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Review of the Neutral-Beam Current Requirements for the Mirror Fusion Test Facility (MFTF)

ABSTRACT

Our study of the neutral-beam current requirements for the Mirror Fusion Test Facility (MFTF) includes an analysis of the expected operating parameters of the neutral-beam sources based on recent tests conducted at the Lawrence Berkeley Laboratory (LBL). We find that the LBL sources will produce a neutral-beam module with an output current of 51 A and an average beam energy of 50 keV. To meet the MFTF goal of a plasma having an average ion energy of 50 keV, this beam energy must be increased. Modification of the sources to increase the energy will reduce the output current.

The techniques used to evaluate the beam-current requirements for MFTF are similar to those in previous studies but incorporate some improvements. In particular, we have enlarged the radial code BUILDUP to allow for a smaller radial grid and to improve the numerical accuracy; we have also improved the model of the atomic physics processes and the particle-equilibrium calculations. Also, a model of plasma containment that conserves energy as well as particles but does not include any effect of the expected drift-cyclotron loss-cone (DCLC) turbulence has been incorporated into the previous studies. We show that the DCLC turbulence increases the average ion energy and decreases the particle confinement time. Because these effects cancel to first order, the beam-current requirements are independent of the turbulence. We find that 24 of the present LBL source modules would sustain a plasma with an average beta of 0.46. This figure is within 10% of the MFTF goal and is within our calculational accuracies. We further show that the beam current requirements for the large-diameter plasma are consistent with those of experiments to study the buildup of a field-reversed plasma.

1. INTRODUCTION

Because the most expensive item in the Mirror Fusion Test Facility (MFTF) is the set of 80-kV power supplies for the sustaining neutral beams, the number of power supplies required to achieve the stated goals¹ has been a controversial topic.^{2,3} The issues involved, as reviewed in this report, fall into two categories:

- What is the expected beam-line output current from each source module (a function of source operating characteristics and the associated beam-line efficiency); and
- How much neutral-beam current is required to achieve the MFTF goals.

We must answer questions from both categories before we can determine the number of power supplies required for the MFTF

Section 2 addresses the first category: expected beam-line output current of each source module. Previous studies preceded experience in operating sources similar to those that will be used in the MFTF.^{2,3} Since those studies, personnel at Lawrence Berkeley Laboratory (LBL) have tested 120-kV source modules for Princeton's Tokamak Fusion Test Reactor (TFTR) and reduced-area, 80-kV modules for General Atomic Company's Doublet III, sources similar in many ways to those that will be used on MFTF. By extrapolating the results of these tests, we obtain the expected performance of the MFTF sources. As the design of the fusion chamber system progresses, we can better estimate the transport efficiencies of the MFTF beam line and determine system availability and how it affects our ability to achieve

the MFTF goals in a reasonable time. Finally, Sec. 2 also contains a re-estimate of the trapping efficiency expected in MFTF. This calculation differs from previous estimates¹ in that here we treat the beams as having a Gaussian density profile in both transverse dimensions. By discreet aiming of these focused beams, we can obtain large-diameter plasmas. Because in the determination of trapping efficiency this treatment accounts for the portion of each beam that misses the plasma, the nomenclature used to discuss the beam-current requirements must be changed. Previously, beam-current requirements were stated in terms of the current incident on the plasma.^{1,4} The beam-profile effects were approximated by saying that 20% of the beams misses the plasma.² The beam currents calculated here, however, refer to the neutral current through the final aperture of the MFTF beam line and are therefore called the beam-line output currents to distinguish them from the currents incident on the plasma.

Sections 3, 4, and 5 contain our re-evaluation of the beam-current requirements for the MFTF reference case. These estimates improve and extend previous work.^{1,4} Sections 3 and 4 treat the reference case, where $\beta = 0.5$ and the plasma radius is large enough to permit stabilization of the drift-cyclotron loss-cone (DCLC) mode. In Sec. 5, we consider the current requirements for an alternate reference case: the buildup of a field-reversed plasma.

An extension of the particle-equilibrium calculations of Ref. 4 is presented in Sec. 3. The plasma confinement parameter and average ion

energy are assumed to scale as found in Ref. 5. We consider two radial plasma profiles, diffuse and flat-topped, and show that although it is relatively easy to achieve a peak beta $\beta_0 = 0.5$ with a diffuse profile, a very large current is necessary for an average beta $\langle\beta\rangle = 0.5$. For the flat-topped profile, we find that 24 source modules with the operating parameters of the present LBL models are sufficient to achieve $\langle\beta\rangle = 0.46$.

Recent results of calculations using the radial code BUILDUP are presented in Sec. 4. These calculations include an investigation of the sensitivity of the beam-current requirements to variations in parameters such as the streaming-gas density, the plasma confinement parameter, and the mean ion energy of the plasma. We show that the currents depend rather sensitively on the mean ion energy. This fact, which was not fully appreciated in the past, is important because achievement of a $\beta = 0.5$ plasma is one of the MFTF goals. The code runs are all aimed at achieving a flat-topped plasma density profile. Results show that this profile is relatively sensitive to beam aiming.

Calculations of the beam-current requirements for a study of the buildup to field reversal are given in Sec. 5. Although these studies were not included in the MFTF proposal,¹ we feel they are important enough to be considered as an alternate reference case. The methods outlined by Shearer and Condit⁶ and Baldwin and Fowler⁷ are used to estimate the required current. We find that the current necessary to achieve a large-diameter, $\langle\beta\rangle = 0.5$ plasma is consistent with that required for the study of the buildup of a field-reversed plasma.

2. BEAM-LINE EFFICIENCIES

The specification for the sustaining neutral-beam power supplies calls for each supply to be capable of producing 88 A at 80 kV. Because of losses, only a fraction of this power is available as neutral-beam input to the plasma.

- The first loss occurs in the power supply for the gradient grid. This power supply is a passive, voltage-divider network that divides the accel voltage down to that necessary for the gradient grid. To prevent voltage sag at the gradient grid, the divider network draws a significant current from the accel power supply. The present design requires an 8-A drain in this network; hence, only 80 A is available for ion-extraction current.

- A portion of this remaining current (roughly 20%) is lost by processes occurring in the grid structures.

- Further losses are incurred because of incomplete neutralization of the ion beam.

- Losses occur in the beam line due to reionization by gas.

- Losses occur because of apertures designed to prevent gas streaming from onto the plasma.

- One effective loss occurs because the average performance of a group of injectors on the MFTF experiment is expected to be below that of a single injector on a test stand.

- Another effective loss is a function of the finite lifetime of the source and the accompanying source availability.

- Finally, there is a loss due to the trapping efficiency of the plasma.

Each of these loss mechanisms will now be considered in detail.

Ion-Beam Loss During Acceleration

Ion beam can be lost two ways during acceleration:

- By charge exchange on cold gas, and
- By generation of a more divergent beam halo by imperfect beam optics. Most of this divergent beam is expected to miss the grids; however, the beam that does strike creates secondary electrons that can backstream and increase the power supply drain.

The charge-exchange loss has been calculated by Fink and McDowell⁸ and more recently by Anderson.⁹ Anderson integrates the loss for analytic approximations to the charge-exchange cross section, with a beam energy increasing linearly and a gas pressure decreasing linearly with distance through the accelerating structure. He calculates an efficiency of 91% at 80 keV for the flow rates used on the LBL 120-keV source now being tested. Following Anderson's model, we calculate losses of molecular ions by charge exchange and dissociation. Using a 5-keV step, we numerically integrate the cross section and the pressure from 0 to 80 keV. The D₂ gas density drops linearly over 1.5 cm from 1.3×10^{11} to 0.65×10^{11} cm⁻³. As shown in Table 1, we find that the fraction of molecular ions lost is 0.169 and 0.157 for D₂⁺ and D₃⁺, respectively, and that the fraction of D₁⁺ lost is only 0.092. The loss rate scales linearly with the gas density.

Table 1. Estimates of ion-beam losses during acceleration in the MFTF 80-keV source. The interaction is with D₂ gas.

Interaction	Reference ^a	Fraction of beam that undergoes the interaction
Charge exchange of atomic species		
$D_1^+ + D_2^0 \rightarrow D_1^0 + D_2^+$	A4.4	0.092
Charge exchange of molecular species		
$D_2^+ + D_2^0 \rightarrow D_2^0 + D_2^+$	A4.30	0.061
Charge exchange and dissociation of molecular species		
$D_2^+ + D_2^0 \rightarrow D_1^+ + D_1^0 + 2(D_1^+ + D_1^0)$	A3.8	0.108
$D_1^+ + D_2^0 \rightarrow D_1^0 + D_2^+ + D_2^0$	A3.22	0.104
$D_1^+ + D_2^0 \rightarrow D_2^+ + D_1^0 + D_1^0$	A3.22	0.053
Dissociation of molecular species		
$D_2^+ \rightarrow 2D_1^+$	A3.2	0.031
$D_1^+ + D_1^0 \rightarrow D_2^+$	A3.20	0.018
$D_1^+ \rightarrow D_2^+ + D_1^0$	A3.20	0.015

^a Page number in Ref. 12 from which cross-sectional data were obtained.

The gas density used in these calculations is the best estimate⁹ of the gas density used on the LBL 120-keV test stand. If this density could be reduced (and the neutralizer lengthened to maintain efficient neutralization), the beam losses during acceleration would decrease.

Berkner¹⁰ measures beam losses of 20% in the LBL 120-keV source being developed for TFTR by determining the difference between the power to the calorimeter and the power supply drain. This number will be refined in the future by more detailed measurements of where beam is lost as well as by independent checks of the calorimeter accuracy. Berkner estimates that the 20% loss is made up of 10% lost because of charge exchange and 10% lost because of a broader, non-Gaussian component to the beam.¹⁰

We use the total acceleration loss of 20% and assume that it consists of the charge-exchange losses listed in Table I plus the losses associated with a broader halo to the beam. The halo is produced by three mechanisms:

- Optical defects (that we assume affect all species equally).
- Slower ions created by charge exchange (these are included in Table I), and
- Slower ions resulting from the dissociation of molecular ions into lighter molecular or atomic ions (also included in Table I).

The last two mechanisms produce ions that cannot be properly focused because they have the wrong momentum; hence, they broaden the beam. For the present species mix of 60% D_1^+ , 30% D_2^+ , and 10% D_3^+ , we thus obtain the following loss breakdown:

$$[0.092(0.60) + 0.17(0.30) + 0.16(0.10)] \\ + [\delta(0.60) + (\delta + 0.031)(0.30) + (\delta + 0.033)(0.10)] = 0.20,$$

where δ is the fraction of the beam with optical defects. The first bracketed term arises from charge-exchange losses, and the second term arises from the halo losses. This results in $\delta = 0.065$, and losses due to halo effects of 0.065, 0.096 and 0.098 for D_1^+ , D_2^+ , and D_3^+ , respectively.

In summary, we have calculated charge exchange and dissociation during acceleration for each of three beam species. We subtracted these losses from the calorimetrically determined loss rate of 0.20, and then allocated the difference of 0.065 equally among the species. This value for the loss caused by optical defects seems reasonable. We assume that the measured 20% grid losses will also be true for the MFTF sources.

Neutralizer Efficiency

The neutralizer efficiency is dependent upon the molecular mix within the source plasma. Molecular ions extracted as either D_2^+ or D_3^+ will be dissociated in the neutralizer and will appear as atoms with energies corresponding to one-half and one-third of the extraction voltage.¹¹ Since the charge-exchange cross section is energy dependent, the neutralizer efficiency and average beam energy are dependent on the molecular mix. We assume here that the extraction voltage for MFTF is 80 keV. The neutralization fraction for 80-keV, 40-keV, and 27-keV deuterium beams on D_2 gas is given in Ref. 12 as 0.625, 0.82, and 0.85, respectively. However, because the neutralizer length required to achieve equilibrium in the 80-keV component is excessively long, we degrade the neutralization fraction to $0.625 \times 0.95 = 0.59$. If f_1 is the fraction of the ion current extracted as D_1^+ , and f_3 is the fraction extracted as D_3^+ , the total neutral-beam current (in equivalent amperes) and power emerging from the neutralizer per ampere of extracted current is given approximately by

$$i^n = 0.59 f_1 + 2(0.82)(1 - f_1 - f_3) + 3(0.85)f_3 \\ p^n \left(\frac{W}{A} \right) = (8 \times 10^4) [(0.59)f_1 + (1/2)(2)(0.82) \\ \times (1 - f_1 - f_3) + 1/3 (3)(0.85)f_3] \quad (1)$$

The average energy in the neutral beam is given by

$$\bar{E}_n = \frac{p^n}{i^n} \quad (2)$$

The neutral current and average beam energy as determined from Eqs. (1) and (2) are plotted in Figs. 1 and 2. If the molecular mix for the MFTF 80-keV sources is the same as that measured in the 2X11B 20-keV sources ($f_1 = 0.72$, $f_3 = 0.02$), we would expect 0.93 A of neutral current per ampere extracted. The average energy in this case is about 56 keV.

The most recent tests on the TFTR and Doublet H sources at LBL indicate a molecular mix of $f_1 = 0.6$ and $f_3 = 0.1$. For these sources, $i^n = 1.10$ and $\bar{E}_n = 50$ keV. This beam energy is inadequate to achieve the MFTF goal of an average ion energy of 50 keV. Sources developed at Oak Ridge National Laboratory (ORNL) improve the molecular mix by containing the source plasma with an array of magnetic multipoles placed around the arc chamber (the so-called MacKenzie bucket). These sources have achieved a molecular mix of $f_1 = 0.85$ and $f_3 = 0.07$; hence, $i^n = 0.79$ and $\bar{E}_n = 64$ keV. Current requirements for both of the LBL and ORNL sources are considered in Sec. 3.

Fig. 1 The expected neutral current as a function of the molecular mix of the source. The neutral current is normalized to the extracted current. The fraction of the beam extracted as D_2^+ is denoted by f_1 and the fraction extracted as D_2^+ by f_3 .

Fig. 2 The average beam energy as a function of the molecular mix of the source. The nomenclature is the same as in Fig. 1.

Ionization Losses

Another beam-loss mechanism in the beam line is the reionization of the neutral beam by gas between the neutralizer and the plasma. The stray magnetic field sweeps these reionized particles from the beam. The transmission efficiency of the neutral beam is given by

$$I/I_0 = \exp(-\sigma_{01} \int n_0 dl),$$

where σ_{01} is the cross section for ionization of D_2^+ by deuterium gas and n_0 is the density of the gas molecules.

The beam-line configuration used in the MFTF proposal¹ provided a transmission coefficient of $I/I_0 = 0.81$. Design modifications and value engineering to increase the pumping area have increased this to $I/I_0 = 0.89$. Because this loss has a very weak dependence on energy in the 20 to 80-keV range, we assume for simplicity that the loss is 11% for all energy components. We are continuing to optimize the pump and aperture designs.

Aperture Losses

Further beam losses are expected on the apertures used to restrict gas flow from the neutral-beam tanks into the plasma. In the MFTF proposal,¹ a duct was used for this purpose. However, a loss of beam and increased cold-gas flow were found with the closely fitted duct associated with the beam line designed for the Princeton Large Torus (PLT) by ORNL. Stewart¹² fitted the PLT results with a model of thermal gas reflux and has applied his analysis to the MFTF duct; he found that with the same reflux coefficient as in PLT, the MFTF beams were blocked after 0.3 s. Therefore, the ducts have been replaced with apertures, and the pumping speed has been increased to reduce gas flow to the plasma.

To estimate the loss of beam on the apertures, we require that the power loading on the aperture be below 1 kW/cm². We have analyzed neutral-beam power profiles by means of the PWRDN code¹³ and find that 97% of the beam will be transmitted by these apertures.

Average Beam Performance

For two reasons, we expect that the average performance of a group of injectors on a confinement experiment will be below that of a single injector on a test stand:

- The experiment has a different environment (e.g., a high magnetic field) than the test stand.
- The attention paid to an individual source and to the beam diagnostics may be less complete and accurate on an experiment than on a test stand; also, the reliable operating level will be lower than the peak level achieved on a test stand.

Recent 2XHB performance is instructive. Through numerous improvements in operation, all 12 sources routinely operate at 18 keV, injecting a total current of up to 530 A of atoms. This is about 90% of the LBL test-stand data obtained

for the same energy, correcting for the different size of the calorimeter. In addition, the operating voltage is 10% low, resulting in a current about 15% below the design level. Therefore, the average operating current level of a 2X11B source is about $(0.9)(0.85) = 0.77$ of peak test performance.

For MFTF, we are planning to improve on the 2X11B performance:

- We are designing an improved magnetic shield based on the design for the Tandem Mirror Experiment (TMX) (note that the MFTF field at the source is 0.08 T rather than the 0.03 T on TMX).

- The computer control system will provide more uniform, attentive operation.

- We are working on obtaining adequate information with fewer diagnostics.

- LBL is developing lower-current-density sources that promise higher reliability, although this makes it harder to find room to inject sufficient current into MFTF.

With these improvements, we anticipate an average operating level of 0.9 of peak test performance.

Source Lifetime and Availability

We expect filament burnout to limit the lifetime of the MFTF sources. LBL has achieved 7000 0.5-s-duration shots and 2X11B has recently achieved 9000 0.01-s-duration shots. On 2X11B, source conditioning typically takes 1000 to 2000 shots; another 1000 shots are required for calorimetry. For MFTF, we estimate 1900 shots to condition and another 100 shots to verify the aim and optimum operating parameters of a previously operated source. We expect computer monitoring and control to provide this more efficient aiming and optimization. Conditioning can be done at 1-minute intervals when plasma experiments are not being run on the MFTF. Each source therefore requires 32 hours to condition, but many or all sources may be conditioned simultaneously at least to some fraction of full power and duration. Optimization and aiming will be done at a rate no faster than at 5-minute intervals, and only beams hitting identified, distinct areas of the calorimeter can be operated simultaneously; each source will require about 8 hours for optimization. We assume similar conditioning and optimizing times for the startup and sustaining beams, although this assumption may need modification as we gain experience with sustaining beams.

After these 2000 preparatory shots, the source is ready to operate for data shots, with 5000 shots remaining before shutdown for maintenance. Each

16-hour day allows 192 shots at 5-minute intervals. At this rate, each source will last for 5.2 weeks of data taking (shots taken during the 8-hour maintenance shift will shorten this period). This is much less than the approximate 13-week data period originally envisioned. However, with occasional days off for data analysis, the filaments might last the experimental period. We recognize that warm-up shots will be required at the beginning of each day and after interruptions in running. These shots will be made at 5-minute intervals and may be comparable in number to the data shots. Typically then, we might expect 2500 data shots and 2500 warm-up shots before changing filaments.

The impact of this source lifetime on the availability of the MFTF neutral-beam source and on the size of the maintenance shop depends on the strategy we adopt for conditioning and maintaining the sustaining (and startup) neutral beams. On 2X11B, we have used batch processing: for MFTF, this would mean maintaining and reconditioning all neutral beams while MFTF is down for 1 month between 2-month-duration data runs. We find that filament lifetime is barely adequate to make this a potential mode of operation. Furthermore, the workload on the maintenance shop would be uneven, with peaks of 3 to 4 times the average workload.

A more desirable operating scenario is that of continuous maintenance, where beam sources are removed from MFTF at regular intervals (such as weekly), and a steady workload is maintained in the beam shop. We now analyze this scenario for two variations: for beams changed at random intervals during the week and for all changing done during the weekend.

- If we change sources at random times, the availability of the beam system is given by

$$\epsilon = 1 + \left| \frac{\alpha R_u}{R_c} \right|^{-1},$$

where α = conditioning/data shots = 2000/2500 = 0.8, and where R_u and R_c are the repetition rates for operation and conditioning, respectively. For $R_u = 0.2 \text{ min}^{-1}$ and $R_c = 1.0 \text{ min}^{-1}$, we obtain $\epsilon = 0.86$.

- By changing beams only on weekends, the conditioning can be nearly completed and optimization and aiming completed with an 8-hour shift on Saturday and on Sunday. Final conditioning would then be done during warm-up and data shots the following day. Although this scenario would yield an efficiency of unity, it involves optimistic assumptions.

We recognize that scheduled maintenance can increase the availability of sources above the 0.86 calculated for random-interval maintenance. However, the factors that prevent achieving unity availability include unexpected failures of sources, and the fact that sources may not be conditioned for 16 hours a day on weekends either because of power-supply maintenance or because of maintenance under the vault that would probably require shutting beams down because of neutron hazards. However, because scheduled maintenance should reduce down time by at least a factor of two, we assume a source availability of 0.93 rather than 0.86.

We can now estimate the overall beam-line efficiency by combining the transmission coefficient for each of the losses. To review, the loss mechanisms and the estimated transmission coefficients are tabulated in Table 2.

Table 2. Beam-line transmission coefficients.

Loss mechanism	Transmission coefficient
Acceleration losses	0.80
Gas reionization	0.80
Aperture losses	0.97
Average beam performance	0.90
Source availability	0.93
Total:	0.58

With an overall transmission coefficient of 0.58, the expected beam-line output current is $(6.58)(80)(0.58)(52)^{1/2}$ (A), where: i^0 is determined in Sec. 2. The beam-line output current for the present LBL sources is 51 A; sources with the MacKenzie bucket to improve the molecular mix will have an output current of approximately 37 A.

Trapping Efficiency

The techniques used here to calculate the beam trapping efficiency follow very closely those introduced in Ref. 4. The main difference is that we account for the spatial dependence of the beam in the plane perpendicular to its direction of propagation rather than just in the direction of the magnetic axis (z-axis). We calculate the trapping efficiency of a single beam aimed at the plasma midplane (i.e., at $z=0$), with the beam center line aimed at an arbitrary distance along the y-axis. The overall trapping efficiency is then found by summing over all beams.

Let $J_B(y,z)$ be the output current density of the beam-line and $n(x,y,z)$ be the density of the plasma. The trapping efficiency is given by

$$\eta_t = 1 - \frac{1}{I_B} \int_{-z}^z dy \int_{-y}^y dz J_B(y,z) \exp \left\{ - \frac{\sigma v_{\text{ion}}}{v_B} \int n(x,y,z) dx \right\} \quad (3)$$

The neutral-beam sources in MFTF will be focused; hence, the current density is bi-Gaussian:

$$J_B(y,z) = \frac{I_B}{\pi z_B y_B} \exp \left\{ - \left(\frac{z}{z_B} \right)^2 - \left(\frac{y}{y_B} \right)^2 \right\} \quad (4)$$

where I_B is the total beam-line output current aimed at y_B , and y_B , z_B are the scale lengths of the current densities. We expect a beam divergence of 0.5° to 1.5° and beam focal length of 7 m; therefore,

$$z_B = 700 \tan 1.5^\circ = 18.3 \text{ cm},$$

$$y_B = 700 \tan 0.5^\circ = 6.11 \text{ cm}.$$

We consider here only the case of a uniform, cylindrical plasma; i.e.,

$$n(x,y,z) = n_0, \quad r \leq (0, R_p), \quad z \in (0, L_p) \\ = 0 \quad \text{otherwise.}$$

This model is a poor representation of the diffuse profile considered in Sec. 3, but it is a reasonable approximation for the flat-topped plasma-density profile.

With these assumptions, we obtain the trapping efficiency for a beam aimed at y , by integrating Eq. (3):

$$\eta_t = \text{erf} \left(\frac{I_B}{z_B} \right) \left\{ \frac{1}{2} \left[\text{erf} \left(\frac{R_p - y_B}{y_B} \right) + \text{erf} \left(\frac{R_p + y_B}{y_B} \right) \right] - \frac{1}{\sqrt{\pi}} \int_{-y_B}^{y_B} \frac{dy}{y_B} \exp \left\{ - \left(\frac{\phi - y}{y_B} \right)^2 - \frac{\sigma v_{\text{ion}}}{v_B} \int n_0 dy \right\} \right\} \quad (5)$$

where $\phi = y/y_B$.

We find the overall trapping efficiency by summing over all beams. Let f_i be the fraction of the total current that is aimed at position y_i . Then for N beams,

$$\eta_t = \sum_{i=1}^N f_i \eta_i.$$

We assume here that the flat plasma density profile is achieved by N individual beam aimings uniformly spaced between $y = 0$ and $y = R_p - y_B$; i.e.,

$$y_i = m \frac{R_p - y_B}{N - 1}, \quad m = 0, 1, \dots, N - 1.$$

This aiming geometry is sketched in Fig. 3 for the case $N = 4$.

Fig. 3 Schematic of the beam pattern required to achieve a large-diameter plasma, showing points y_i along the plasma radius R_p , at which the beam is aimed.

The individual trapping efficiencies η_i for $R_p = 30$ cm, $y_B = 6.11$ cm, and $N = 4$ are plotted in Fig. 4 versus $n_0 / \langle \sigma v \rangle_{ion} v_B$. Note that the trapping efficiency is divided by $\text{erf}(1_{p0}/Z_B)$. In Ref. 4, the plasma length L_p is found to be 112 cm. Then, $1_{p0}/Z_B = 56/18.3 = 3.06$ and $\text{erf}(1_{p0}/Z_B) = 1$. Thus, the finite length of the beam is negligible for beams focused at $z = 0$. Note that in Ref. 4 it is assumed that the beams are focused at the beam dumps rather than the plasma center. Hence, the beam width Z_B was considerably larger. We show in Sec. 3 that flat plasma density profiles require more current aimed at the edges than in the center; we assume that $f_1 = 0.21$, $f_2 = 0.21$, $f_3 = 0.26$, and $f_4 = 0.32$. The overall trapping efficiency for $n_0 / \langle \sigma v \rangle_{ion} v_B = 0.02$ is found to be $\eta_t = 0.60$ for the case shown in Fig. 4. For all cases considered in the following section, we assume that $y_B = 6.11$ cm, $N = 4$, and $\{f_i\} = (0.21, 0.21, 0.26, 0.32)$.

Fig. 4 The beam trapping efficiency as a function of the plasma density n_0 for a cylindrical plasma. The trapping efficiency η_i is calculated for beams aimed at four points equally spaced along the y -axis from $y = 0$ to $y = R_p - y_B$. We assume the plasma radius $R_p = 30$ cm and the beam width $y_B = 6.11$ cm.

3. SENSITIVITY OF THE MFTF CURRENT REQUIREMENTS TO PARAMETRIC VARIATION

Definition of Approach

Perhaps the fastest way to assess the neutral-beam requirements for the MFTF reference case is by a simple particle-equilibrium calculation. This permits us to determine the sensitivity of the current requirements to many parameters. Once a particularly interesting configuration has been found, we can more accurately determine the current requirements using the BUILDUP code discussed in Sec. 4.

In this section, the MFTF reference case is considered to be the production of a large-diameter plasma with $\beta = 0.5$. Early work on this geometry¹ concentrated on the development of a flat-topped plasma density profile. The plasma confinement parameter in the boundary of this profile, $(n\tau)_b$, was obtained by quasi-linear scaling of the 2XIB experimental results. The confinement parameter in the interior was assumed to be $10^{12} \text{ cm}^{-2} \text{ s}$. In this report, we used the model proposed in Ref. 5 to determine the plasma confinement parameter. In this way, both particle and power balance are maintained. In addition to the flat-topped profile, we consider here a diffuse profile (assumed to be Gaussian).

If we adopt the notation of Ref. 4, the trapped current required to sustain plasma-density distribution $n(r, z)$ is given by

$$\eta_b I_b = I_{\infty} + 2\pi e \int_0^L r dr \int_{-R_p}^{R_p} \frac{dz}{n\tau} n^2(r, z), \quad (6)$$

where η_b = beam trapping efficiency,
 I_b = beam-line output current,
 I_{∞} = Plasma losses due to the flux of thermal gas incident on the plasma surface, and
 $n\tau$ = plasma confinement parameter.

We start with a general evaluation of Eq. (6). This is intended to be useful only in elucidating the dependence of the beam-line current I_b on parameters such as plasma β , average ion energy, and magnetic field. Then, we determine the current requirements for two specific plasma-density distributions: a Gaussian profile, and a flat-topped profile. To determine the general scaling of current, the plasma is modeled as a cylinder of length L_2 with a radial density profile given by $n_0 f(r/R_p)$,

where $f(0) = 1$ and R_p is in some sense the radial scale length of the plasma. We further assume that $n\tau$ is independent of radius so that

$$\eta_b I_b = I_{\infty} + \frac{2\pi L_2 e}{n\tau} (n_0 R_p)^2 \int_0^1 f^2(x) x dx,$$

where $x = r/R_p$.

Stability of the plasma against the DCLC mode requires that the radial plasma-density scale

$$\text{length } \rho_p = \left(\frac{1}{n} \left(\frac{\partial n}{\partial r} \right)^2 \right)^{-1/2} \text{ satisfy } \frac{\rho_p}{\rho_i} = N_s(T_e, \beta),$$

where ρ_i is the local ion gyroradius and $N_s(T_e, \beta)$ is the number of gyroradii across the plasma, as determined in Ref. 1. For this initial calculation, it is convenient to ignore finite- β effects on the gyroradius; this assumption cannot be justified for some profiles and will be treated correctly later. Furthermore, it is convenient to assume $R_p = \rho_{p0}$. Then,

$$\eta_b I_b = I_{\infty} + \frac{2L_2}{n\tau} \frac{N_s B^2}{2\mu_0} \frac{2m}{e^3 E_i} \beta_{0i}^2 \int_0^1 f^2(x) x dx,$$

where $\beta_{0i} = (n_0 e^2 L_2) / 2\mu_0$, μ_0 is the permeability of free space, E_i is the average ion energy, and B is the vacuum magnetic field.

Note that $2\beta_{0i} \int_0^1 f(x) x dx = \langle \beta \rangle$, the average plasma beta. For the diffuse profiles considered here, the value of $\langle \beta \rangle$ will be significantly less than the peak value β_0 .

We can now write the generalized current scaling equation

$$I_b = \frac{1}{\eta_i} \left[I_{\infty} + \frac{\pi L_2 m}{e^3 E_i n\tau} \left(\frac{N_s B \langle \beta \rangle}{2\mu_0} \right)^2 G \right],$$

where $G = \langle \beta \rangle^2 \beta_0$ is a profile-dependent geometry factor. We assume that the cold gas surrounding the plasma can be pumped fast enough to make the surface charge-exchange losses I_{∞} negligible. Because this is not necessarily a valid assumption, the currents calculated here will be smaller than actually required. The BUILDUP code treats these losses properly.

In Sec. 2, we saw that for small values of

$$\frac{dV}{dR} \approx n_0 R_p, \text{ the trapping efficiency is proportional to } n_0 R_p, \text{ i.e.,}$$

$$\eta_{tr} \propto \frac{N_B}{I_{tr}}.$$

Then to this accuracy, the required neutral beam current scales as

$$I_{tr} \propto G \frac{I_p N_s}{n_T (E_p)^{1/2}} \beta^{1/2} B. \quad (7)$$

There are several interesting points about this general scaling equation:

- There is only a relatively weak dependence on E_p . This is important since there is much uncertainty in predicting this parameter. For example, Fokker-Planck calculations with an injection energy of 60 keV and an electron temperature of 1.33 keV predict an average energy of 34 keV.⁴ The model that is used here (to be discussed later) finds an average energy of 40 keV. Scaling 2X11B results indicates that the ion energy could be as high as 50 keV.⁵ This difference may be caused by heating from the DCLC turbulence. This possible variation in the average ion energy alone causes an apparent 47% uncertainty in the energy and hence about a 20% uncertainty in the required beam current.

- The required beam current is determined by the average beta together with a profile-dependent geometry factor. This means that a plasma profile in which the average and peak betas are nearly equal (i.e., a flat profile) provides a more efficient use of beam current. This point will become more evident in comparing the flat-topped and diffuse profiles considered later.

- Uncertainties in the parameters L_q , N_s , and n_T are reflected linearly in uncertainties in the required beam current. The length used here is that determined by Stallard and Rensink¹ (we round the 68-cm length found in Ref. 4 to 70 cm). This length is dependent upon the electron temperature in the sense that losses from plasmas with higher electron temperatures are more nearly dominated by Coulomb collisions; hence, the plasmas are longer. However, this dependence is not included in this report.

- The value of $N_s = 13$ is as determined in the MFTF proposal¹ for an electron temperature of 1 keV. Again, the dependence of this parameter on electron temperature is not included in this report.

- Finally, we assume that plasma confinement is dominated by electron drag and that therefore n_T scales as proposed in Ref. 5. The scaling laws are given by:

$$n_T = 3.8 \times 10^{19} (1.1)^2 \left(1 + \ln \frac{E_p}{E_i} \right) \left(m^{-1/2} s \right), \quad (8)$$

$$E_i = T_e \left(\frac{61.4}{\log_{10} R} \right)^{2/3} \text{ (eV)}, \quad (9)$$

$$E_p = E_i \left[\frac{1 - E_i/E_p}{\ln E_i/E_p} \right] \text{ (eV)}, \quad (10)$$

where E_p is the average beam energy, E_i is the average plasma ion energy, and R is the mirror ratio [assumed to be $R_{crit}/(1 - \beta)$]. Note that there are two differences between these equations and those found in Ref. 5: electron temperature rather than mean electron energy is used as a variable, and the Coulomb logarithm is 15, rather than 20.

Diffuse Plasma-Density Profile

The plasmas produced in the 2X11B experiment typically have a diffuse (Gaussian) radial profile. The density profile is then fitted by

$$n(r) = n_0 \exp \left[- (r/R_p)^2 \right]. \quad (11)$$

We find the neutral-beam current required to sustain this profile by inserting Eq. (11) into Eq. (6) and integrating. The plasma radius R_p is determined by the requirement that the DCLC mode be stable at the desired electron temperature. This stability requires that the ratio of the local plasma-density scale length to the local ion gyroradius be greater than the number N_s , i.e.,

$$\frac{\rho_p}{\rho_i} = \frac{1}{n} \frac{1}{r} \left(\frac{\partial n}{\partial r} \right)^{-1} \geq N_s. \quad (12)$$

For a Gaussian profile, $\rho_p = R_p^2/2r$; hence, the scale length is dependent on the radius. We assume here that the DCLC stability condition must be satisfied from the axis to the radius that contains half the plasma; i.e., it must be satisfied for $r \leq 0.83 R_p$. Furthermore, we assume that the local ion gyroradius can be determined from the long, thin model; i.e., $\rho_i = (\rho_i)_{vac} (1 - \beta)^{1/2}$. Inequality (12) then becomes

$$\frac{\rho_p}{\rho_i} = \frac{R_p}{(\rho_i)_{vac}} \frac{(1 - \beta)^{1/2}}{1.66} \geq N_s. \quad (13)$$

Integration of Eq. (6) with the plasma distribution given by Eq. (11) yields

$$\eta_b I_b = I_{\text{ex}} + \frac{e 2 \pi R}{n \tau} \left(\frac{n \lambda \rho_b}{4} \right) \left| \frac{R_p}{(\rho_b)_{\text{ex}}} \right|^2. \quad (14)$$

The radially averaged density of a diffuse profile is significantly lower than the peak density. For the Gaussian profile assumed here, the average density to radius R is

$$n = \frac{2}{R} \int_0^R n(r) r dr = n_0 \left(\frac{R_p}{R} \right)^2 \left\{ 1 - \exp \left[- (R/R_p)^2 \right] \right\}$$

Clearly, if we assume that the profile is Gaussian for all radii (i.e., for $R \rightarrow \infty$), the average density is zero. A more realistic assumption is that the profile is Gaussian over approximately one order of magnitude, i.e., $R = \sqrt{2} R_p$. Then,

$$\frac{n}{n_0} = \frac{\beta}{\beta_0} = 0.43. \quad (15)$$

Thus, if a plasma is formed with a peak beta of $\beta_0 = 0.5$, the average beta $\beta = 0.215$.

We can now express Eq. (14) in terms of the β by noting that

$$n \lambda \rho_b = \frac{1}{0.43} \frac{2 \pi}{e E} \frac{\beta \cdot B}{2 e \mu_0},$$

where B is the vacuum magnetic field. Using this relationship together with Eqs. (8) and (13), we can write Eq. (14) as

$$\eta_b I_b = I_{\text{ex}} + 9.5 \times 10^{23} \frac{L_2 (\beta \cdot B N)^2}{E_b n \tau (1 - \beta)}, \quad (16)$$

where E_b and $n \tau$ are determined from Eqs. (10) and (8), respectively.

The required trapped current, i.e., $\eta_b I_b = I_{\text{ex}}$, is plotted as a function of electron temperature in Fig. 5. The trapping efficiency found in Sec. 3 is really only applicable to flat profiles. However, because the trapping efficiency for diffuse profiles would not be expected to be larger than for a flat profile, $\eta_b = 0.67$ is expected for $T_e = 1$ keV. Over 50 source modules would be required for $\langle \beta \rangle = 0.5$. It is evident, then, that for the Gaussian profile, the $\langle \beta \rangle$ that is achievable with reasonable beam

Fig. 5 The trapped current requirements $\eta_b I_b = I_{\text{ex}}$ for a Gaussian plasma profile as a function of the electron temperature for four values of average beta $\langle \beta \rangle$.

currents is low. It is desirable to produce a profile that uses the beams more effectively and fills the magnetic well more completely. Such a profile is the flat-top-profile considered next.

Flat-Topped Plasma-Density Profile

The flat-topped plasma-density profile used here is shown in Fig. 6. In the interior ($r < R_p - \lambda \rho_b / 2$), the plasma confinement parameter is $(n \tau)_b$; the plasma confinement parameter is $(n \tau)_b$ in the boundary $\{r \in [R_p - \lambda \rho_b / 2, (R_p + \lambda \rho_b / 2)]\}$.

Integration of Eq. (1) with this profile yields

$$\eta_b I_b = I_{\text{ex}} + \frac{\pi m}{2(\mu_0 e)^2} \frac{\langle \beta \rangle^2 B^2 L_2}{(E_b)_0 G^2} \left[\frac{1}{(n \tau)_b} \left(\frac{R_p}{\rho_b} - \frac{\lambda \rho_b}{2 \rho_b} \right)^2 + \frac{2 \lambda \rho_b}{3 \rho_b} \left(\frac{R_p}{\rho_b} - \frac{\lambda \rho_b}{4 \rho_b} \right) \right] \quad (17)$$

where

$$G = \frac{\langle \beta \rangle}{\beta_0} = \frac{\left(\frac{R_p}{\rho_b} - \frac{\lambda \rho_b}{2 \rho_b} \right)^2 + \frac{(E_b)_b \lambda \rho_b}{(E_b)_0 \rho_b} \left(\frac{R_p}{\rho_b} - \frac{\lambda \rho_b}{6 \rho_b} \right)}{\left(\frac{R_p}{\rho_b} + \frac{\lambda \rho_b}{2 \rho_b} \right)^2} \quad (18)$$

and where all units are in the MKS system except for the electron and ion energies, which are expressed in eV. The use of the subscript b in Eq. (17)

Fig. 6 Schematic of the flat-topped plasma-density profile. The interior (flat) region is defined to be $r < R_p - \lambda \rho_0 / 2$ and the boundary region is defined to be $r \in (R_p - \lambda \rho_0 / 2, R_p - \lambda \rho_0 / 2)$.

refers to the value of a parameter in the boundary; subscript 0 refers to the interior, or flat, portion of the profile.

Equation (17) is written with the assumption that the plasma radius required for stabilization is determined by $R_p / (\rho_0)_{var}$. Finite- β effects are less severe for flat profiles than for the diffuse profile. If the profile is truly flat, $\rho_0 = \left(\frac{1}{n} \frac{dn}{dr} \right)^{-1} \rightarrow \infty$ in the interior region, and the plasma is stable against the DCLC mode. In fact, the condition for stability, including finite- β effects, is

$$\frac{\rho_0}{\rho_1} > \frac{\rho_1}{(\rho_0)_{var}} \cdot (1 - \beta_0)^{1/2} > N_s(T_e, \beta).$$

Then, if we assume that the density decreases linearly with radius in the interior, the maximum permitted density change over radius R_p is

$$\frac{\Delta n}{n} < \frac{R_p}{(\rho_0)_{var}} \cdot \frac{(1 - \beta_0)^{1/2}}{N_s(T_e, \beta)}. \quad (19)$$

Finite- β effects require that the "flat" profile be more nearly flat. For example, if we choose $N_s \approx 50$ and $R_p / \rho_0 \approx 13$, then from Eq. (19) it is evident that at $\beta_0 = 0.5$, the density decrease in the interior can be as much as 20%. Since there will be radial mixing of the plasma over distances of at least an ion gyrodiameter, the plasma radius must be chosen to be at least several local ion gyrodiameters. In this report, we choose $R_p / \rho_0 = 13$.

It is interesting to compare the trapped current calculated using Eq. (18) (with $l_{ex} = 0$) with that determined using the BUI.DUP code. We have done this for two cases, the first using the following parametric values: $(E_e)_0 = (E_e)_b = 50$ keV, $(n\tau)_0 = (n\tau)_{ex} = 3 \times 10^{11}$ cm⁻³s, $L_2 = 0.7$ m, $\beta_0 = 0.5$, $R_p / \rho_0 = 13$, and $\lambda = 4$.

We find the required trapped current, using Eq. (18), to be 413 A compared to the 570 A determined using the BUI.DUP code. The second comparison was made with the same parameters except $(E_e)_0 = (E_e)_b = 30$ keV. In this case, the required trapped current was found to be 688 A using Eq. (18) and 905 A from the BUI.DUP code.

In both comparisons, the BUI.DUP code finds an approximately 35% higher trapped current. Including the surface charge-exchange losses (calculated from the BUI.DUP code) in Eq. (18) reduces the discrepancy to approximately 20%. This difference is attributable to differences between the plasma-density profile achieved with the BUI.DUP code and that assumed here. Since the density profile calculated by the BUI.DUP code is consistent with the beam deposition rate, it is more realistic. To account for these corrections, we increase the trapped current calculated by Eq. (18) (with $l_{ex} = 0$) by 35%.

The value of the plasma confinement parameter $(n\tau)_0$ obtained from Eq. (8) is approximately a factor of two higher than that used in the MFTF proposal.¹ Including enhanced scattering due to DCLC turbulence is expected to reduce the confinement. It is not clear how to include this turbulence in a manner that preserves both particle and power balance. One method, useful to assess the effect, is to increase the coefficient of the ion Coulomb scattering time used in deriving Eq. (9). This has the effect of increasing the particle loss rate and hence increasing the average ion energy. Both of these increases are expected from DCLC turbulence. We find that the required beam current is nearly (within 10%) independent of the Coulomb scattering coefficient. The effect of reduced particle confinement is just balanced by the increase in the average ion energy. It seems reasonable, then, to neglect the effect of DCLC turbulence and to use Eqs. (8) and (10) to determine the particle confinement time and average ion energy in both the interior region and the boundary. The values of the electron temperatures in these regions are chosen consistent with R_p / ρ_0 and λ . Thus, for $R_p / \rho_0 = 13$ and $\lambda = 4$ we choose $(T_e)_0 = 1000$ eV and $(T_e)_b = 200$ eV.

The $\langle \beta \rangle$ that can be achieved is plotted in Fig. 7 as a function of the number of source modules

Fig. 7 The achievable average plasma beta $\langle \beta \rangle$ as a function of the number of source modules. Curves (a) and (b) are for the flat-topped profile, with (a) being for the present LBL sources ($E_{ii} = 50$ keV) and (b) being for a future source with higher beam energy ($E_{ii} = 64$ keV). Curve (c) is for a Gaussian plasma-density profile and the present LBL source.

(and power supplies) available on MFTF. As previously discussed, the current calculated from Eq. (18) is increased by 35% to calibrate it with the BUILDUP code results. We obtain the trapping efficiency η_t using the techniques outlined in Sec. 2,

and use the beam-line output current per source module that is also determined in Sec. 2. We consider two source modules: the present LBL module and an anticipated module with better molecular mix and therefore higher beam energies. The corresponding curve for a diffuse profile obtained with the present LBL source module is also included in Fig. 7. (The trapping efficiency is assumed to be $\eta_t = 0.67$ for this case.) With the LBL source, we find that the average ion energy calculated from Eq. (10) is about 35 keV, while it is about 43 keV for the "future" source. The interior confinement parameter $(n\tau)_{ii} \approx 2 \times 10^{12} \text{ cm}^{-3}\text{s}$ for both sources. DCLC turbulence is expected to increase the average ion energy and to reduce the plasma confinement, but the current requirements will remain approximately the same as shown in Fig. 7.

The sensitivity of the current required to achieve $\langle \beta \rangle \approx 0.5$ to variations in parametric values is shown in Fig. 8. In Fig. 8(a), we show the sensitivity to the boundary parameters λ and $(T_e)_{ii}$, and in Fig. 8(b) we show the sensitivity to the interior parameters R_p/ρ_0 and $(T_e)_{ii}$. The reference case of $\lambda = 4$, $R_p/\rho_0 = 13$, $(T_e)_{ii} = 1000$ eV, $(T_e)_{ii} = 200$ eV requires approximately 1430 A, and the plasma confinement and average energy are $(n\tau)_{ii} = 2.2 \times 10^{12} \text{ cm}^{-3}\text{s}$, $(\bar{E}_i)_{ii} = 34$ keV, $(n\tau)_{ii} = 3.4 \times 10^{11} \text{ cm}^{-3}\text{s}$, and $(\bar{E}_i)_{ii} = 20$ keV.

The current requirements can be significantly reduced by decreasing λ , even if there is a resultant decrease in $(T_e)_{ii}$. This arises because of an increase in the value of $G = \langle \beta \rangle / \beta_{ii}$. However, the BUILDUP code results indicate that the beam aiming required to produce a flat profile in the interior will also produce a boundary region with $\lambda = 4$.

Fig. 8 The dependence of the beam-line output current I_{ii} on the parameters of a plasma with a flat-topped density profile with an average beta $\langle \beta \rangle \approx 0.5$. Dependence upon the electron temperature and $(T_e)_{ii}$, and the parameters in the boundary is shown in (a) and dependence on the central-plasma parameters is shown in (b). Data points show values for the MFTF reference case.

Hence, the size of the boundary region is probably not an independently adjustable parameter.

If the radius of the interior is reduced from $R_p/\rho_e = 11$, the electron temperature will probably decrease to 800 eV.¹ Therefore, the required neutral beam current will increase from 1430 A to 1560 A, and attempting to make a smaller plasma will not reduce the required current. Increasing the plasma radius so that $R_p/\rho_e = 15$ could reduce the current required to 1350 A if the electron temperature increases to 1200 eV.

In summary, we have studied the neutral-beam current requirements for two radial plasma profiles.

The first, a diffuse (Gaussian) profile, was found to require in excess of 50 source modules to sustain a large-diameter plasma with an average beta of $\beta = 0.5$. This large current is required because $\beta = 0.4 \mu_n$ for the assumed Gaussian profile. The

current requirements are somewhat more modest for a flat topped profile in which $\beta/\beta_n = 0.75$. Then, only 28 source modules are required to achieve $\beta = 0.5$. The 24 modules specified in Ref. 1 are sufficient to achieve $\beta = 0.46$, which is within 10% of the MFEF goal. This is within the accuracy of these calculations and therefore does not indicate the need for redefinition of the MFEF goals.

4. CALCULATIONS WITH THE BUILDUP CODE

Description of the Code

In Sec. 3, we used analytic models to study the effect of variations in the assumed values of certain parameters. In this section, we present results obtained with the aid of a finite difference code, BUILDUP, that solves for the radial profiles of density as a function of time, thereby allowing us to study the evolution of the plasma. This code was originally described in Ref. 15; it has since undergone considerable modification to improve the accuracy of the numerical procedures and to add some new physics to the model.

The basic equation is that for the density N of guiding centers at radius r , written as

$$\frac{dN(r,t)}{dt} = S_{\text{ion}} - S_{\text{ce}} - S_{\text{w}} - S_{\text{fl}} \quad (20)$$

where S_{ion} is the volume rate of addition of guiding centers at r resulting from ionization of both the incident beam and the "charge-exchange beam" (atoms resulting from charge exchange off the incident beam); S_{ce} is the rate of loss of guiding centers at r resulting from charge exchange off either the incident beam or the charge-exchange beams; S_{w} is the rate of loss of guiding centers due to charge exchange with atoms or molecules refluxing from the wall, and S_{fl} is the rate of loss of guiding centers resulting from Coulomb collisions or rf fluctuations and is proportional to $(n_T)^{-1}$. The particle density at radius r is related to N via

$$n(r,t) = \frac{2}{\pi} \int_0^{\pi} \theta(r',t) \frac{1 - \rho(r',t) \theta(r',t) \rho(r',t)}{\{[r - r']^2 + \rho(r',t)^2\} \{[r' + \rho(r',t)]^2 + r^2\}^{1/2}} N(r',t) r' dr' \quad (21)$$

where $\theta(x) = x_+/x$ is the Heaviside function.

In computing S_{ion} and S_{ce} , BUILDUP accounts for the finite Larmor radius; i.e., the absorption of a beam atom adds to the guiding-center density at a location $\rho_A(\mathbf{v} \times \mathbf{B})/|\mathbf{v}|$ away. This important effect is illustrated in Fig. 9. Ionization or charge exchange at T adds to N at B ; charge exchange subtracts from N at A . Thus, in the orientation of $\mathbf{v}$ and $\mathbf{B}$ shown in Fig. 9, charge exchange off the beam causes a net outward diffusion of guiding centers. This effect can be used to advantage in balancing the losses due to surface erosion S_{w} in Eq. (20). In the strong density gradients at the edge of the plasma, the absorption of beam atoms occurs

at the inner portion of the ion orbit, where the density is higher, thus ensuring good trapping efficiency. Surface erosion occurs where density is lower, namely, on the outermost portion of the orbit. In the calculations for MFTF, we have assumed beam aiming for outward displacement.

BUILDUP computes the attenuation of both injected and charge-exchange beams along the center-line of the beams. Multiple generations of charge-exchange atoms are considered. However, these atoms are assumed to propagate only with or counter to the injected beams, thereby neglecting angular scattering.

Three beams of two different energies, six beams in total, are allowed for in the code. The plasma, likewise, is considered to consist of two energy groups, for MFTF, one component is furnished by the start-up beams at an assumed mean energy of 14 keV; the other is the main sustaining beam at 50 keV. No energy equations are used in the code, but the (n_T) value comes from energy considerations discussed elsewhere in this report.

To evaluate the surface charge-exchange term S_{w} , we must know the densities of the molecules and the reflux atoms at the plasma surface. We assume that plasma ions lost by charge exchange reflux either as atoms or as molecules. In the present case, because of high plasma energy, charge-exchange particles penetrate the chamber surface and atomic reflux is probably negligible. To be conservative, we have taken the atomic reflux

Fig. 9 Schematic of beam trapping in plasma. Trapping at T deposits a guiding center at B . Charge exchange at T moves a guiding center from A to B .

coefficient as $\Gamma_{1a} = 0.1$. Because of the deposit of titanium on the walls, there is probably no molecular reflection, $\Gamma_{1m} = 0$, although a special case considered *below* allows full molecular reflux to be turned on at $t = 0.15$ s. There are, however, several other sources of molecules in the volume V_1 surrounding the plasma: background density n_{atom} at the initiation of the experiment, streaming gas down the neutral beam lines (given as equivalent current), and gas streaming in through openings in the magnet (equivalent area A_{12}) from the volume V_2 outside of the magnets. The molecular density around the plasma n_m varies with time as a result of these effects, as does the molecular density n_{m2} in the outer volume V_2 . Additional sources of molecules in V_2 are the ions that scatter into the loss cone and the atoms and molecules that charge exchange on the plasma surface and are swept out by the ambipolar potential. Both are assumed to reflux in V_2 as molecules. A pumping area A_2 with sticking probability $S_{2m} = 0.3$ is also included in the outer volume.

The loss term S_1 is computed with a model involving two zones:

- A central region of radius r_p where the DCLC instability is stabilized by finite β and small density gradient and where losses are via classical processes; and
- A boundary layer of thickness δr where the DCLC mode is suppressed by a warm, streaming plasma, but at the expense of lowered T_p and reduced n_T . The thickness of the boundary layer is not known *a priori*, but is obtained as part of the solution. Typical solutions yield $\delta r \approx 4\rho_{\text{De}}$, where ρ_{De} is based on the vacuum field.

A typical BUILDUP calculation for MFTF proceeds as follows: at $t = 0$, the streaming-plasma guns are turned on to provide a target plasma, as are the startup- and sustaining-beam modules. The code solves Eq. (20) together with the appropriate expressions for the injection beams, the charge-exchange beams, reflux beams, and molecular and atomic densities in volumes V_1 and V_2 . The target stream is turned off at 5 ms (but a stabilizing stream must be left on in the boundary layer) and the startup beams are terminated at 10 ms. The evolution of the plasma can be followed for the 0.5-s duration of the experiment; steady state is usually found after about 0.15 s. We have run a reference case, corresponding to the parameters in Table 3, and also several variations. The results are described in the following discussions.

Reference Case

For the reference case, we used the parameters listed in Table 3. The currents in the three available beams as well as their positions were ad-

Table 3. Parametric values for the MFTF reference case.^a

Parameter	Value
Startup beams:	
Average beam energy, E_0	14 keV
Beam current, I_0	1000 A
Beam duration, Δt	10 ms
Sustaining beams:	
Average beam energy, E_m	50 keV
Beam current, I_m	750 A
Beam duration, Δt	0.5 s
Startup conditions:	
Stream density, n_{atom}	2×10^7 particles/cm
Stream radius, r_{atom}	27.5 cm
Stream duration, Δt_{atom}	5 ms
Molecular density at $t = 0$, n_{m0}	3×10^7 particles/cm
Magnetic field, B	2.0 T
Electron plasma confinement parameter, $(nT)_e$	10^7 cm ⁻³ s
Boundary plasma confinement parameter, $(nT)_b$	3×10^7 cm ⁻³ s
Plasma length, L	134 cm

$$\text{First density moment} = \langle r^2 \rangle = 2 \int_0^{1.2} n^2 dr / n_0 I_0 = 0.836$$

$$\text{Second density moment} = \langle r^4 \rangle = 2 \int_0^{1.2} n^4 dr / n_0 I_0 = 0.522$$

Wall conditions:

Reflux coefficients	Γ_{1a}	0.1
	Γ_{1m}	0.0
	Γ_{2a}	0.0
	Γ_{2m}	0.5
	Γ_b	0
Sticking coefficients	$\{S_{1a}, S_{1m}\}$	0
	$\{S_{2a}, S_{2m}\}$	0.3

(Note: for both reflux and sticking coefficients, subscripts denote the following: $a = \text{atomic}$, $m = \text{molecular}$, and 1 and 2 refer to surfaces surrounding the plasma and outside the magnets, respectively.)

Areas and volumes:

Pumping area surrounding plasma, A_1	30.9 m ²
Pumping area outside magnets, A_2	88 m ²
Area of openings in magnet (connects V_1 to V_2), A_{12}	12 m ²
Volume around plasma, V_1	30 m ³
Volume outside magnets, V_2	400 m ³

^aFrom Ref. 15.

justed to obtain a flat plasma density profile with $n = 0.5 \text{ cm}^{-3}$ at $r = 50 \text{ keV}$ in the central region. Because only three beams were available in the BUII DUP code (as contrasted to the 24 beams available in the experiment), it was not possible to obtain a completely flat central profile.

The plasma density profile of the 14-keV plasma component at $t = 0.01 \text{ s}$ together with the beam currents and positions are shown in Fig. 10. We note that although far less beam current is "aimed" at the outer region than the center, the density profile is quite flat, implying that there is a fairly uniform rate of addition of ions. The apparent contradiction is resolved by noting that the beams aimed at the center also pass through the outer regions, where they deposit ions. At 14 keV, because of the large charge-exchange cross section, the trapping in the outer layers is substantial.

Density profiles for both plasma components as well as total density at $t = 0.01 \text{ s}$ are shown in Fig. 11. The radius of the flat central region is about 32 cm. Total density has already risen to about $7 \times 10^{13} \text{ cm}^{-3}$ at this time.

The plasma has reached steady state with central density $n = 10^{13} \text{ cm}^{-3}$ at $t = 0.2 \text{ s}$. The profile of density as well as the aiming for the 50-keV beam is given in Fig. 12. The sustaining beams require the direction of more beam current at large radii than the startup beams because of the lower trapping

Fig. 10 Density of 14-keV plasma component at $t = 0.01 \text{ s}$ together with startup-beam current distribution for MFTF reference case (see Table I).

Fig. 11 Density of 14-keV and 50-keV plasma components and total density at shut-off of startup beams ($t = 0.01 \text{ s}$) for MFTF reference case.

cross section. As mentioned earlier, the finer control furnished by more beams would allow a flatter profile to be attained. We see that a sustaining-beam current of 750 A incident on the plasma is just adequate to achieve $\beta_n = 0.5$ in a central region of radius $R_p = 30 \text{ cm}$ with a sharp falloff of density outside this region. This is the calculation we used to normalize the analytical results in Sec. 3.

Fig. 12 Plasma density at $t = 0.2 \text{ s}$ with sustaining-beam current distribution for MFTF reference case. The Larmor radius ρ_0 at the plasma center is shown. The plasma confinement parameter $n\tau$ is $10^{12} \text{ cm}^{-3} \cdot \text{s}$ for $r < 27 \text{ cm}$ and $3 \times 10^{11} \text{ cm}^{-3} \cdot \text{s}$ for $r > 27 \text{ cm}$.

Fig. 13 Total neutral-beam and Coulomb loss (equivalent) currents vs time for MFTF reference case.

Several additional quantities of interest for the reference case are shown in Figs. 13 through 16. The total beam current (equivalent amperes) as well as the total losses due to Coulomb scattering are shown in Fig. 13 as a function of time. Barely visible near $t = 0$ is the finite rise time of the beam current, taken as 1 ms. Surface losses are given in Fig. 14. The slow rise in surface losses reflects the slow rise in molecular density outside the plasma.

Fig. 14 Plasma loss rate via charge exchange on reflux at 0.01 s and molecules at surface (equivalent current) for MFTF reference case.

Fig. 15 Unabsorbed neutral beam and charge exchange off the neutral beam that leave the plasma (equivalent current) for MFTF reference case.

The total unabsorbed beam current as well as the charge-exchange current off the beam that leaves the plasma is shown in Fig. 15. The unabsorbed beam peaks at 1 ms, reflecting the finite rise time of the injected beam. The charge exchange off the beam peaks at the later time, when the density has built up enough to cause appreciable charge exchange off the plasma.

The net current to the plasma (i.e., the right-hand side of Eq. (20) integrated over the entire plasma) is shown vs time in Fig. 16. An interesting feature is the net loss of plasma that occurs just after 0.01 s. This loss is associated with the shut off of the startup beams. When both startup and sustaining beams are on, the plasma builds up to a radius larger than can be supported by just the 750-A sustaining-beam current. When the startup

Fig. 16 Net rate of addition of ions to plasma for MFTF reference case.

beams are shut off, the Coulomb and surface charge-exchange losses are greater than the beam absorption, causing the plasma to shrink slightly to a size that the sustaining beams can support.

Effects of Changes in $n\tau$

If the plasma confinement times do not meet the predicted values of 10^{12} and 3×10^{11} cm³·s in the central and boundary regions, respectively, then the beam-current requirements will be altered. Rather than attempt to find the current requirements under changed conditions, we hold the currents as specified for the reference case and study the plasma properties when the confinement times are reduced.

The steady-state plasma-density profile for a central $(n\tau)_c = 5 \times 10^{11}$ cm³·s is shown in Fig. 17. Beam aiming was the same as for Figs. 10 and 12. We note a reduction in central density to about 7×10^{13} cm⁻³ particles and somewhat of a bump in density near the edge of the central region, but the plasma radius remains at about 30 cm. Clearly, β_0

0.5 could be attained at this lowered $n\tau$, but only by re-aiming the beams for a smaller plasma radius. Some idea of the scaling of r_p and n with $n\tau$ can be obtained by noting that most of the absorbed beam current is lost in Coulomb scattering at steady state (see Fig. 13). Thus, we have an approximate relation for the central region:

$$\eta_1 I_b = \frac{n^2 \pi r_p^2 L}{n\tau}$$

Fig. 17 Steady-state plasma-density profile for $(n\tau)_c = 5 \times 10^{11}$ and $(n\tau)_b = 3 \times 10^{11}$ cm³·s.

If the trapping efficiency η_1 and other parameters remain fixed when $n\tau$ is reduced, then

$$n \propto (n\tau)^{-1/2}$$

and a reduction in $(n\tau)_c$ from 10^{12} to 5×10^{11} cm³·s should reduce n_c from 10^{14} to about 7×10^{13} particles cm⁻³, as it does. Inspection of the results shows that η_1 also drops from 78% to 67%.

Another possibility is that $(n\tau)_c$ will not be as large as predicted by scaling from 2XHB results. Figure 18 shows the steady-state plasma-density profile for the same conditions as the reference case but with $(n\tau)_c$ reduced to 1.1×10^{11} cm³·s. The total beam current remained the same, but the beam current distribution was shifted somewhat, as shown in Fig. 18, to maintain a flat central density profile. We note that the plasma radius has shrunk from 30 to 25 cm as a result of the enhanced losses in the boundary layer. Thus, we would obtain $R_p/p_0 \approx 11$ rather than 13 as desired. Such a decrease in R_p/p_0 would reduce T_e in the interior and hence reduce $(n\tau)_c$.

Effects of Changes in I_b

Each beam module is expected to furnish about 50-A equivalent current. Experience with the neutral-beam sources on 2XHB shows that on occasion a module fails to deliver current. We have studied the effect of dropping out 50 A in each of

Fig. 18 Steady-state plasma-density profile for $(n\tau)_c = 10^{12}$ and $(n\tau)_b = 1.1 \times 10^{11}$ cm³·s. Beam currents distributed as shown.

the beams shown in Fig. 12. The largest effect occurs when the outermost beam is reduced. The resultant density profile for this latter case is shown in Fig. 19. We find only a slight shrinkage of the density profile over the reference case.

Effects of Changes in Molecular Sources

The reference case has included estimates for the sources of molecular gas outside the plasma. It is desirable to study possible increases in two sources: wall reflux, and molecular gas streaming down the beam line from the neutral-beam source. In the former case, we assume that good wall preparation yields a zero reflux coefficient of incident energetic atoms as molecules. We estimate the steaming molecular current at 8% of the neutral-beam current I_B . The effect on the steady-state density of doubling the molecular stream to 16% of I_B is shown in Fig. 20. The added erosion of the surface has caused the plasma radius to shrink by about 3 cm. The molecular density surrounding the plasma has increased from 2.4×10^{11} to 3.3×10^{11} particles/cm³.

To study the effect of molecular reflux of charge-exchange atoms, we have arbitrarily assumed that after $t = 0.15$ s, all charge-exchange atoms reflux as molecules. Figure 21 shows the

Fig. 19 Steady-state plasma-density profile when the outermost beam from the case of Fig. 12 is reduced by 50 A. Figure 12 plasma-density profile shown dashed.

Fig. 20 Steady-state plasma-density profile for a molecular gas stream equal to 16% of neutral-beam current. Figure 12 plasma-density profile shown dashed.

erosion of the density profile to a steady-state value near $t = 0.5$ s. Both of these results show that the plasma should be tolerant to a somewhat enhanced molecular density; that is, build up to a steady state is not prevented, but there is some reduction in plasma radius.

Fig. 21 Evolution of plasma-density profile when all charge-exchange atoms are assumed to reflux as molecules after $t = 0.15$ s. Otherwise as Fig. 12.

Effects of Changes in $\bar{E}_1$

The parametric variation discussed in Sec. 3 indicated that the required beam current should increase considerably if the mean plasma energy were reduced. We can study this effect also with the BUILDUP code, but not in as much detail because of the number of iterations in beam aiming and current required to establish a flat density profile. We therefore choose to study one variation on the base case, a reduction in the mean ion energy from 50 keV to 30 keV.

Maintenance of $\beta_0 \approx 0.5$ requires a density of 1.7×10^{13} particles/cm³. The requirement $R_p/\rho_0 = 13$ allows a smaller radius, $R_p \approx 22$ cm. Re-aiming

the beams to yield a flat density profile for a plasma of this radius, we find the density distribution shown in Fig. 22(a). The plasma radius is about 19 cm with a mean density of 1.6×10^{14} ; both values are somewhat below the MFTF goals.

An increase in beam current to 1000 A yields the density shown in Fig. 22(b). The radius and density have improved to 22 cm and 1.8×10^{13} particles/cm³, respectively. We thus find agreement with the results of Sec. 3: increased beam current is required if the mean energy is indeed less than the beam energy, as predicted by Fokker-Planck codes.⁴

Fig. 22 Plasma-density profiles for $\bar{E}_1 = 30$ keV and with beam aiming to produce $R_p \approx 22$ cm: (a) other parameters as in Table I, and (b) with sustaining-beam current of 1000 A.

5. NEUTRAL-BEAM CURRENT REQUIREMENTS FOR FIELD-REVERSAL EXPERIMENTS

In Secs. 3 and 4, we assumed that the MFTF plasma is a large-diameter $\beta = 0.5$ plasma; this was the initial goal proposed in Ref. 1. An alternative to this conventional mirror configuration is the field-reversed geometry.¹⁰ In addition to several studies of the possibility of achieving this geometry with neutral-beam injection,^{6,7} there have been experimental investigations in 2XIB.¹¹ Since the advantages of the field-reversed geometry are great, we expect that the MFTF will be used for studies of the plasma buildup to field reversal. The possibility of these experiments has been reviewed.⁶ Subsequently, the physics requirements for field reversal by buildup from neutral beams were more completely analyzed and reassessed.⁷ In this section, we present some additional estimates of the current requirements for plasma buildup to field reversal.

In Ref. 7, the requirements for buildup to field reversal were to be:

- The plasma should contain some higher atomic number (higher-Z) impurity, such as 10% He⁺⁺ or 1% C³⁺; and
- The minimum injection current is that required to reach $\Delta B/B = 1$ with open confinement, where the plasma radius R_p is

$$R_p/p_i = 4, \quad (22)$$

where p_i is the deuterium ion gyroradius in vacuum.

The first requirement is necessary to produce an "Okawa current" near the field null; such impurities can be added either from streaming-plasma sources or from some of the neutral-beam modules. We shall now use the methods developed in Sec. 3 to estimate the injection current needed to achieve the second requirement.

The scaled radius R_p/p_i specified by Eq. (22) is much smaller than that used in the previous sections of this report. Reducing the ratio R_p/p_i by direct reduction of the radius R_p is limited by the divergence of the neutral-beam modules. Lowering R_p/p_i by increasing the average ion energy $\bar{E}_i$ would require much higher energy beams because of the square root dependence of p_i on $\bar{E}_i$. Such neutral beams are not presently being planned for MFTF, although they have been discussed.¹⁸ The magnetic field B is thus the most effective parameter for

lowering the scaled radius R_p/p_i by raising the gyroradius p_i . Therefore, we choose the low-field example (the 1.07-T case of Ref. 6) as the starting point for these buildup calculations.

The trapped current required to achieve $\Delta B/B = 1$ can be calculated using the techniques developed in Sec. 3. For these small-diameter plasmas, we assume that the plasma profile is Gaussian; hence, we use Eq. (16) to determine the required trapped current for the long, thin model. Since $R_p/p_i = 4$ and $B = 1.07$ T, this plasma is quite similar to the present 2XIB experiment, and we scale the plasma parameters from those results. We expect the average ion energy to be near the beam energy, which (including both the startup and the sustaining beams) is approximately 35 keV. Thus, we assume $\bar{E}_i = 30$ keV and $n\tau = 2 \times 10^{11}$ cm⁻³s. We use the same plasma length as in Ref. 6: $L_z = 50$ cm.

The trapped current required is plotted as a function of $\langle\beta\rangle$ in Fig. 23, where the effect of plasma pressure on R_p/p_i is approximated using the long, thin model. In this case, the field on the center is zero; i.e., $\Delta B/B = 1$ for $\beta_0 = 1$ or $\langle\beta\rangle = 0.42$. This requires a trapped current of only 450 A. Because the trapping efficiency for a beam aimed at the center with this plasma is only 0.3, we estimate a total beam current (assuming a 35% increase for surface charge-exchange losses) of approximately 2000 A. This is nearly the total current we expect to obtain with 24 sustaining and 24 startup source modules.

Because the plasmas described here are actually rather short and fat, the long, thin model is a poor representation. Therefore, to null the field on the axis we must achieve $\beta_0 > 1$. Since this plasma is rather similar to the 2XIB plasma, we expect $\beta_0 \approx 2$ for $\Delta B/B = 1$. We obtain a lower limit for the required current by neglecting the plasma-pressure corrections for R_p/p_i , as suggested in Ref. 7. The trapped current required for no finite- β correction is also shown in Fig. 23. For this case, $\langle\beta\rangle = 0.86$, the trapped current required is 1051 A, and the trapping efficiency is approximately 0.4. Therefore, more than 2500 A is required. Thus, for both plasma models assumed here, at least 24 sustaining and 24 startup neutral-beam modules are required for experiments to study the plasma buildup to field reversal.

Fig. 23 The trapped current $\eta_T B$ required for field-reversal studies as a function of average plasma beta $\langle \beta \rangle$. The condition $\Delta B/B \approx 1$ requires $\langle \beta \rangle = 0.43$ for a long, thin plasma and $\langle \beta \rangle = 0.86$ for a short plasma with no finite- β correction. We assume that the plasma density has a Gaussian profile with $R_s/\rho_s = 4$.

6. SUMMARY AND CONCLUSIONS

To summarize, we have reassessed the number of neutral-beam power supplies required to achieve the goals of the MFTF. We began with an examination of the beam-line output current expected from each module and found that the molecular mix of the present LBL sources will produce an output current of 51 A with an average beam energy of 50 keV. Improvements in source design to increase the average beam energy will lead to a reduction in beam current since the neutralizer efficiency decreases as the energy increases. For example, the molecular mix in sources using the so-called MacKenzie bucket will produce a module with an output current of 37 A and an average ion energy of 64 keV. This source improvement will be required to achieve the MFTF goal of an average ion energy of 50 keV.

The neutral beam current requirements for a plasma with $\beta = 0.5$ have been examined for two different radial plasma profiles. The first, a diffuse (Gaussian) profile, was found to require in excess of 50 source modules to sustain a large-diameter plasma. This large current is required because the average beta is only four tenths the peak beta for the assumed Gaussian profile. The current requirements are somewhat more modest for a flat-topped profile in which the ratio of the average beta to peak beta is approximately three-fourths. For this profile, only 28 source modules are required to achieve an average beta of 0.5. The 24 modules specified in Ref. 1 are sufficient to achieve an average beta $\sim \beta = 0.46$, which is within 10% of the

MFTF goal. This is within the accuracy of these calculations.

Calculations of the average ion energy *that will be achieved on the MFTF* remain somewhat uncertain. Simple models that neglect the effect of DCLC turbulence predict an average ion energy varying from 35 keV to 45 keV, depending on the average beam energy. Turbulence from the DCLC mode is expected to raise the energy. The MFTF goal of $E_i = 50$ keV will be possible only with sources in which the molecular mix is improved over that of the present LBL source. Since the neutralizer efficiency is lower, these sources will require more modules to achieve $\sim \beta = 0.5$. The current requirements estimated here are relatively insensitive to the effects of DCLC turbulence. We expect that this activity will both increase the average ion energy and decrease the plasma confinement time. To first order, these effects cancel, and the current requirements are independent of DCLC turbulence.

Finally, we examined the current requirements for experiments to study plasma buildup to field reversal. We found that the combination of 24 startup (20-keV) and 24 sustaining (80-keV) modules is just sufficient to achieve a plasma in which $\Delta B/B = 1$. This is possible at low fields ($B = 1.07$ T) and small-radius plasmas ($R_p/\rho_i = 4$). Hence, we find that the current requirements for both a large-diameter, $\beta = 0.5$ plasma and a field-reversed plasma are consistent with the MFTF proposal.¹

7. REFERENCES

1. F. H. Coensgen, Project Leader, *MX* [now MFTF] *Major Project Proposal*, Lawrence Livermore Laboratory, Rept. LLL-Prop-142 (1976).
2. *Report of the Open Systems Technical Review Panel*, W. R. Ellis, Chairman, USERDA, Rept. ERDA 76-140 (1976).
3. F. H. Coensgen, LLL, Internal Document MFE CP-77-1 (1977) Readers outside the Laboratory who desire further information on LLL internal documents should address their inquiries to the Technical Information Department, Lawrence Livermore Laboratory, Livermore, California 94550.
4. B. W. Stallard and M. E. Rensink, *Neutral Beam Current Requirements for MX*, Lawrence Livermore Laboratory, Rept. UCRL-52205 (1977).
5. J. W. Shearer, *Analytical Estimates for Higher Energy Neutral Beams in MFTF*, Lawrence Livermore Laboratory, Rept. UCID-17692 (1977).
6. J. W. Shearer and W. C. Condit, *Field Reversal Experiments in the Mirror Fusion Test Facility (MFTF)*, Lawrence Livermore Laboratory, Rept. UCRL-52373 (1977).
7. D. F. Baldwin and T. K. Fowler, *A Reassessment of the Requirements to Obtain Field Reversal in Mirror Machines*, Lawrence Livermore Laboratory, Rept. UCID-17691 (1977).
8. J. H. Fink and C. E. McDowell, "Ionization, Charge Exchange, and Secondary Electron Emission in the Extraction of an LBL LLL Neutral Beam Source," in *Proc. Sixth Symp. Engineering Problems Fusion Research, San Diego, CA, 1975* (IEEE, 1975); also Lawrence Livermore Laboratory, Rept. UCRL-77105 (1975).
9. O. A. Anderson, *Parasitic Components from Charge Transfer in Neutral Beams for Fusion*, Lawrence Livermore Laboratory, Rept. UCID-17581 (1978).
10. K. H. Berkner, Lawrence Berkeley Laboratory, private communication (1978).
11. K. H. Berkner, R. V. Pyle, and J. W. Stearns, "Intense, Mixed-Energy Hydrogen Beams for CTR Injection," *Nucl. Fusion* **15**, 249 (1975).
12. C. F. Barnett, J. A. Ray, E. Ricci, M. I. Wilker, E. W. McDaniel, E. W. Thomas, and H. B. Getbody, *Atomic Data for Controlled Fusion Research*, Oak Ridge National Laboratory, Rept. ORNL-5206 (1977).
13. L. Stewart, Princeton Plasma Physics Laboratory, private communication (1978).
14. A. C. Paul, *Evaluation of High Powered Neutral Beam Energy Deposition*, Lawrence Berkeley Laboratory, Rept. UCID-3827 (1976).
15. B. W. Stallard, *Radial Plasma Buildup Code for Neutral Beam Injection into a Mirror Machine*, Lawrence Livermore Laboratory, Rept. UCRL-51784 (1976).
16. W. C. Condit, T. K. Fowler, R. F. Post, *Status Report on Mirror Alternatives*, Lawrence Livermore Laboratory, Rept. UCRL-52008 (1976).
17. J. F. Clauser, F. H. Coensgen, D. L. Correll, W. F. Cummins, R. P. Freis, R. K. Goodman, A. L. Hunt, T. B. Kaiser, G. M. Melin, W. E. Nexsen, T. C. Simonen, B. W. Stallard, and W. C. Turner, *Field Reversal Experiments in a Neutral Beam Injector Mirror Machine*, Lawrence Livermore Laboratory, Rept. UCRL-80857 (1978).
18. C. C. Damm, F. H. Coensgen, R. S. Devoto, A. W. Molvik, G. D. Porter, J. W. Shearer, and B. W. Stallard, *Directions for Possible Upgrades of the Mirror Fusion Test Facility (MFTF)*, Lawrence Livermore Laboratory, Rept. UCRL-80475 (1977).