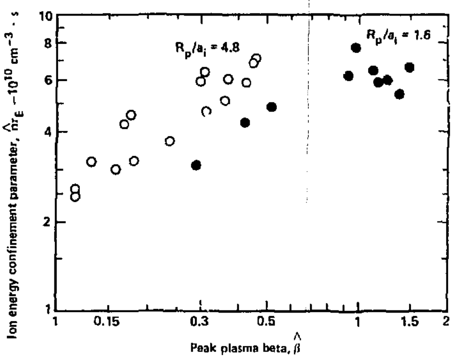

Fig. 10. Energy confinement parameter $n\tau_E$ for two plasma radii.

IMPURITY STUDIES

Mirror machines do not confine high-z impurities well because the impurities are expelled by the positive ambipolar potential. A study of impurities in 2XIIB included experiments in which small amounts of neon gas were puffed toward the plasma surface (Drake and Moos, 1979). The inward flux of neon ions Γ was determined from measurements of the ultraviolet brightness. Figure 11 shows that the flux decreased from one ionization state to the next. This indicates that ions were being lost in less time than is required for them to diffuse inward and ionize. These results show that the mirror machine acted as a diverter--the neon ions were expelled before they penetrated into the plasma.

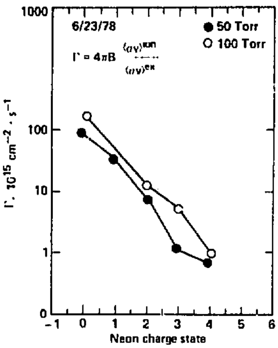

Fig. 11. The observed neon flux shows a sharp decline as charge state increases, indicating high-z impurities are expelled by the mirror plasma.

Studies showed that the concentration of natural impurities such as titanium, carbon, and nitrogen was about 0.4%. We found that the plasma contained a 3% concentration of oxygen that was introduced into the plasma at high energy from the neutral beams and was not expelled until the plasma cooled down. The power radiated by all these impurities was small compared to the power deposited by the neutral beams.

MFTF EXPERIMENTS

The resolution in 2XIIB of the principle issues for plasma confinement in minor systems (control of microinstability, scaling of $n\tau$ with ion energy, and energy startup in a steady-state magnetic field) together with the development of theoretically derived scaling laws which describe 2XIIB behavior provides a basis for the design of magnetic mirror reactor systems. However, the extrapolation to reactor systems is so large that an intermediate facility known as the Mirror Fusion Test Facility (MFTF) is being constructed at the Lawrence Livermore Laboratory (LLL). MFTF will provide a technology bridge between present experiments and experimental reactors, as well as provide a test bed for physics scaling laws. The desired objectives of MFTF are:

- A technological prototype of an experimental reactor.

- Early completion (1981-82) so that an experimental reactor could become operational in the late 1980's.

- $n\tau$ and β as large as possible to provide a convincing demonstration that mirror physics can be extrapolated to reactor conditions.

- Physical dimensions (L_p/a_i and R_p/a_i) large enough to test the theoretical scaling laws for all kinds of known instabilities.

Startup in MFTF is essentially that developed in 2XIIB; i.e., a fully ionized, low-energy, plasma stream injected along the magnetic axis forms a target for *buildup of an energetic plasma by ionizing beams of energetic neutral atoms that* are injected across the magnetic field. Twenty-four 20-keV, 10-ms beams like those used in 2XIIB are used to inject 1000 A for plasma buildup on the stream target. As in 2XIIB, following buildup, warm plasma generated by ionization of gas fed in at one magnetic mirror will replace the plasma stream. The plasma will be further heated and sustained for 0.5 s by means of twenty-four 80-keV beams delivering 7[illegible] atom amperes at the plasma.

The objectives, operating sequence, schedule, and cost constraint, largely deter[illegible] MFTF design. To meet schedule, Nb-Ti superconductor (requiring a minimum of development) is used in the steady-state magnet. This limits the field at the ma[illegible] to 7.5 T and, to accomodate a mirror ratio of $R_m = 2$ with adequate [illegible]am access, the central field is limited to 2.0 T. The length between mirrors L is chosen to provide adiabatic confinement of the high-energy tail of the ion distribution (several times T_i) and to provide an adequate test of scaling laws for the convective loss-cone mode. Both requirements depend on L/a_i and hence on the product BL and on B. The present design will accomodate T_i as great as 100 keV. To realize the increase in $n\tau$ expected from higher values of T_i, it is necessary to fill a large volume corresponding to larger R_p/a_i. In designing MFTF, the beam power was chosen to provide a density and plasma beta at the low end of the experimental reactor range and to increase $n\tau$ an order of magnitude beyond that in 2XIIB.

The most important scientific objective of MFTF is a better test of theoretical scaling laws for microinstabilities. Three types of instability are relevant:

- The DCLC mode, which occurs for small R_p/a_i;

- The convective loss-cone mode and negative energy wave, which occur for large L/a_i; and

- The Alfvén ion cyclotron (AIC) mode, which occurs at high β with anisotropic pressure ($p_\parallel << p_\perp$).

As discussed above, the DCLC mode has tended to dominate in 2XIIB. The beam system for MFTF is designed to sustain a 50-keV mean ion energy with $\beta = 0.5$ and $R_p/a_i = 13$. This radial dimension, although below the theoretical stability limit for the DCLC mode in the absence of stabilized warm plasma, reduces the required value of n_{warm}/n_{hot} by more than an order of magnitude below that required in 2XIIB, allowing T_e to rise to 1 keV and $(n\tau)_{drag}$ to rise to $10^{12} cm^{-3} \cdot s$. At $T_i = 50$ keV, ion-ion collisions limit $n\tau$ to approximately $2 \times 10^{12} cm^3 \cdot s$, so energy containment in MFTF is dominated by energy loss through electrons. Still larger values of R_p/a_i can be explored at the *sacrifice of plasma . Plasma radii up to* R_p/a_i = 50 *can be explored for* 10 ms, at T_i = 13 keV using only the startup beams.

The greatly weakened DCLC activity in MFTF and the large value of L/a_i compared to 2XIIB should permit a more definitive study of the stability boundaries for the convective loss-cone mode than has been possible. Although it was strongly suspected that the convective loss-cone mode dominated the low-energy (quiescent) runs in old 2XII experiments, the high-frequency plasma oscillations characteristic of this mode were never directly identified. In MFTF the possibility of exploring the convective loss-cone mode is enhanced over that for 2XII because we can increase its drive by increasing L/a_i and by reducing competing plasma losses.

As for the AIC mode, in MFTF we should be able to observe this mode and determine its consequences according to present theoretical predictions based on an infinite-medium model. However, at this time the AIC mode has not been identified in 2XIIB, although the same theory predicts it to occur there also. The origin of this discrepancy is being actively investigated, and there is some uncertainty as to what beta limitations might be encountered in MFTF. In any case, the capability in the absence of the mode to reach β = 0.5 in MFTF at R_p = 30 cm and large L should be adequate to provide conclusive data as theory develops.

As noted above, one of the objectives of MFTF is the development of technology that will provide a transition from the present small mirror experiments to large steady-state devices. Specific areas of concern that will be explored and developed in MFTF include:

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

- Control and reliable operation of both pulsed and continuous neutral beams that are necessary to start and sustain an appreciable volume of plasma at reactor energies. The control problem is not only augmented by increased numbers of beams but also by the increased complexity associated with higher-energy beams.

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

- Disposal with little (preferably no) backstreaming of either the intense flux of plasma particles emerging through the mirrors or the intense flux of energetic ions emerging from the neutralizer. There are similar problems for the fraction of the neutral beam that is not ionized in the plasma.

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

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

CONCLUSIONS

Plasmas near thermonuclear conditions have been produced in magnetic mirror machines. A number of concepts and technologies had to be developed before such plasmas could be produced. In this paper, we have described several of the fundamental mirror physics results that were demonstrated by the LLL 2XIIB experiment. Several experiments at other laboratories are underway to develop further understanding and to demonstrate improved stabilization and confinement techniques. A larger experiment, MFTF, is under construction at LLL to demonstrate confinement scaling to higher energies and larger plasma dimensions. A new thrust of mirror research is now being directed toward systems that utilize attributes of mirror confinement in reactor designs offering performance unachievable in single-cell-mirror devices. Experiments are underway in configurations such as tandem mirrors, field-reversed mirrors, and high-density multiple mirrors.

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