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NUCLEAR TESTING APPLICATIONS

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THE DEVELOPMENT OF MAGNETIC MIRROR SYSTEMS FOR
NUCLEAR TESTING APPLICATIONS*

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ABSTRACT

Several system studies have concluded that the small size and steady state nature of magnetic mirror systems provide attractive features for nuclear-testing applications. The principle shortcoming of mirror systems is their small data base relative to that of tokamaks. This paper summarizes the present data base and describes experiments that could be carried out with small modifications of existing facilities to explore plasma physics issues associated with the production of high neutron fluxes in magnetic mirror configurations. The experiments would demonstrate physics principles important to such future applications of fusion power neutrons as blanket testing, tritium production, fissile fuel production, or decontamination of high-level radioactive nuclear-reactor wastes.

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I. INTRODUCTION

The magnetic fusion program focuses on the development of a fusion reactor for central-station electric power generation. This focus places a premium on high plasma confinement. In this context, the tokamak concept is the furthest developed and therefore the leading candidate. For different applications other concepts may have advantages. For example, system studies have shown magnetic mirror systems to be well suited for nuclear-testing purposes. These studies have included the minimum-B mirror configuration [FERF (1)], conventional tandem-mirror configurations [original TDF (2), TASKA-M (3), and FEF (4)], as well as thermal-barrier tandem-mirror configurations [TASKA (5), TDF (6), and MFTF-B Upgrade (7)]. These magnetic mirror systems are attractive because they produce neutron wall loadings of 0.5 to 2.0 MW/m² in small size systems. Tokamak designs generally have lower wall loading and are larger in size. Because of the small size, capital costs and tritium consumption for magnetic-mirror systems are projected to be much less than those for tokamak designs. Even though the mirror system designs require from 150 to 250 MW of electrical power for production of about 10 MW of neutron power, the direct plant costs plus power costs integrated over a 10-year lifetime can still be less than the direct costs of tokamak designs (3).

Other applications besides nuclear testing of magnetic fusion blankets that utilize the unique features of fusion could play early roles in helping to develop fusion into a practical and reliable source of central-station electricity. Fusion, relative to fission, generates eight times more neutrons per unit plant heat capacity, has lower radioactivity, and is inherently safe (meltdown cannot occur). Therefore, fusion has qualitative advantages for

processes that require neutrons (8-10), such as tritium production, fissile fuel production, and decontamination of high-level radioactive nuclear wastes. For such applications, nonignited systems that can employ direct energy conversion (11,12) may have a role. Magnetic mirrors have this feature.

This report describes experiments to address key physics issues associated with the development of mirror systems for nuclear-testing applications. These experiments could be carried out with small modifications of existing facilities such as TMX-U and MFTF-B, employing their high-power neutral-beam injection systems to create dense hot-ion plasmas. Fusion power production levels of about 10 MW could be achieved in the MFTF-B Upgrade. Alternates, not described here, would employ neutral beams with one minimum-B end cell (1) or ion-cyclotron resonance heating (ICRH) [FEF (4)] in an axisymmetric geometry. In the single minimum-B cell system the neutron source would have an elliptical cross section, rather than a circular one better suited for blanket testing. The existing data base for axisymmetric systems is less than for minimum-B systems. However, the axisymmetric geometry has many conceptual advantages.

Experiments in 2XIIB (13), TMX (14), and TMX-U (15) have already addressed a number of plasma physics issues associated with these nuclear-testing or neutron-production applications even though they were not designed expressly for that purpose. A summary of the pertinent experimental results is given in Sec. II. In Sec. IV we outline possible modifications of the TMX-U and MFTF-B central cell to investigate physics issues associated with the goals outlined in Sec. III.

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II. DEVELOPMENT OF A NUCLEAR TECHNOLOGY DATA BASE FOR MAGNETIC MIRRORS

There are two modes of operation of present tandem mirror experiments: the thermal-barrier mode and the sloshing-ion mode. The first mode is best for efficient electric power production, whereas the second one is of interest for neutron production or hybrid reactor applications.

TMX-U was built to investigate the thermal-barrier configuration, so naturally TMX-U experiments have concentrated on the thermal-barrier mode. Although these experiments have successfully achieved the thermal-barrier configuration (16), operation to date has been limited to densities below 10^{13} cm^{-3} . Continuing TMX-U experiments have implemented various improvements that have increased the central-cell density from 1×10^{11} to $3 \times 10^{12} \text{ cm}^{-3}$. In the second mode, the sloshing-ion mode, TMX-U operates at densities near 10^{13} cm^{-3} .

The Japanese GAMMA-10 thermal-barrier tandem-mirror experiment (17) has reached a central-cell density of $3 \times 10^{12} \text{ cm}^{-3}$. A major difference between GAMMA-10 and TMX-U is the magnet geometry. The GAMMA-10 central cell and thermal-barrier end plug differ from those of TMX-U. The GAMMA-10 central cell is axisymmetrized like that of MFTF-B. The TARA experiment (18) at MIT incorporates the favorable magnetic geometry of GAMMA-10 in a possibly more attractive reactor magnetic configuration, but in a more risky MHD stable configuration.

TMX-U is well suited for high-density experiments because of its 5-MW neutral-beam power capability (see Table I). The motivation of such TMX-U experiments would be toward plasma physics associated with eventual blanket development, tritium and fissile fuel production, radioactive waste decontamination, or hybrid reactors. If these dense hot-ion TMX-U experiments

were successful, they could lead to a 40-MW MFTF-B D-D physics scaling demonstration followed by demonstration of neutron production in a D-T upgrade of MFTF-B (7) or in a new facility similar in size such as TASKA-M (3).

Even though TMX-U was designed for thermal barrier operation, it is easier to produce high-density sloshing-ion plasmas than to produce thermal-barrier plasmas. In fact, TMX-U experimentalists often use this mode to condition the machine and test diagnostics because it does not require the very fine adjustments of the thermal-barrier mode. Based on this experience, the modifications of TMX-U to optimize the hot-ion neutron-production mode are apparent. These modifications include (1) adding small high-field 6-T magnets [constructed for the throttle coil mode (19)] to make a smaller, higher-field, axisymmetric central-cell plasma; (2) repositioning several 20-keV deuterium neutral-beam injectors to increase the central-cell injection power from 1.2 to 3.2 MW; (3) moving the fundamental-frequency 28-GHz microwave electron-heating system from the end plugs to the transition regions; (4) removing the central-cell radio-frequency heating system; (5) relocating the gas fueling to the transition regions away from the hot neutral-beam injected ions; and (6) removal of central-cell midplane limiter. Based on past experience these modifications could be accomplished in about six months.

The purpose of the TMX-U experiments would be to address specific physics issues as well as to achieve parameter goals that would strengthen the data for application of magnetic mirrors for neutron testing. TMX-U results would provide confidence in a next-step MFTF-B experiment, with 8 times higher neutral-beam power (40 MW). Three key physics issues are

1. Microstability of beam injected ions. To date results from TMX-U are very encouraging, but higher ion densities are needed for neutron-production applications.
2. MHD stability of the central cell. Theory predicts that certain trapped-particle modes may develop although TMX-U results are encouraging with central-cell beam injection.
3. Electron heat leakage must be limited. For future applications it will be necessary that the electron temperature reach 5% of the mean energy of the ions injected by neutral beams.

Parameter goals of the TMX-U central cell plasmas are listed in Table II. With the higher central-cell beam power, the smaller central-cell volume, and the higher magnetic fields (the beam power density is 50 times higher), the ion density and temperature of the dense hot-ion mode are both projected to be double those projected for the thermal-barrier mode. The electron temperatures would be equal. This mode would operate at a density several times higher than possible with the thermal-barrier mode.

The TMX-U hot-ion experiment is simpler than TMX-U operation in the thermal-barrier mode. The simplicity arises from not needing ion-cyclotron resonant heating and using electron-cyclotron resonant heating (ECRH) for auxiliary electron heating rather than for thermal-barrier formation. Hot electrons are present only to aid MHD stability. The emphasis will be on neutral-beam heating.

Follow-up experiments could be carried out in MFTF-B. The dense hot-ion mode would require relocating the small 12-T high-field magnets closer together (about 5 m apart rather than 20 m), an arrangement similar to that

planned for MFTF-B Upgrade. These MFTF-B experiments would then extend the TMX-U results with 5 MW of 20-keV beam injection to 40 MW of 80-keV beam injection. These experiments would reconfirm at higher densities and temperatures the key issues of high frequency microstability, low frequency MHD stability, and increased electron temperature. The operating parameters for this D-D operation would nearly equal those planned for the next step D-T demonstration.

For D-T operation and blanket testing a substantial upgrade of MFTF-B would be required (7). Besides making possible blanket testing at reactor-level neutron fluxes, the upgrade would also permit demonstration over a period of years of several production capabilities: (1) production of 1 kg of tritium; (2) production of 1 ton of nuclear reactor fuel; and (3) decontamination of 1 ton of high level nuclear reactor radioactive waste by transmutation.

III. SUMMARY OF PREVIOUS HIGH-DENSITY HOT-ION MIRROR EXPERIMENTS

In this section we review results from previous mirror experiments related to neutron-production applications. These experiments have been carried out with neutral-beam injection in minimum-B mirrors and with central-cell neutral-beam injection in tandem mirrors.

III.A. SINGLE-CELL MIRROR EXPERIMENTS

The 2XIIB minimum-B mirror experiment (13) was the hottest and densest mirror produced plasma (10-keV ion energy and 10^{14} cm^{-3} density). The scaling of plasma density as a function of neutral-beam current is shown in Fig. 1.

The neutral-beam injection was at 90° to the magnetic field lines. As a result the plasma was subject to the drift cyclotron loss cone instability (20), which required an additional source of plasma for ion microstability. This plasma, flowing from the end walls, kept the electron temperature below 140 eV. As a result the maximum ion-energy confinement product was $3 \times 10^{10} \text{ cm}^{-3} \text{ s}$. However, because of the small plasma volume (5 liter), betas that were locally as high as 2 were achieved.

III.B. END-PLUG TANDEM MIRROR EXPERIMENTS

End-plug experiments were carried out in the TMX tandem-mirror experiment (14). In the tandem-mirror configuration, the additional plasma for DCLC microstability was supplied by the central cell with consequently less heat leakage to the end walls so electron temperatures of 270 eV were achieved (double the best achieved in 2XIIB). Again, the neutral-beam injection was at 90° to the magnetic field lines. In this case the anisotropy-driven Alfvén ion-cyclotron mode (21) was driven unstable and provided a limitation on performance not experienced in subsequent TMX-U experiments.

The first TMX-U experiments were with 47° neutral-beam injection into the 4:1 mirror-ratio minimum-B end cells (22-24). For the first time, in a beam-driven mirror machine, the plasma in these experiments was not dominated by ion-cyclotron fluctuations. This remarkable result was attributed to improved DCLC stability and AIC stability due to sloshing ions. The sloshing-ion density was about $3 \times 10^{12} \text{ cm}^{-3}$ at the midplane and $6 \times 10^{12} \text{ cm}^{-3}$ at the turning points. The results of these experiments were explained with a Fokker-Planck code as shown in Fig. 2. The 3-ms hot-ion lifetime was accounted for by charge exchange (primarily in the thin elliptical fans) and

by electron drag. Shown in Fig. 3 is the scaling of plug sloshing-ion density with neutral-beam current.

III.C. CENTRAL-CELL TANDEM-MIRROR EXPERIMENTS

TMX-U experiments with central-cell neutral-beam injection have produced central-cell plasmas with $6 \times 10^{12} \text{ cm}^{-3}$ density, 2-keV mean ion energy, 150-eV electron temperature, and 5.3% volume-average beta (14% on axis). These experiments are discussed in more detail in Ref. (16). Variations of parameters with central-cell gas-feed rates are shown in Fig. 4. Results of experiments at 120 Torr·L/s have been compared with a radial Fokker-Planck code (25) calculations in Table III. The agreement between measured and calculated radial profiles shown in Fig. 5 suggests that the dominant processes are being accounted for. However, the measured ion end-loss energy is higher than calculated suggesting the presence of some additional processes.

IV. PROPOSED HIGH-DENSITY HOT-ION TMX-U CENTRAL-CELL EXPERIMENTS

The objective of the proposed experiments is to increase the central-cell density to about $4 \times 10^{13} \text{ cm}^{-3}$. In a proposed TMX-U experiment, the injected central-cell beam current would be increased from 100 to 270 atom amperes and the mirror-to-mirror length decreased from 8 m to 2 m. This would increase the delivered beam current per unit length by an order of magnitude. In addition, the 90° central-cell neutral beams would be injected at a 2.5:1 mirror ratio to form a sloshing ion distribution for increased microstability.

The main modification to TMX-U would be the insertion of two small 6-T magnets into the central cell. These magnets were constructed for use in the thermal-barrier throttle-coil configuration (19). The axial magnetic field profile with these coils inserted is shown in Fig. 5. An expanded profile is shown in Fig. 7. The hot-ion lifetime in previous TMX-U experiments was limited by charge exchange and electron drag as shown in Fig. 8. To increase the hot-ion lifetime, we will reduce charge exchange by moving the gas feed from the central cell to the transition and by increasing the magnetic field to decrease the ion gyro radius. To reduce electron drag, we will increase T_{ec} with additional neutral beam heating and auxiliary 28-GHz fundamental-frequency ECRH electron heating in the transition region. We estimate here that T_{ec} would reach 350 eV for the end-loss currents measured in previous TMX-U operation.

IV.A. MAGNETIC GEOMETRY

The 6-T magnets introduce several important features:

1. Decreased effective $(B_0 \int dl/E)$ central-cell length (150 cm vs 500 cm). The resulting smaller volume allows higher densities to be achieved with a given neutral-beam injection current.

2. Increased magnetic field strength (0.8 vs 0.3 T) confines high-density hot-ion plasma with 7% average beta. The higher field also decreases the gyro radius of the 20-keV beam injected ions (from 10 cm to 3.5 cm). The hot ions in the plasma core are thereby better localized away from the plasma edge where cold-gas charge-exchange losses are prevalent.
3. The transition region, separated by the 6-T axicoil and the 2-T cee-coil, provides a location for gas puffing well isolated from the central cell and end-cell sloshing ions. This will reduce hot-ion charge-exchange losses and provide plasma connecting the central cell to the end plug for MHD stability.
4. Neutral beam injection on the rising magnetic field results in a sloshing-ion distribution to enhance ion-cyclotron microstability.
5. The optional 1.0-T plateau (shown dotted in Fig. 6), produced by an additional solenoid, provides a region of uniform magnetic field for 28-GHz fundamental-frequency auxiliary electron heating.
6. Particle orbits in the transition region are satisfactory (26). Without electric fields the orbits are unconfined if the ratio of perpendicular to parallel energy is between 0.7 to 1.0. However, 200-volt potentials produce adequately small elliptical distortions for all pitch angles of particles with energy less than 1 keV.

IV.B. MHD STABILITY

The MHD beta limits are shown in Fig. 9. Here the maximum central-cell beta β_c is shown as a function of the anchor beta β_A for flute and rigid modes (27). Curves are shown corresponding to 0 or 0.4% beta in the transition. The 0.4% beta case corresponds to a transition density of $6 \times 10^{12} \text{ cm}^{-3}$ (equal to the plug density) with electron and ion temperatures of 0.35 keV. To determine a possible operating point we determine the anchor beta, based on already achieved TMX-U end-cell anchor-beta values.

Previous TMX-U experiments have achieved sloshing-ion densities of $3 \times 10^{12} \text{ cm}^{-3}$ with 7-keV average ion energy. This translates into a 5% ion beta at the 0.5-T end-cell midplane. Previous TMX-U experiments have achieved an average hot-electron beta of 16% (approximately $1 \times 10^{12} \text{ cm}^{-3}$ density and 200-keV average energy). This is the highest hot-electron beta produced in TMX-U. The effective anchor beta for this case is

$$\beta_{\text{anchor}} = \beta_{\text{eh}} \frac{\beta_{\text{si}}}{\beta_{\text{si}} + 2r/R} ,$$

where R is the radius of curvature of the field line at radius r. For the TMX-U end plugs, $2r/R = 2 \times 10/1000 = 0.02$. In this case,

$$\beta_{\text{anchor}} = 0.15 \frac{0.05}{0.05 + 0.02} = 0.11 .$$

Operating points for 5% beta (for sloshing ions) and 11% (for hot electrons) shown in Fig. 7 correspond to maximum MHD stable central cell beta values of 3% and 6%. For 7-keV central-cell ion energies these betas translate into a hot-ion density of

$$n^{13} = \frac{\beta B_T^2}{0.004 \times T_1} = \frac{(0.03 \text{ or } 0.06)(0.825)^2}{0.004 \times 7} = 0.75 \text{ or } 1.5 .$$

The on-axis density would be twice as high,

$$\hat{n}_c = 1.5 \text{ or } 3 \times 10^{13} \text{ cm}^{-3} .$$

For sloshing ions in a 2:1 mirror ratio the hot-ion density at the turning point $\hat{n}_c^{\text{max}}$ is about two times higher

$$\hat{n}_c^{\text{max}} = 3 \text{ or } 6 \times 10^{13} \text{ cm}^{-3} .$$

Because the 15% average hot-electron beta is the best ever achieved in TMX-U we derate the central cell beta to ensure MHD stability with hot-electron betas, which can be produced on a routine basis. Therefore, in further calculations we select a design point hot-ion central-cell density of $4 \times 10^{13} \text{ cm}^{-3}$, although somewhat higher densities might be possible. If, however, hot-electron beta is not effective for stabilization, as may be indicated by the TARA experiment (28), then this value is 33% too high.

IV.C. REQUIRED CENTRAL-CELL NEUTRAL-BEAM CURRENT TO SUSTAIN

$4 \times 10^{13} \text{ cm}^{-3}$ DENSITY

Here we estimate the neutral-beam current required to sustain an on-axis density of $4 \times 10^{13} \text{ cm}^{-3}$ against Coulomb scattering. We consider on axis to be a 5-cm-radius core. We solve the density build up equation

$$\frac{dn}{dt} = \frac{I_b}{eV_{core}} (1 - \exp - (\sigma_1 + \sigma_x)(fndl)) \frac{\sigma_1}{\sigma_1 + \sigma_x} - \frac{n^2}{n\tau} .$$

Taking $\sigma_1 = 3 \times 10^{-16} \text{ cm}^2$, $n\tau = 1.5 \times 10^{11} \text{ cm}^{-3}\text{s}$,

$$V_{core} = \pi(5)^2 150 = 1.2 \times 10^4 \text{ cm}^3 ,$$

$$fdl = 2 \times 5/\sqrt{2} = 7 \text{ cm} ,$$

$$I_b = \frac{en^2 V_{core}}{n\tau \sigma_1 fndl} = \frac{(4 \times 10^{13} \text{ cm}^{-3})^2}{1.5 \times 10^{11} \text{ cm}^{-3}\text{s}} \frac{1.2 \times 10^4 \text{ cm}^3 \times 1.6 \times 10^{-19} \text{ C}}{3 \times 10^{-16} \text{ cm}^2 \times 10/\sqrt{2} \text{ cm} \times 4 \times 10^{13} \text{ cm}^{-3}} ,$$

= 240 A .

To provide this beam current one could employ 16 neutral-beam injectors that will deliver 270 A at full performance.

In the above estimate we used $n\tau = 1.5 \times 10^{11} \text{ cm}^{-3}\text{s}$. This value is half that of ion-ion scattering ($3 \times 10^{11} \text{ cm}^{-3}$) and half that of electron drag at $T_{ec} = 350 \text{ eV}$. This calculation thus allows only little degradation in ion-ion scattering due to low-level ion-cyclotron fluctuations. We could achieve higher densities and electron temperatures if the sloshing-ion end plugs sustained without gas feed. However, this has never occurred in past TMX-U experiments.

IV.D. AUXILIARY ELECTRON HEATING

Auxiliary electron heating may be employed to increase the electron temperature and thereby reduce electron cooling of the hot ions. Here we estimate the auxiliary electron heating power required to achieve $T_e = 350$ keV. For electron temperatures below this value electron drag will dominate the hot ion energy loss.

The electron power balance equation is

$$\frac{dT_{ec}}{dt} = \frac{n_e n_{i_{hot}} W_{i_{hot}} V_{hot}}{n_e \tau_{drag}} + P_{aux} - j_{||} \phi_e \pi r_c^2.$$

Here $n_{i_{hot}}$, $W_{i_{hot}}$, and V_{hot} are the hot-ion density, energy, and volume. The hot ions are assumed to fill out to half the limiter radius so that their volume is $\pi(r_c/2)^2 L_c = \pi(15/2)^2 (180) = 3 \times 10^4 \text{ cm}^3$. The electron density is n_e and the auxiliary electron heating power is P_{aux} . The end loss power is calculated from $j_{||}$ (the end-loss current density), the plasma radius, r_c , and the central-cell potential, ϕ_e . For $j_{||} \pi r_c^2$ we take the 100-A current required in past TMX-U experiments to support the required end-cell sloshing-ion density of $3 \times 10^{12} \text{ cm}^{-3}$. We take $\phi_e = 10 T_{eV}$. Now solving the power balance equation

$$P_{aux}^{Watts} + \frac{(4 \times 10^{13})^2 (7 \times 10^3) (1.6 \times 10^{-19}) 3 \times 10^4}{4.4 \times 10^7 T_{eV}^{3/2}} = 100 \times 10 T_{eV},$$

or

$$P_{aux}^{kW} + \frac{1.3 \times 10^6}{T_{eV}^{3/2}} = T_{eV}.$$

For $T_{ev} = 350$ eV we find $P_{aux}^{kW} = 350 - 200 = 150$ kW. To supply this power we would employ three 200-kW, 28-GHz gyrotrons heating in the transition region. The three gyrotrons would deliver 300 kW to the plasma. Using the magnetic plateau (dashed line on Fig. 6) we anticipate 50% heating efficiency (150 kW absorbed). Without a plateau, fundamental heating in the TMX-U end plugs has a lower efficiency.

IV.E. VACUUM REQUIREMENTS

IV.E.1. End-Cell Vacuum

Charge-exchange loss of the end-cell sloshing ions is an important process. We have not assumed any increase in the end-cell sloshing-ion density above that already achieved ($6 \times 10^{12} \text{ cm}^{-3}$ at the turning point). The proposed experiment thus assumes that the end-cell vacuum conditions will be the same as those already achieved in past TMX-U experiments. Therefore, careful wall conditioning and gettering are required as in past TMX-U experiments.

IV.E.2. Central Cell Vacuum

For these experiments, it is also very important to keep the neutral density low in the central-cell region. In past experiments, high central-cell gas pressures were present near the gas box and the beam-injected ions reached near the gas box. Figure 10 shows that neutral densities at the edge of the plasma near the gas box were up to $7 \times 10^{11} \text{ cm}^{-3}$ (2×10^{-5} Torr). In the proposed experiment we expect to reduce this component by an order of

magnitude by locating the gas box in the transition region. There will be no limiting apertures in the central cell other than the 6-T magnets themselves. This should increase the hot-ion cold-gas charge-exchange time due to gas puffing to 50 ms. In this case, the primary source of neutrals will be beam-induced charge-exchange wall reflux calculated below.

The beam-induced charge-exchange current is

$$\begin{aligned}
 I_{\text{ox}} &= I_b [1 - \exp(-(\sigma_1 + \sigma_x)(fndl))] \frac{\sigma_x}{\sigma_1 + \sigma_x} , \\
 &= 280 \text{ A} \left[1 - \exp\left(1.6 \times 10^{-15} \times 4 \times 10^{13} \times \frac{4}{3} \frac{15}{\sqrt{2}}\right) \right] \frac{1.3}{1.6} , \\
 &= 280 (1 - e^{-0.9}) \frac{1.3}{1.6} = 136 \text{ A} = 12 \text{ Torr}\cdot\text{L/s} .
 \end{aligned}$$

The plasma pumping speed is

$$\begin{aligned}
 S_p &= \frac{(1/4) n_0 v_0 A e / 11.3}{p} = \frac{1/4 \times 3 \times 10^{16} \times 10^5 (2\pi) \times 15 \times 200 \times 1.6 \times 10^{-19}}{11.3} , \\
 &= 2 \times 10^5 \text{ L/s} .
 \end{aligned}$$

The conductance to the disc liner region is

$$\begin{aligned}
 C_{\text{pd}} &= \frac{(1/4) n_0 v_0 A e}{p \times 11.3} = (1/4) \times 3 \times 10^{16} \times 10^5 \times \frac{60 \times 4 \times 100 \times 1.6 \times 10^{-19}}{11.3} , \\
 &= 2.5 \times 10^5 \text{ L/s} .
 \end{aligned}$$

Therefore, the total central-cell pumping speed is

$$S_p + C_{pd} = 4.5 \times 10^5 \text{ L/s} .$$

The TMX-U disc-region pumping speed is also $2.5 \times 10^5 \text{ L/s}$. Thus, the disc liner region of the central-cell midplane plays an important role in these experiments. It provides a large 5.4-m^3 ballast volume and provides a pumping speed equal to the plasma pumping speed.

The expected background pressure is then

$$p = \frac{12 \text{ Torr}\cdot\text{L/s}}{4.5 \times 10^5 \text{ L/s}} = 2.6 \times 10^{-5} \text{ Torr} ,$$

$$n_{\text{gas}} = 8 \times 10^{11} \text{ cm}^{-3} .$$

The neutral attenuation to $r = r_c/2$ would then be (29)

$$\text{Attn} = 50 \frac{\int n dl}{10^{13}} = 50 \times \frac{4 \times 10^{13} \times 5}{10^{13}} = 1000 .$$

In this case

$$n_0 = \frac{n_{\text{gas}}}{\text{Attn}} = \frac{8 \times 10^{11}}{10^3} = 8 \times 10^8 \text{ cm}^{-3} .$$

The resultant core charge-exchange time would be

$$\tau_{x0}^{\text{core}} = \frac{1}{10^{-7} n_0} = 10 \text{ ms} .$$

This time exceeds the core beam-driven charge-exchange time

$$\begin{aligned} \tau_{xb}^{core} &= \frac{en V_{core}}{I_{xb}^{core}} \\ &= \frac{1.6 \times 10^{-19} \times 4 \times 10^{13} \pi \times 5^2 \times 200}{280 \frac{1.3}{1.6} (1 - e^{-1.6 \times 10^{-15} \frac{2}{3} 15 \times 4 \times 10^{13}}) \times 1.6 \times 10^{-15} \times 10 \times 4 \times 10^{13}} \\ &= \frac{6.4 \times 5\pi \times 10^{-3}}{227 (0.47) (0.4)} = 2.3 \text{ ms} \end{aligned}$$

Thus, the central-cell plasma is sufficiently burned out that it is not charge-exchange dominated.

IV.F. RADIAL FOKKER-PLANCK CODE MODELING

The radial Fokker-Planck code (25) has been used to model the plasma buildup in the proposed high-density hot-ion experiments in TMX-U. For these calculations, a three component beam of neutral deuterium atoms is injected into an initial background plasma having a density of $4 \times 10^{12} \text{ cm}^{-3}$. The plasma has a midplane-to-mirror length of 100 cm and a radius of 15 cm. The three components of the neutral beam have energies of 16 keV, 8 keV, and 5.3 keV, respectively. The flux of incident neutral gas is modeled as Franck-Condon atoms incident on a plasma surface area of $1.7 \times 10^4 \text{ cm}^2$. In these calculations the neutral beam current was taken to be 170 and 270 amperes and the equivalent current of Franck-Condon atoms was 150 atom amperes. Anomalous loss rates due to instabilities are neglected.

The results of these calculations, which are summarized in Fig. 11 and Table IV, show that plasmas with 7-keV ion energy and densities of 10^{14} ions/cm³ are achievable in the modified TMX-U experiment in the absence of MHD beta limits or microinstabilities. In Table IV, two lifetimes are given. The smaller lifetime is the plasma lifetime on axis, and the longer lifetime is a global lifetime determined by dividing the total particle density by the total current trapped by the plasma. The lifetime on axis is much smaller than the global lifetime because charge-exchange-driven radial transport results in a rapid loss of particles from the plasma center. This charge-exchange-driven radial loss rate averages to zero over the total plasma volume. The central-cell beta (for 10^{14} cm⁻³ density, 7-keV ion energy, and 0.5-keV electron temperature) would be 46%, well above the limit indicated in Fig. 9. This calculation thus indicates that the beam current and vacuum are more than adequate to reach the densities of 3 to 6×10^{13} cm⁻³ estimated in Sec. V.B and therefore this experiment is well equipped to test MHD beta limits. Electron temperatures of 400 eV are predicted. The radial profiles of density and electron temperature are shown in Fig. 11 at different times.

V. SUMMARY

In this paper we reviewed the parameters achieved in magnetic mirror experiments and described experiments that could bridge the gap between the achieved parameters and those needed for nuclear-testing applications. These parameters are summarized in Table V. In comparing 2XIIB with MFTF-B Upgrade the density and ion energy are low by only a factor of 4. However, because of DCLC microinstabilities the electron temperature and consequently the energy confinement is much lower. The objective of intermediate experiments such as

modified operation of TMX-U and MFTF-B would be to progressively close this gap while maintaining ion cyclotron microstability.

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Table I. Operating tandem-mirror neutral-beam capabilities.

Facility	Location	Injection power (MW)
TMX-U	LLNL	5.0 ^a
GAMMA-10	Japan	1.8
TARA	MIT	1.5
AMBAL	USSR	1.0
Phaedrus	U. Wisc.	0.7

^aCan be increased to 10 MW for 10-to-20-ms pulse duration with accelerators modified to earlier 2XIIB style.

Table II. TMX-U central-cell parameters.

Parameter	High density (projected)	Hot-ion mode (achieved)	<u>Thermal-barrier mode</u>	
			(projected)	(achieved)
$n_0 (10^{13} \text{ cm}^{-3})$	4	0.6	2	0.14
$E_i (\text{keV})$	5	2.0	2	0.2
$T_{ea} (\text{keV})$	0.35	0.29	0.35	-
Volume (L)	20	400	400	400
$P_{\text{beam}} (\text{MW})$	3.2	1.2	1.2	1.2
Beam power density (kW/L)	160	3	3	3

Table III. Comparison of radial Fokker-Planck code with experiment.

Parameter	Code	Experiment
$\int nd\ell$ (ions/cm ²)	2.6×10^{14}	2.4×10^{14}
n (ions/cm ³)	6×10^{12}	6×10^{12}
E^+ (keV)	1.5	2.1
T_e (eV)	263	182 ± 52
Hct ion radius (cm)	11	10.5
Ion loss energy (eV)	63	400
τ_E (ms)	4.7	7.8
τ_p (ms)	1.4	2.0
I_{gas} (A) ^a	900	-
I_{beams} (atom A)	160	160
ϕ_{ec} (kV)	1.17	-
β ($r = 0$)	0.12	0.14

^aTotal atomic gas deposited in plasma by ionization and charge exchange; incident gas estimated to be ~4500 A.

Table IV. Fokker-Planck modeling of high-density hot-ion experiments in TMX-U.

Beam current (A)	Thermal gas (A)	Equilibrium parameters on axis				Global ion lifetime (ms)
		Ion density (10^{14} cm $^{-3}$)	Mean ion (keV)	Electron temperature (eV)	Ion lifetime (ms)	
270	150	1.5	7.6	530	0.70	3.7
170	150	0.9	6.1	409	0.36	2.6

Table V. Parameters of magnetic-mirror fusion experiments relating to nuclear-testing applications.

	<u>Measured parameters</u>		<u>Projected parameters</u>			
	2XIIB	TMX-U	TMX-U modified	MFTF-B 0.5 s	MFTF-B Upgrade	TASKA-M
Plasma density (10^{20} m^{-3})	1.0	0.06	0.4	0.3	4.6	3.3
Mean hot-ion energy (keV)	12	2.0	5.0	20	49	84
Electron temperature (keV)	0.14	0.29	0.35	2	6	14
Neutral-beam power (MW)	5.0	3	3	40	23	21
Energy confinement, $n\tau_E$ ($10^{18} \text{ m}^{-3} \text{ s}$)	0.03	0.02	0.15	1.0	16	10

FIGURE CAPTIONS

Figure 1. Scaling of (a) plasma line density and (b) plasma radius with neutral-beam current. An on-axis density of $1 \times 10^{14} \text{ cm}^{-3}$ corresponds to a line density of 1.3×10^{15} and a 7-cm radius. (From Ref. 13.)

Figure 2. Measurements of the (a) charge-exchange angular distribution in arbitrary units and (b) diamagnetic axial distribution. Both measurements are described by an ion Fokker-Planck code. Measurements are by T. Orzechowski and W. E. Nexsen (24).

Figure 3. Scaling of (a) sloshing-ion density [$n_{s1}(b)$] and (b) end-cell density [$n_e(b)$] as a function of the injected deuterium atom current (I_{sb}). Both densities are at the end-cell midplane, denoted by $z = b$.

Figure 4. (a) Central-cell density, (b) central-cell diamagnetism, and (c) electron temperature vs central-cell gas fueling. Measurements are by R. K. Goodman and J. H. Foote (16).

Figure 5. (a) Measured and calculated hot-ion signal vs radius. Calculations are radial Fokker Planck (26) and hot ion measurements are by A. W. Molvik (16). (b) Line density vs the displacement from the plasma center. Line density measurements are by J. H. Foote (16).

Figure 6. Axial magnetic-field profile for a possible modification of TMX-U.

Figure 7. Enlarged view of central-cell magnetic-field profile shown in

Fig. 6. R is the mirror ratio.

Figure 8. Energy confinement time (τ_E) vs central-cell gas feed rate (Torr·L/s). Shown are the measured diamagnetic decay time constant (τ_{DML}), calculated electron drag time (τ_{drag}), and calculated charge-exchange time (τ_{cx}). The combination of drag and charge exchange to $1/\tau_{total} = 1/\tau_{drag} + 1/\tau_{cx}$ is also shown to be close to the measured times.

Figure 9. Stability boundaries for the magnetic-field profile shown in Fig. 6. Shown are boundaries for rigid and flute modes and boundaries without and with 0.4% beta in the transition region.

Figure 10. Neutral gas density, n_0 , (cm^{-3}) vs central-cell gas feed rate. The curve labeled n_{gas} is from ionization gauge measurements by W. C. Pickles (16).

Figure 11. Radial Fokker-Planck code calculations of (a) central-cell ion density, n_e , and (b) electron temperature, T_e , for TMX-U experiments with 170 atom amperes of 20-keV neutral-beam injection.