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MASTER

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FIELD-REVERSAL EXPERIMENTS IN THE MIRROR FUSION TEST FACILITY (MFTF)

ABSTRACT

We have begun detailed consideration of several aspects of a field-reversal experiment in the Mirror Fusion Test Facility (MFTF): Model calculations have provided some plausible parameters for a field-reversed deuterium plasma in the MFTF, and a buildup calculation indicates that the MFTF neutral-beam system is marginally sufficient to achieve field reversal by neutral injection alone. However, the many uncertainties indicate the need for further research and development on alternate buildup methods. A discussion of experimental objectives is presented and important diagnostics are listed. The range of parameter space accessible with the MFTF magnet design is explored, and we find that with proper aiming of the neutral beams, meaningful experiments can be performed to advance towards these objectives. Finally, we point out that if we achieve enhanced $n\tau$ confinement by means of field reversal, then quasi-steady-state operation of MFTF is conceivable.

INTRODUCTION

In this report, we describe the preliminary formulation of plans for experiments on field reversal in the Mirror Fusion Test Facility (MFTF). This large facility is scheduled to be brought on-line in 1981,^{1,2} and conventional mirror experiments are planned for the initial operations.³ Early on, however, perhaps as soon as 1982, field-reversed mirror experiments are desirable because of the attractive possibilities offered by field-reversed mirror (FRM) reactors.^{4,5}

Our first step in this report is a survey of possible field-reversed configurations in the present MFTF design. For this purpose, we use the same calculational model that was developed in the reactor studies^{4,6} and find some useful possibilities. Secondly, we examine the neutral-beam capability for buildup of such configurations and find that it is only marginally sufficient. Further knowledge, both theoretical and experimental, is needed to clarify this buildup problem.

For both steady-state and buildup conditions, we list a number of physics questions that must be ad-

dressed by experiment. One of the most important of these, the stability question, depends on the shape of the magnetic field. We compare the magnetic field of the present MFTF magnet design with the 2XIIB field and with the fields in recent experiments to determine the stability of relativistic electron rings⁷; we find roughly the same range of quadrupole field strengths in the three cases. 2XIIB experiments in progress are thus directly relevant to similar MFTF experiments and may provide the data needed to evaluate the effect of the MFTF quadrupole field component on MFTF field-reversal experiments.

This report is obviously only a "first cut," since both relevant theory and experiments are in preliminary stages of development. The final section describes some implications for MFTF operations, if a successful field-reversed plasma with high plasma containment $n\tau$ can be achieved. We find that quasi-steady-state operation might be possible and that it could provide information which could be extrapolated to designs for FRM reactors.

It should be immediately pointed out that the beam current required for this model is much lower than that needed for a conventional mirror plasma. The reason is that the field-reversed model has a longer particle escape time. (If it didn't, there would be no reason to reverse the field.) The implications of this difference will be discussed later. Other consequences of the longer particle escape time are that the ratio of ion energy to neutral-beam energy E_i/E_B is lower than for a conventional mirror plasma, and the electron energy E_e is higher.

The specified MFTF beam-extraction potential is 80 kV. For the field-reversed case, the computed overall plasma dimensions using 80-kV beams are a little smaller than the conventional mirror plasma defined for the first MFTF experiment. In particular, the 23.6-cm plasma radius and the 10.7-kG vacuum field are both clearly compatible with the MFTF design parameters.¹⁻³

In the second set of computer runs, we ask what the field-reversed plasma conditions will be using the 80-keV beam energy and a fixed geometry corresponding to a fixed neutral-beam alignment. We were guided by scaling laws⁸ derived from the computer model equations⁶ under the assumption that $T_i \propto E_B$ and $T_e \propto E_B$:

$$S \equiv \frac{a}{\rho_i} \propto \frac{aB_0}{E_B^{1/2}}, \quad (9)$$

$$n_0 \propto \frac{\beta B_0^2}{E_B}, \quad (10)$$

$$\tau \propto a^2 B_0^2 E_B^{1/2}, \quad (11)$$

$$M \propto \beta B_0^2 \frac{\langle \sigma \rangle}{E_B}, \quad \text{and} \quad (12)$$

$$(1 - e^{-2M}) I_B \propto a \left(\frac{R}{a} \right) \left(\frac{L}{a} \right) \beta^2 \frac{B_0^2}{E_B^{5/2}}, \quad (13)$$

where $S = a/\rho_i$, $\langle \sigma \rangle$ is the mean ionization cross section of the beam, and the other quantities are as defined above. In the first computer calculations (Fig. 1), β , S , and M are held fixed and the other parameters are allowed to vary as a function of E_B . In the second set of runs, E_B is fixed and β , S , and M are the independent variables. Each combination of β , S , and M is chosen so as to hold the geometry constant (minor radius a is held constant, and the shape is fixed as before). The two sets of computer runs overlap at the values $E_B = 80$ kV, $B = 10.7$ kG.

Figure 2 shows the results of the second set of computer runs; they agree well with the scaling laws [Eqs. (9) through (13)]. We find that the higher field capability of the MFTF allows one to explore the possibilities of field-reversed plasmas that are many Larmor radii in diameter (see the R_p/ρ_i vs B curve). The scaling law predicts an $n\tau$ exceeding 5×10^{13} near $B = 20$ kG. However, the plasma absorption efficiency η is so high in this case that shielding of the inner regions by the outer plasma may prevent the plasma doughnut from reaching the "fat" shape that was assumed.

Table 1 is a summary of the plasma parameters calculated by this model for three cases.* The parameter I_{BTP} is of interest to the buildup calculations; it represents the total charge injection required to suddenly produce this equilibrium state. The values for $n\tau_p$ are admittedly optimistic; they are based on the assumption that there is no additional plasma on the open field lines and on the diffusion parameter assumptions of Eq. (8). The Larmor radius ρ_i of a deuterium ion is given in the code calculations by

$$\rho_i = 0.2T_i^{1/2}/B, \quad (14)$$

Table 1. Three computed steady-state models for $E_B = 80$ kV, $(R/a) = 2$, $(L/R) = 3$, and tangential injection into D_2 plasma.

Parameter	A	B	C
β	1.5	1.5	2.0
$S = a/\rho_i$	3.	4.24	4.24
M	1.0	2.0	2.67
B (kG)	10.7	15.7	15.7
I_B (A)	22.0 ^a	30.3 ^a	48.8 ^a
P_B (MW)	1.76 ^a	2.42 ^a	3.90 ^a
P_{in} (MW)	1.00	1.89	3.55
E_i (keV)	26.7	27.3	27.3
E_e (keV)	9.7	11.6	11.5
n (10^{14} cm ⁻³)	1.68	3.53	4.72
τ_p (s)	0.103	0.092	0.069
a (cm)	7.86	7.44	7.42
$R_p = R + a = 3a$ (cm)	23.6	22.3	22.3
$L = 3R = 6a$ (cm)	47.2	44.7	44.7
I_{BTP} (C)	2.3 ^a	2.8 ^a	3.4 ^a
$n\tau_p$ (10^{13} s·cm ⁻³)	1.7	3.2	3.2

*Values have been corrected by the absorption approximation described in the Appendix to this report.

*This same equilibrium calculation can also be compared with results based on the 2XIIIB geometry, where the ratio R_p/ρ_i is much smaller than we have assumed here. This work is in progress and will not be discussed here.

Figure 2. Plasma parameters vs magnetic field B_0 for 80-keV beam computer runs based on scaling relations. Where the $\beta = 2$ calculation differs from the $\beta = 1.5$ case, it is shown by a dotted line.

- (a) Peak density n_p and plasma radius R_p .
- (b) Particle lifetime τ_p , neutral-beam current I_B , and normalized plasma radius R_p/ρ_i .
- (c) Required injection charge $I_B \tau_p$.
- (d) Beam-trapping efficiency η , computed by the method described in the Appendix.

where T_i is the ion temperature in eV, and B is the magnetic field in kG. In these runs, we find that $T_i \approx E_B/4$; thus, a freshly injected 80-kV ion will have a Larmor radius $\rho_B = 2\rho_i = 5.28$ cm in the 10.7-kG vacuum field. Of course, in the actual field-reversed plasma, the orbits are more complicated and span even more space.^{9,10}

Our computer calculations have thus established that the MFTF can support interesting, field-

reversed plasmas for the study of stability, lifetime, and similar questions. By varying the magnetic field and the beam focusing, one can span a range of scaled plasma size R/ρ_i that runs from 2XIIIB (~3) to the proposed reactor designs (10 to 20). The required sustaining current is much lower than is actually available—the buildup requirement, however, is larger and will be described in the next section.

BUILDUP CALCULATIONS

We are attempting to build up a field-reversed mirror plasma on the 2XIIIB experiment; if successful, we can extrapolate the result to the MFTF geometry.

We begin by outlining (in Fig. 3) the four stages of buildup by means of neutral beams. Stage (a) is the injection of an initial target plasma, shown in the figure as plasma from streaming-plasma guns. Stage (b) is the buildup of a "conventional" $\beta \approx 1$ mirror plasma by intense neutral-beam bombardment of the target plasma; that plasma is stabilized by additional plasma from streaming-plasma guns. Both stages (a) and (b) have been successfully achieved in the 2XIIIB experiment.

In Fig. 3, stage (c) is the transition stage in which sufficient net positive-ion current is produced to reverse the center field and produce closed field lines. The inner plasma, on the closed field lines, should have a larger containment parameter $n\tau$ and a higher electron temperature T_e . The outer plasma, on the open field lines, would have the conventional mirror containment $n\tau$. Stage (d) is the final desired state, which is obtained by lowering the incident flux of the neutral beams and of the stabilizing plasma as far as possible.

Buildup in the MFTF device along open field lines is described by Stallard and Rensink¹¹; we apply their method to the plasmas of Table 1. To do this, we first correct the total absorption parameter M [Eq. (7)] as follows:

$$\frac{M(1, E_B)}{M(\beta, 80)} = \frac{1}{\beta} \frac{\sigma_T}{\sigma_{80}} \quad (15)$$

This correction is necessary because the open field line buildup calculation is only valid for $\beta < 1$ and because the cross-section correction is necessary for the calculation of the effects of the 20-keV buildup beams.

The beam-trapping efficiency η is then estimated from the equation derived in the Appendix [Eq. (A12)]:

$$\eta = \frac{\sigma_i(1 - e^{-2M})}{\sigma_i + \sigma_x e^{-M}} \quad (16)$$

The condition that there be sufficient total current to achieve buildup is then

$$\eta_{20} I_{20} + \eta_{80} I_{80} > \frac{en}{\tau_p} V_p = \frac{en^2 V_p}{n_p} \quad (17)$$

where the left-hand side is the sum of the trapped currents, and the right-hand side is the hot-ion loss current, τ_p is the particle-loss time, and the plasma volume V_p is estimated from Table 1:

$$V_p = \pi R_p^2 L_p \quad (18)$$

As in the previous calculations,¹¹ $n\tau_p$ is scaled from 2XIIIB results:

$$\frac{n\tau}{(n\tau)_0} = \left(\frac{B}{B_0} \right) \left(\frac{L_p}{L_0} \right) \left(\frac{\beta}{\beta_0} \right) \left(\frac{\Delta_0}{\Delta} \right)^{1/2} \quad (19)$$

where $(n\tau)_0 = 7 \times 10^{10}$, $B_0 = 6.7$ kG, $L_0 = 40$ cm, $\beta_0 = 0.5$, and $\Delta_0 = 0.02$. The parameter Δ is the ratio of the density of the warm, stabilizing plasma to that of the hot plasma. Also, this scaling uses the fact that electron drag is the predominant mechanism for particle loss. For the MFTF plasma, we obtain the magnetic field B and the plasma length L_p from Table 1, $\beta \approx 1$, and we estimate Δ from Fig. B-6 of Ref. 3. In our case, $R_p/\rho_i = 9$ to 13; thus, $\Delta \approx 0.005$.

In Table 2, we apply Eqs. (15) through (19) to the cases of Table 1. When we use the specified total

(a)

(b)

(c)

(d)

Figure 3. Four stages in the buildup of field-reversed mirror plasma:

- (a) Stream injection.
- (b) Conventional mirror plasma.
- (c) Transition stage.
- (d) Field-reversed plasma.

MFTF beam current capability of 1000 A at 20 kV plus 750 A at 80 kV, the buildup capability and the total current requirement are almost equal, within estimated uncertainties.

A somewhat smaller $\beta = 1$ plasma (radius $R_p = 15$, for example) would have required less buildup current and would be a more conservative choice. Such a calculation was done earlier,¹¹ and it did demonstrate a greater buildup current surplus. The smaller plasma, of course, requires a tighter focus.

More detailed studies of this part of the buildup problem are needed. The details of plasma geometry, secondary neutrals, and the fractional mix of 20-kV and 80-kV beams should be studied.

Stages (c) and (d) of the neutral-beam buildup scenario are under active study, both experimentally and theoretically, and it is not yet possible to present scaling relations in this $\Delta B/B$ regime. There is considerable theoretical concern about the possibility that large electron currents in low-field

Table 2. Buildup calculations to achieve $\beta = 1$ plasma for the geometries of Table 1.

Parameter	A	B and C
B (kG)	10.7	15.7
V_p (litres) (Eq. 18)	81.7	69.8
n (10^{14} cm^{-3}) (at $\beta = 1$)	1.12	2.35
$n\tau$ ($10^{11} \text{ cm}^{-3}\text{-s}^{-1}$) (Eq. 19)	3	5
$E_B = 20\text{-kV beams:}$		
M (Eq. 15)	1.61	3.22
η (Eq. 16)	0.33	0.64
I_{20} (A)	1,000	1,000
$E_B = 80\text{-kV beams:}$		
M (Eq. 15)	0.67	1.33
η (Eq. 16)	0.43	0.68
I_{80} (A)	750	750
$\eta_{20} I_{20} + \eta_{80} I_{80}$ (left-hand side of Eq. 17)	652	1,150
$en^2 V_p / n\tau_p$ (right-hand side of Eq. 17)	547	1,233
Current margin (A)	+105	-83

regions would inhibit the transition to field reversal. A small component of high-Z ions (e.g., helium)

would produce a so-called Ohkawa current that may solve the problem. A theoretical analysis of this matter is in progress.¹²

An alternate injection method, use of the Intense Pulsed Ion-Neutral Source (IPINS), was recently proposed and is being investigated at Lawrence Livermore Laboratory under the aegis of the Applied Plasma Physics group of the Department of Energy's Division of Magnetic Fusion Energy. The objective of this program is, briefly, to produce neutral-beam currents of the order of kA/cm^2 for a time of the order of $1 \mu\text{s}$. The system uses a reflex triode ion source to provide the high intensities.¹³ The total charge required is estimated from the steady-state code calculations by multiplying the sustaining current I_B by the loss time τ_p ; it is plotted in Figs. 1 and 2 as the injection charge $I_B \tau_p$. For the nominal Table 1 examples, one finds $I_B \tau_p = 2$ to 4 C, if we assume that the IPINS with an average energy equal to the average ion energy (30 kV) is required to do the whole job of injection. Higher-energy ions would lower the required charge.

Overall, it appears that the neutral-beam capability being planned for the MFTF is just sufficient to produce field-reversed plasmas. The many uncertainties in our present theoretical knowledge of field reversal provide a stimulus to further research and development on alternate buildup methods, of which the IPINS is one example.

EXPERIMENTAL OBJECTIVES

In the following discussion, we assume that the MFTF is an operating facility which has been previously "broken in" with conventional mirror experiments.^{2,11} Then, for field-reversal experiments, the experimental plans can be naturally divided into three broad classes: startup and scaling, steady-state and plasma conditions, and reactor-related experiments.

Startup and scaling experiments proposed here are modeled on the 2XIIB field-reversal experiments. A suggested sequence of experiments is as follows:

- Try startup with narrowly focused, 20-keV beams alone. The buildup calculations suggest that field reversal is problematical.
- Try again with both 20-keV and 80-keV beams. Here the buildup calculations indicate that field reversal may be attained.
- Add the pulsed IPINS option to expand the buildup capability.

Each of these options would be carried out over a range of magnetic field values and with various focusing options in order to sample a variety of values of the parameters $S = a/\rho_i$ and the aspect ratio R/a . Methods for detecting field reversal are described later, in the diagnostics section.

The second class of experiments concerns the behavior of the plasma in a field-reversed steady state. These experiments must address the following questions:

- Is the field-reversed plasma stable, or does it break up again soon after buildup? Are electron current effects observed, or is plasma behavior described by an ions-only model (i.e., the SUPERLAYER code)?
- What is the range of parameters for which stability is observed? Here we mean especially the size and shape of the plasma (R_p/ρ_i , R/a , L/a) and also the shape of the magnet field.

- What is $n\tau$ and what are the plasma loss rates? Ways to study this include turning off the beams in order to observe the decay of the plasma parameters and observing the minimum beam current required to maintain the steady state.

- Are there gross changes in behavior at various characteristic times after buildup? Such times include τ_{ie} (electron drag), τ_{ii} (ion-ion equilibration), and τ_n (resistive diffusion).

- What are the effects of impurities? Are there pumping problems and similar cold-boundary effects?

From the experimental evaluation of such questions, one could draw conclusions concerning the

relevant plasma instabilities and the proper transport matrices to use for energy and particle losses. Thus, the assumptions of the FRM reactor calculations⁵ can be tested, and modified if necessary.

The third class of experiments would be more closely related to reactors; an example would be cold-gas refueling tests. These would be later work, and their planning depends on the results of the experiments in the first two classes.

This concludes our evaluation of the experimental objectives. We emphasize that we anticipate a considerable evolution and development of ideas and concepts before actual experimentation can begin.

IMPORTANT DIAGNOSTICS

Next, we briefly discuss the diagnostics techniques that should be the most useful for field-reversal experiments in MFTF.

Ideally, a direct measurement of magnetic field B in the center of the plasma is the most straightforward diagnostic. In a proposed method for doing this at one instant of time, the Zeeman effect in the optical spectrum of a beam of helium ions is used. The magnetic field is deduced from optical measurements involving two polarized laser beams. This method will be tested soon on 2XIIB; if successful, it can be used for the MFTF experiment. A small helium neutral-beam source, two dye laser beams, and an optical fluorescence-detection channel will be required.

Faraday rotation of a polarized light beam is another promising diagnostic. This technique measures $\int Bnd\ell$ along the optical path. Careful choice of optical path, combined with simultaneous interferometric measurements of $\int nd\ell$, should permit the unfolding of information concerning the magnetic field B . This method will also be tested on 2XIIB. For MFTF, we will re-evaluate whether to use the HCN laser at $\lambda = 337 \mu\text{m}$ (as on 2XIIB) or to choose another laser such as CO_2 at $\lambda = 10.6 \mu\text{m}$.

Diagnostic loop measurements outside the plasma are simple and will undoubtedly be done; however, the effect of field reversal at the center of the plasma is obscured by other effects, such as the

details of the shape of the distribution of the plasma currents.

A different diagnostics approach is the indirect one—to look for changes in the plasma that can be attributed to the effects of field reversal. A good example of this is variation in the electron temperature T_e ; T_e should increase within the closed field lines, and its variation can be measured at a few selected times and places by Thomson scattering of ruby laser light (as is now done on 2XIIB). Continuous monitoring of T_e is conceivable with x-ray detectors of bremsstrahlung radiation; this should be simpler on MFTF than on 2XIIB because of expected higher values of T_e .

Another indirect method is to measure the confinement parameter $n\tau$, as described in the discussion on experimental objectives. As shown by the steady-state calculations earlier in this report, a dramatically lower steady-state neutral-beam current is all that may be required to maintain a field-reversed plasma.

A final indirect approach relies on a characteristic of the spatial distribution of a field-reversed plasma: it should have a midplane density peak that is well off-axis. This might be detected by unfolding measurements of $\int nd\ell$ (interferometric or beam absorption techniques). It might also be seen by the proposed neutron pinhole camera diagnostics.¹⁴

MAGNETIC FIELD SHAPE

A preliminary assessment suggests that the MFTF coil design allows us to explore a significant range of parameters for field-reversed plasmas that are built up and sustained by neutral beams.

We compare the MFTF coil magnetic field with the 2XIIB magnetic field as it is used in current experiments. The total magnetic field along the axis $B(0,z)$ and along the midplane axes $B(R,0)$ is normalized to the center field B_{00} . The axial and radial dimensions are normalized to the Larmor radius ρ_i of the average energy ions (27 kV for MFTF and 9 kV for 2XIIB). The change in magnetic field $\Delta B/B_{00}$ is plotted in Figs. 4 and 5 vs z/ρ_i and R/ρ_i , respectively. The specific cases chosen for comparison are the $\beta = 1.5$, $B = 15.7$ -kG calculation (Tables 1 and 2) for MFTF, and the 2XIIB "gas box" experiment, which has the highest beta yet reported.¹⁵

Figure 4 shows the fractional change in total magnetic field vs axial distance for the two cases. One finds that the MFTF field is flatter than the 2XIIB field, which is reasonable because it was deliberately designed for experiments with larger-sized plasmas. The highest value of the ordinate of Fig. 4 is unity, corresponding to a mirror ratio of $R_m = 2$; this is much higher than the lower limit of the vacuum mirror ratio that was used in the initial FRM reactor studies⁵ ($R_m \gg 1.0001$ there). However, for a better comparison with these studies, one should pick a point on the axis of 2XIIB or MFTF which is closer to the plasma. But

Figure 4. Comparison between the 2XIIB and MFTF vacuum fields: axial magnetic field change vs normalized axial distance, with plasma length indicated.

even in that case, choosing $1 < Z/\rho_i < 10$ leads to an axial magnetic field change that is 10 to 100 times greater than the lower limit of the FRM reactor study. No upper limit is given to this parameter in that study; the authors imply that it is limited by economic rather than physical considerations. In any case, the MFTF design is slightly closer to the FRM reactor design than is the 2XIIB experiment.

Figure 5 shows the radial variation of the fractional change in total magnetic field, corresponding to the quadrupole component of the coils. In addition, a comparison is made with the parameter range of the Cornell electron-ring quadrupole experiments.⁷ As in Fig. 4, the MFTF field is flatter than the 2XIIB case. Although the normalized radii are different, the quadrupole strengths of both MFTF and 2XIIB are within the range studied with the electron rings.

The quadrupole field is necessary for minimum-B stabilization of magnetohydrodynamic (MHD) modes in the open-field-line mirror plasmas, but its role in the field-reversed case is more ambiguous. Recent results from the electron-ring quadrupole experiment at Cornell⁷ are interesting, even though there are obvious differences between an electron ring decaying in a partially-ionized plasma and a plasma that is fully ionized, has a multi-Larmor radius, and is sustained by neutral beams. The electron experiments⁷ show that sufficient quadrupole field stabilizes very weak, non-field-reversed electron rings ($\Delta B/B < 0.1$) against the precessional

Figure 5. Comparison between the 2XIIB and MFTF vacuum fields: radial magnetic field change (mainly the quadrupole component) vs normalized radial distance, with plasma radius indicated. The hatched bar shows the parameter range of the Cornell electron-ring (E-ring) quadrupole experiments (see text).

mode. On the other hand, slightly stronger rings ($\Delta B/B > 0.25$) decay more rapidly with than without quadrupole fields—the decay rate being proportional to the strength of the quadrupole field component. The hypothesis of orbital resonance ef-

fects has been advanced to explain the enhanced decay of the axis-encircling electrons in the Cornell experiment.⁷ This hypothesis is being investigated by computer calculations at LLL.¹²

SOME CONSEQUENCES OF A SUCCESSFUL FIELD-REVERSAL EXPERIMENT ON MFTF OPERATING PROCEDURES

Clearly, a favorable evolution of theoretical and experimental understanding is needed to achieve a field-reversed plasma in any facility. For example, Post's orbit theory¹³ (admittedly only two-dimensional) predicts that field reversal can occur only when the plasma is large ($R/\rho_i > 3$), which favors MFTF over 2XIIB. If surface effects (charge exchange or radial heat loss) are limiting, MFTF will have a significant advantage over 2XIIB because the larger MFTF plasma has a smaller surface-to-volume ratio.

Should field reversal be achieved under the conditions given by the sustaining equilibrium calculation described above, this would have important implications for the programming of the 80-keV neutral beams. During buildup, all 20 to 24 beams are on; after field reversal is achieved, only 20 to 60 A may be required, and that can be supplied by just two modules.

If all the modules are left on, the plasma would continue to try to grow, as shown by SUPER-LAYER⁹ calculations, unless or until it is disrupted by an instability. It may be necessary to throttle back the beams before this happens. This throttling could be programmed in ahead of time; however, it may be more desirable to use a feedback control based on some field-reversal diagnostic such as a diamagnetic loop or a Faraday rotation measurement.

Consider again the hoped-for steady-state, field-reversed plasma. The n_T is 10^{13} instead of 10^{12} ; the loss-power fluxes are lower than in the standard MFTF design by a factor of 10. Thus, it is conceivable that the field-reversed plasma might be

sustained for a long time. As each pair of 80-keV modules reaches its design limit of 30 s, another pair is programmed in to sustain the field-reversed plasma for another 30 s. Assuming that there are 22 operating modules (11 pairs), one would cycle through all the 80-keV neutral beams in 5-1/2 min. Because the power supply design calls for a 5-min repetition period, in principle one can start the cycle all over again. Thus one can envision the possibility of long time operation of a field-reversed mirror experiment in MFTF.

However, the present 30-s water-cooled beam-dump design is awkwardly matched to this operational possibility. The water is stored in tanks, and can only be cycled once through the beam dumps; for this throttled-back operation, water would be available only for about 30×11 s (5-1/2 min). It would be better to reinvestigate the possibility of heat exchangers or direct conversion for this application.

There are indeed many more immediate milestones to be attained before detailed consideration of such a sustained experiment is needed. It is important, however, to keep this optimistic possibility in mind. The plasma size and the magnetic field are only factors of 2 to 4 less than the corresponding parameters for the prototype optimum FRM reactor,⁵ and they are factors of 2 to 4 greater than the present 2XIIB experiment. If it becomes possible to run the MFTF in this long-term, sustained, field-reversed mode, then such experiments would be an important intermediate step towards a prototype FRM reactor.

SUMMARY

This preliminary survey of a possible field-reversed mirror plasma experiment in the MFTF is based on the assumption that neutral beams are capable of both building up and sustaining such a plasma. We find that the MFTF design is suitable for such field-reversal experiments, with the possible exception of a marginal neutral-beam buildup capability. Successful production of a well-contained ($n\tau \approx 10^{13}$) field-reversed plasma would

open up the possibility of long-term, steady-state operation of the MFTF.

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APPENDIX. A SIMPLE APPROXIMATION FOR BEAM-TRAPPING EFFICIENCY

The absorption of energy from the neutral beam by the plasma depends mainly on two interactions. The ionization reaction (cross-section σ_i) is

The charge-exchange reaction (cross-section σ_x) is

The estimate of beam-trapping efficiency is complicated by the second reaction because the secondary neutral particle that is produced may interact again by means of reactions (A1) or (A2). The tertiary neutral may also interact in the same way, and so forth.

As mentioned in the main text, the steady-state code calculations assume that the plasma is "thick," that is, that all of the secondaries, tertiaries, etc. are absorbed. Thus, the total interaction cross-section σ_T is used to calculate the absorption parameter M [Eq. (7)]:

$$\sigma_T = \sigma_i + \sigma_x . \quad (A3)$$

In this case, the only escaping neutral particles are those that do not interact. Such an approximation is too optimistic, and needs to be corrected.

On the other hand, the previous study of MFTF neutral-beam injection¹¹ used the forward scattering approximation

$$M \approx \sigma_i \int_{l_{\min}}^{l_{\max}} n \, dl . \quad (A4)$$

This equation assumes that reaction (A2) has a negligible effect on the beam; that each secondary neutral is emitted in approximately the same direction as the primary neutral and can be considered a substitute for it. This approximation works best at high energies, but is questionable for the 50-keV beams. We believe that it is too pessimistic, underestimating the amount of absorption of secondary neutrals.

We have formulated a third approximate model for the beam-trapping efficiency. Let F_{2M} be the interaction fraction of the tangentially injected primary neutral beam:

$$F_{2M} = 1 - e^{-2M} , \quad (A5)$$

where M is defined by Eq. (7) and the factor 2 is needed because the beam goes in and out of the plasma. Let f_i be the fraction that is ionized:

$$f_i \equiv \frac{\sigma_i}{\sigma_T} F_{2M} . \quad (A6)$$

Then the fraction f_x that is charge-exchanged to form a population of secondary neutrals is given by

$$f_x \equiv \frac{\sigma_x}{\sigma_T} F_{2M} . \quad (A7)$$

The next step is to determine the average path length of the secondary neutrals. An exact calculation would require either elaborate Monte Carlo methods or complicated integrations. We avoid this labor by assuming that the length of the average secondary escape path is only half as long as the length of the primary path because it is born inside the plasma and merely has to get out. Thus, for the secondary we take the interaction fraction to be

$$F_M = 1 - e^{-M} . \quad (A8)$$

The ionized and charge-exchanged fractions f_i, f'_x are then obtained as before:

$$f_i = \frac{\sigma_i}{\sigma_T} F_M , \quad (A9)$$

and

$$f'_x = \frac{\sigma_x}{\sigma_T} F_M . \quad (A10)$$

We also ignore the shift in energy between the primary and the secondary and use the same cross sections. Tertiary and higher-order neutrals are approximated in the same manner as the secondaries.

Finally, we sum the ionization fractions in order to find the overall beam-trapping efficiency η :

$$\begin{aligned} \eta &= f_i + f_x f'_i + f'_x f'_i + f'^2_x f'_i + \dots \\ &= f_i + f_x f'_i \frac{1}{1 - f'_x} . \end{aligned} \quad (A11)$$

By substituting Eqs. (A5) through (A10) into Eq. (11), we then obtain

$$\eta = \frac{\sigma_i F_{2M}}{\sigma_T - \sigma_x F_M} = \frac{\sigma_i (1 - e^{-2M})}{\sigma_i + \sigma_x e^{-M}} . \quad (A12)$$

When Eq. (A12) is used, the computed trapping efficiencies are lower than the optimistic predictions of Eq. (A3) and higher than the pessimistic estimates of Eq. (A4); we believe that they are realistic estimates for a pure-hydrogen plasma without impurities. Equation (A12) is therefore the expression for beam-trapping efficiency that we use in the main text.