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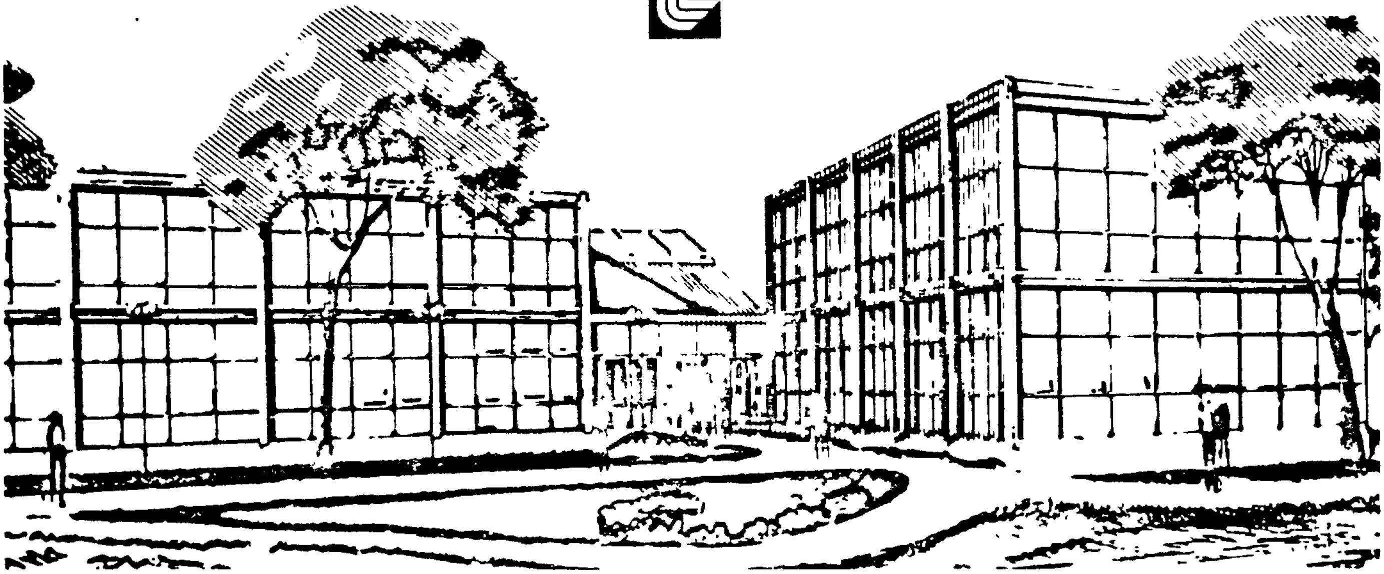

DISCLAIMER

DIRECTIONS FOR POSSIBLE UPGRADES OF THE MIRROR FUSION TEST FACILITY (MFTF)*

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ABSTRACT

The Mirror Fusion Test Facility (MFTF) may be upgraded by extending the time of plasma sustenance in an approach to steady-state operation and/or by increasing the neutral-beam injection energy. Some parameter bounds for these upgrades are discussed as they relate to a definition of the required neutral-beam development.

INTRODUCTION

We have made a preliminary study of possible Mirror Fusion Test Facility (MFTF) upgrades. Some results of this study are presented here to help define the neutral-beam development required to achieve these improvements in the capabilities of MFTF.

Preliminary design of the MFTF, based on the original Proposal,[1] has been underway for more than a year, and line-item funding for the construction project began in FY1978. Completion is expected in FY1981. The heart of the facility is a large, superconducting "Yin-Yang" magnet that confines a plasma fed by an array of energetic neutral beams (Fig. 1). The main machine parameters and the "base-case" plasma parameters are listed in Table 1. These parameters were specified in the Proposal [1] to achieve the main scientific objective of the facility, which is to extend the theoretical scaling laws for the microinstabilities characteristic of the mirror loss-cone ion distribution. The technological objectives of

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MFTF

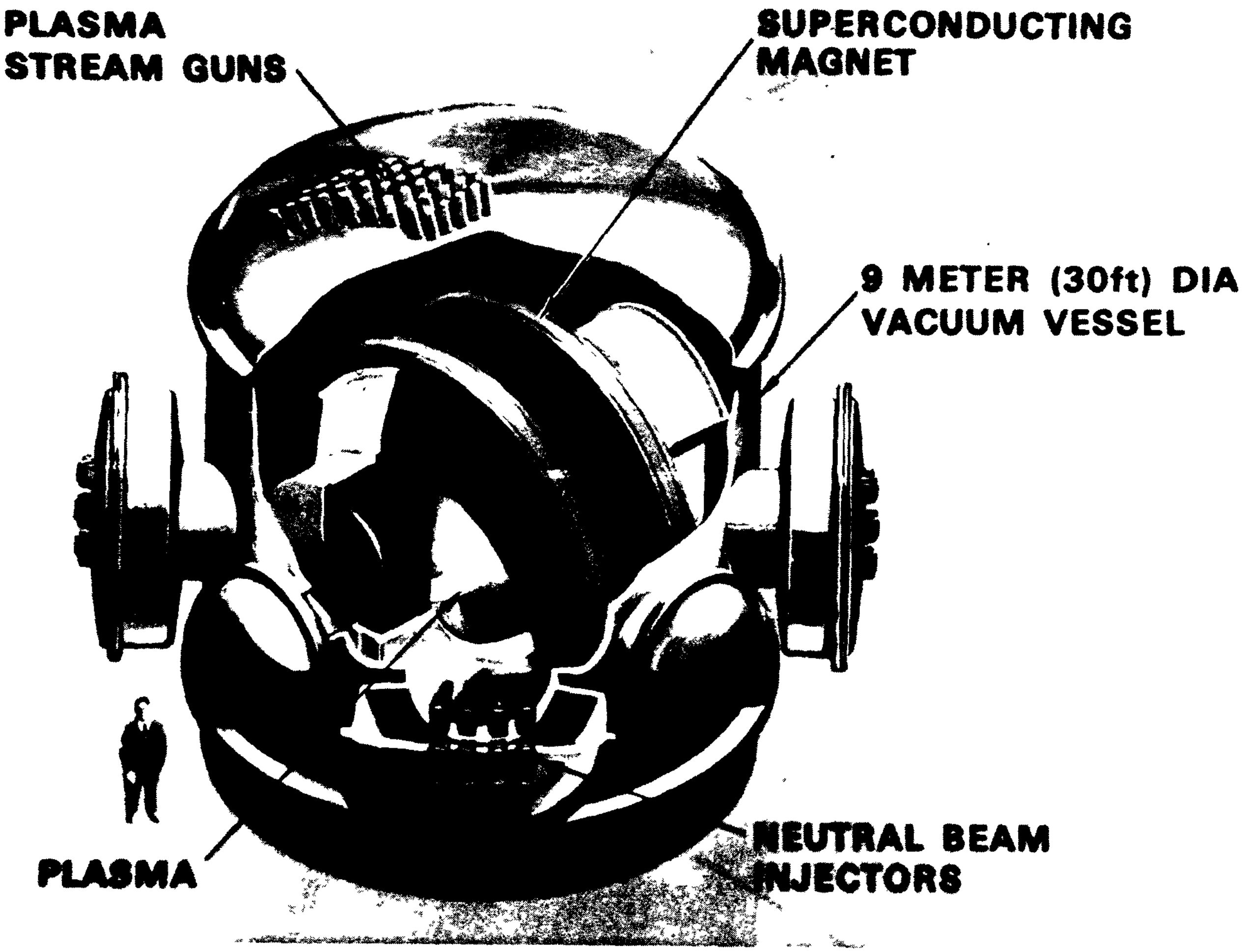

Figure 1 Conceptual drawing of MFTF experiment.

TABLE 1 MFTF PARAMETERS

Plasma (goals)	
$n\tau$ ($cm^{-3} \cdot s$)	10^{12}
T_i (keV)	50
T_e (keV)	1.0
R_p/ρ_i	13
L/ρ_i	100
β	0.5
Machine	
$B_{central}$ (T)	2.0
$L_{between\ mirrors}$ (m)	3.4
Mirror ratio (R_m)	2
Startup	Plasma stream
Startup beams	1000 A, 20 keV
Sustaining beams	750 A, 80 keV

MFTF as described in the Proposal[1] are oriented by our conception of what a mirror fusion reactor would be like. In all of its variations, the mirror reactor involves superconducting magnets, neutral-beam fueling and heating, and steady-state operation. The directions for possible upgrade of MFTF which we have looked at are

- An approach to steady-state operation, and
- Injection at higher beam energy.

These upgrades address an extension of both the scientific and technological goals of the experiment towards the regime of interest for mirror reactors.

APPROACH TO STEADY-STATE OPERATION

With the 0.5-s injection pulse now specified for initial MFTF operation, the getter surfaces used for vacuum pumping during startup are not in equilibrium with the impinging particle flux and continue to absorb these particles after the buildup is completed. If the injection time is extended to tens of seconds, the surfaces will saturate and begin to re-emit an atom for each atom incident, allowing us to evaluate plasma confinement with equilibrium vacuum conditions. Since the MFTF magnet is continuously energized and the vacuum cryopumping is adequate for more than 9 h of continuous injection before renewal is necessary, an extension of the beam injection time would enable us to test all aspects of steady-state plasma sustenance.

We have recently completed a study[2] of the effect of extended injection pulse length on MFTF operation and have identified a need for improved high-power-density beam dumps, in addition to the basic requirement for steady-state beam sources. The 80-kV sustaining-beam power supplies are capable of 30-s operation, at a 10% duty cycle, so that beam sources designed for true steady-state operation can be tested.

One additional limitation inherent in extended-pulse injection was revealed by our study.[2] With deuterium injection, neutron activation of the MFTF apparatus poses a radiation hazard during maintenance when personnel must work within the vacuum chamber. For standard plasma parameters and a typical cycle of machine operation, injection time would be limited on this account to about twenty 30-s injection pulses each day. Although this may be acceptable, any increase in plasma volume or density would aggravate the problem. We therefore desire to retain a hydrogen option with beam sources designed for steady-state injection.

Interestingly, the activation problem is eased with increased beam energy, (assuming a constant plasma volume), primarily because the plasma density decreases at constant β. This is illustrated in Fig. 2, where the normalized neutron production rate is plotted against T_i.

INJECTION AT HIGHER BEAM ENERGY

The motivation for injecting at high energy in mirror systems arises from the opportunity to improve the confinement, which is basically limited by ion-ion scattering into the loss cone. Provided no other loss processes (such as electron drag or nonclassical diffusion) contribute, the confinement parameter is a strong function of ion energy:

$$n\tau_{ii} \approx 2 \times 10^{10} E_i^{3/2} \log R_m,$$

where R_m is the mirror ratio. The ion energy is ultimately limited, in a given machine, by nonadiabatic losses arising from the large orbit dimensions.

We have estimated the nonadiabatic limits for MFTF[1] and reproduce the result here in Fig. 3. The base-case parameters from Table 1 lie well below the limiting curves, even for a short plasma characteristic of the beam size (half length $L_p \approx 34$ cm). For such short plasmas, the maximum ion energy could be increased to ∿200 keV at $\beta = 0.5$; for a longer plasma (which could be achieved in MFTF with proper beam aiming) the adiabatic limit is raised to ∿440 keV at $\beta = 0.5$. Higher β values provide a greater restriction. Lower β values lead to rapid increase in the adiabatic limit, but stability questions become more serious, as we shall see below.

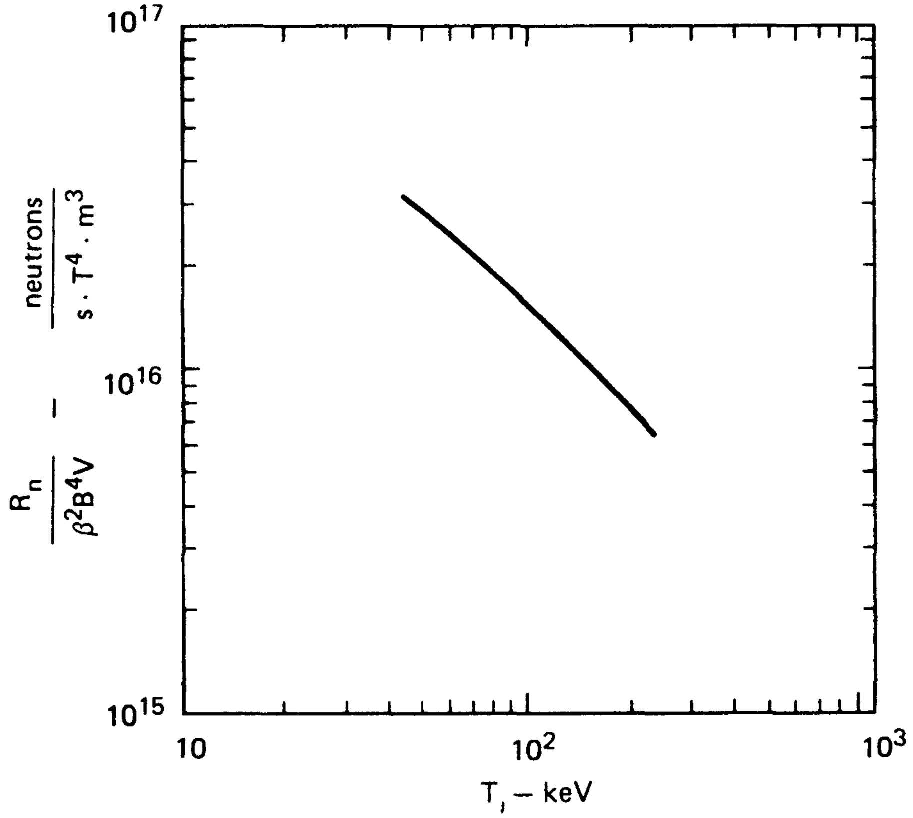

Figure 2. Normalized neutron production rate vs ion temperature.

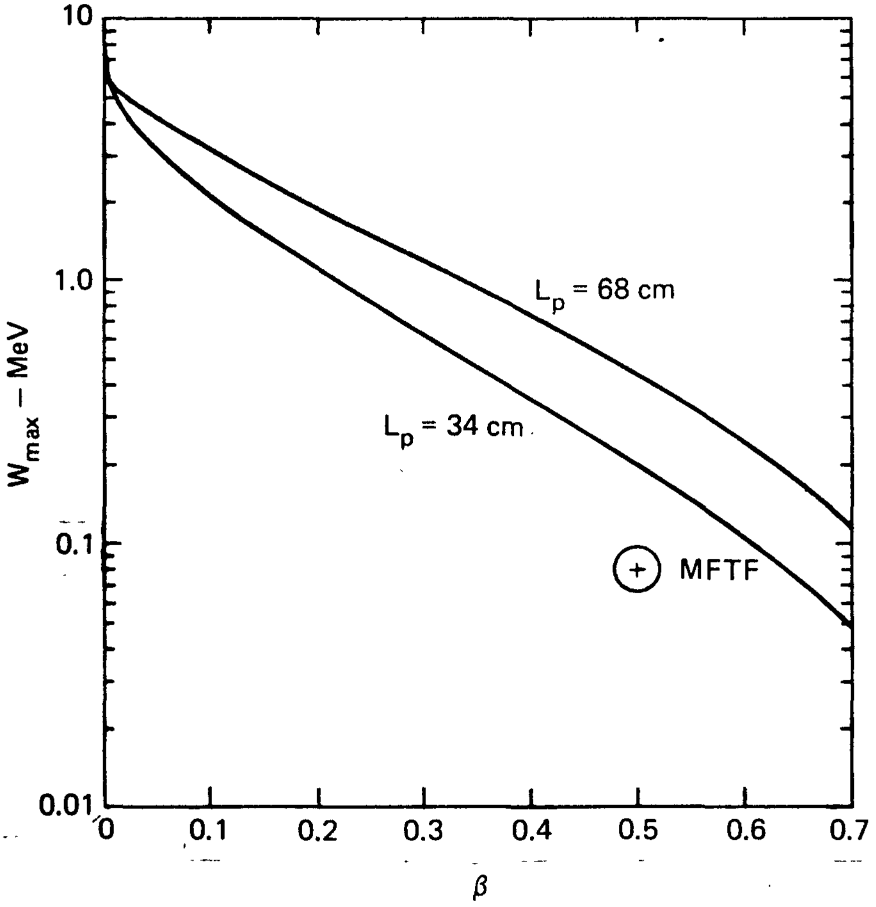

Figure 3. Maximum deuteron energy for adiabatic confinement in MFTF vs plasma β, at a central vacuum field of 2.0 T. L_p is the plasma half-width. The "base-case" MFTF point is shown.

The design of MFTF is oriented towards the study of microinstability scaling laws and, in particular, the scaling of the requirements for stabilization of the drift-cyclotron loss-cone (DCLC) mode. This has been discussed extensively[1,3]; for our present purposes, we reproduce in Fig. 4 a simplified version of a stability boundary curve from Ref. 3. The DCLC mode is driven by the radial density gradient of the plasma and can be stabilized by partial filling of the loss-cone ion distribution with warm plasma. The amount of warm plasma required is determined by the scale length of the radial density gradient measured in ion gyroradii, as seen in Fig. 4. The 2XIIB plasma, with $R/\rho_i \sim 2\text{-}3$, requires substantial warm plasma, whereas our MFTF base case, which is scaled at $R/\rho_i \approx 13$, is expected to require about an order of magnitude less for stability. In 2XIIB, the energy confinement is dominated by electron drag on the ions, with a confinement parameter given by

$$n\tau_E \approx 1.4 \times 10^{12}\ T_e^{3/2}.$$

Reduction of the warm-plasma component in MFTF would allow T_e to rise from the 2XIIB value of ∿140 eV to ∿1 keV (Fig. 4), improving the confinement correspondingly. Further approach to the ion-ion scattering limit then depends on increasing the scale length of the radial gradient. In a plasma of fixed radius, we can "flat-top" the density distribution so that the plasma core has a very large effective radial scale size. The warm-plasma requirement in the core would then be reduced, and T_e and confinement would increase. Successful flat-topping would then permit us to increase the ion energy in the core even though the number of orbits across the plasma would be reduced. The sharp plasma edges would, of course, be maintained by substantial beam injection to overcome the relatively poor edge confinement.

That such a configuration can be realized is illustrated in Fig. 5. Using our numerical rate-equation code,[4] we have calculated an equilibrium distribution with an injection of 30 A of D^0 at 200 keV distributed uniformly to 25 cm, with 100-A injected beam at 80 keV maintaining the plasma edge. Charge-exchange, wall refluxing of gas, and finite orbit dimensions

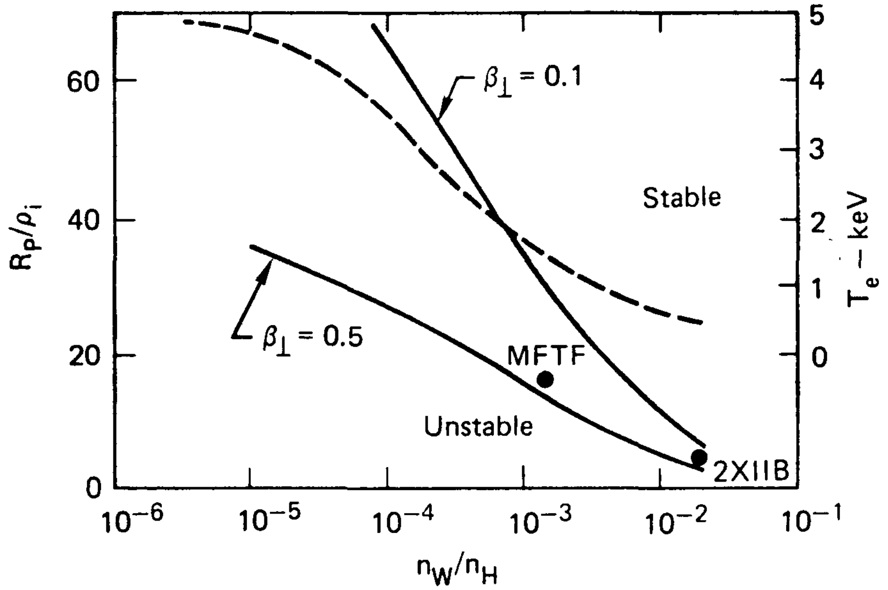

Figure 4. Simplified stability boundaries (solid curves) for the DCLC mode. R_p/ρ_i is the scale size of the radial density gradient, n_W/n_H is the fraction of warm plasma. The dashed curve gives an estimate of T_e for various fractions of n_W in MFTF.

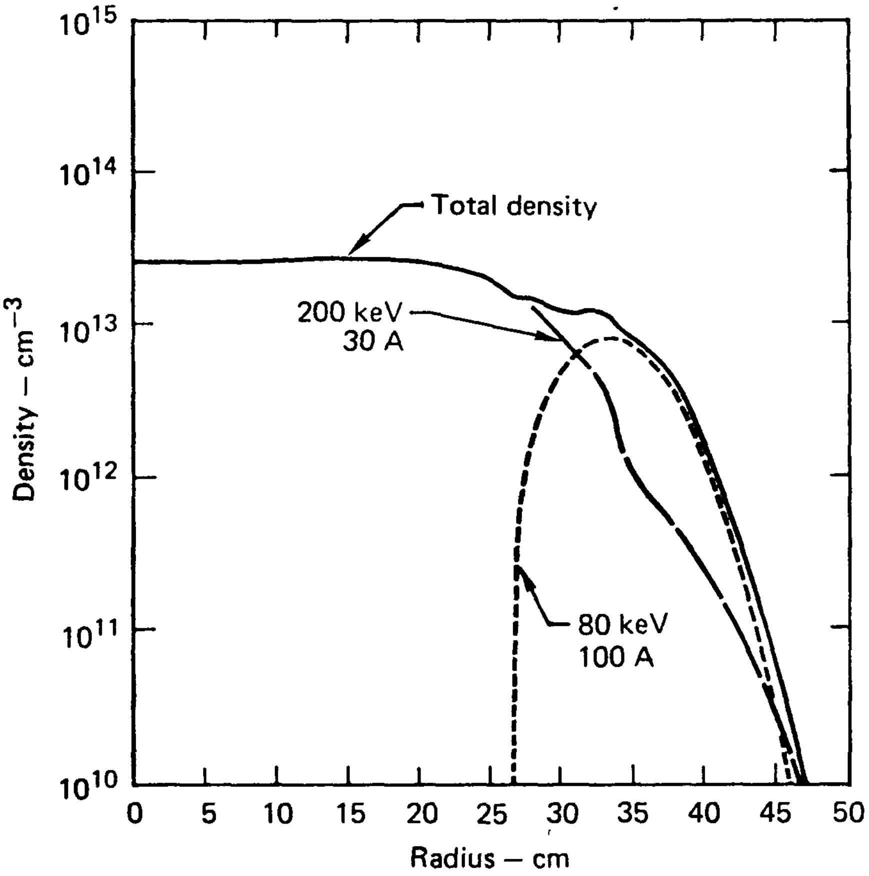

Figure 5. Results of numerical injection calculation. Dashed curves show radial distributions of trapped 200-keV and 80-keV deuterons; solid curve shows the resultant "flat-topped" distribution.

are included in this calculation, with confinement specified as classical (ion-ion scattering) for the core and with $n\tau = 3 \times 10^{11}$ cm^{-3}-s for the edge (the latter is scaled from 2XIIB parameters). The main point of this calculation is that a flat-topped distribution can be achieved in MFTF with reasonable beam parameters.

We cannot predict with certainty the degree of success to be achieved by the flat-topping technique. Consequently, to estimate the beam required to sustain the plasma core at higher energy and the $n\tau$ that could be realized, we have retained T_e as a parameter in our calculations. These estimates have been made[5] for a plasma at constant $\beta = 0.5$ and core radius = 30 cm, with a half-length of $L_p = 60$ cm; we assumed a core stabilized by warm plasma and an edge maintained by other beams (such as the 80-keV beams of Fig.5). Loss processes are ion-ion scattering and electron drag, combined in these calculations with appropriate integration and averaging over the ion distribution.

The $n\tau$ to be expected is shown in Fig. 6, with 2XIIB and MFTF base-case points blocked in. Above ~400 keV, curves are dashed to indicate failure of adiabaticity at $\beta = 0.5$. The neutral-beam current required to maintain the core can be determined after calculating the average ion energy and density (at constant β). Curves for constant core radius, R = 30 cm, are shown in Fig. 7. The current requirement levels off at energies above ~300 keV because the increasing $n\tau$ is balanced by the decreasing beam absorption (from lower density at constant β).

For these curves, the number of gyro-orbits across the core decreases as E_B is increased, perhaps altering the effectiveness of the flat-topping. If instead of keeping the core radius constant, we maintain R/ρ_i above some limit, the plasma size and required current will increase. An example for $R/\rho_i \geq 8$ is shown by dashed lines in Fig. 7. For $T_e = 4$ and 8 keV, these curves terminate at ~500 keV, indicating a plasma size exceeding the maximum radius we can support in MFTF, $R \approx 60$ cm. However, this energy is already above the adiabatic limit. The important result from Fig. 7 is that the current requirements drop to very reasonable values as E_B is raised above 100 keV, <u>if</u> T_e can be increased above ~2 keV. When these data are translated to beam power requirements (Fig. 8) we observe a broad minimum in the range of E_B between 100 and 300 keV.

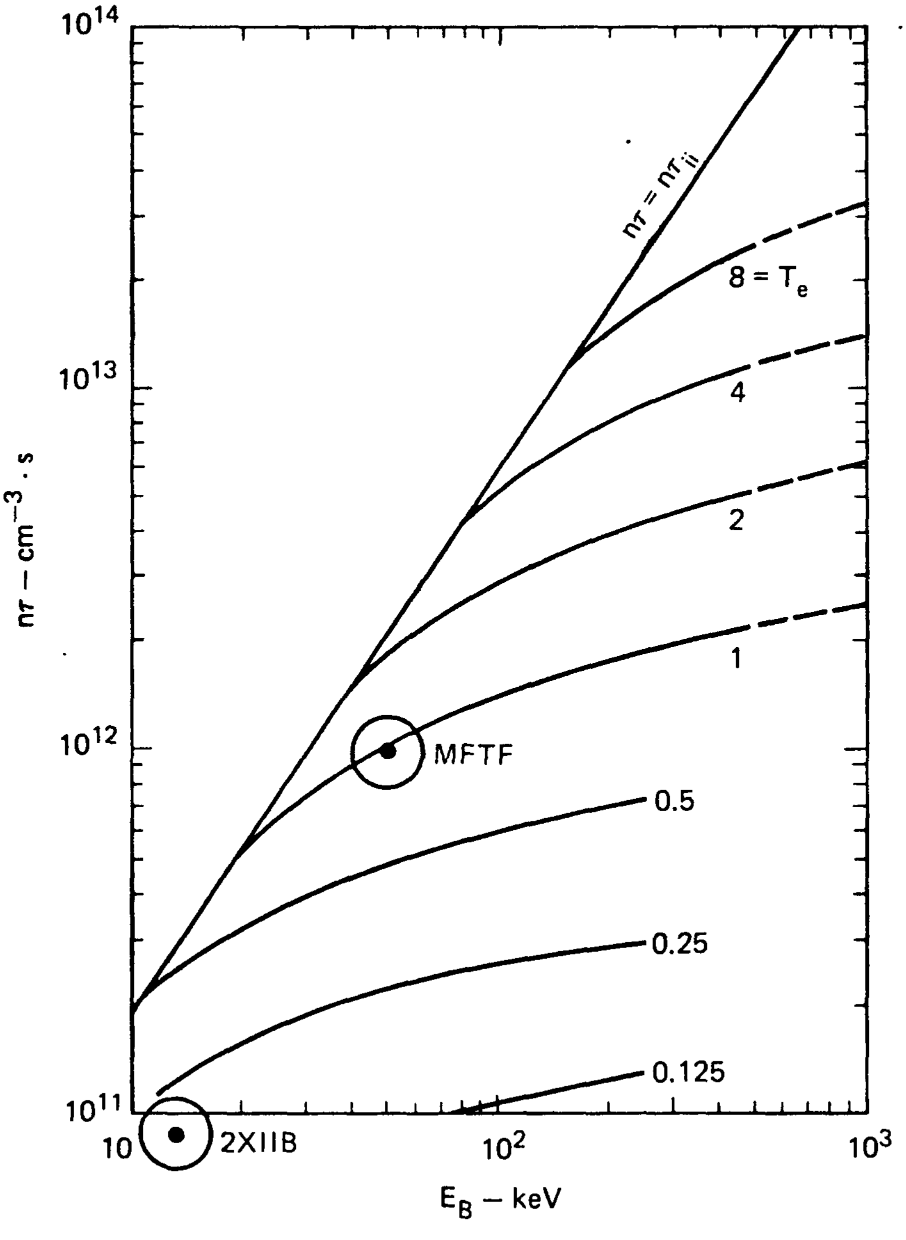

Figure 6. Estimate of confinement parameter, $n\tau$ vs beam energy E_B.

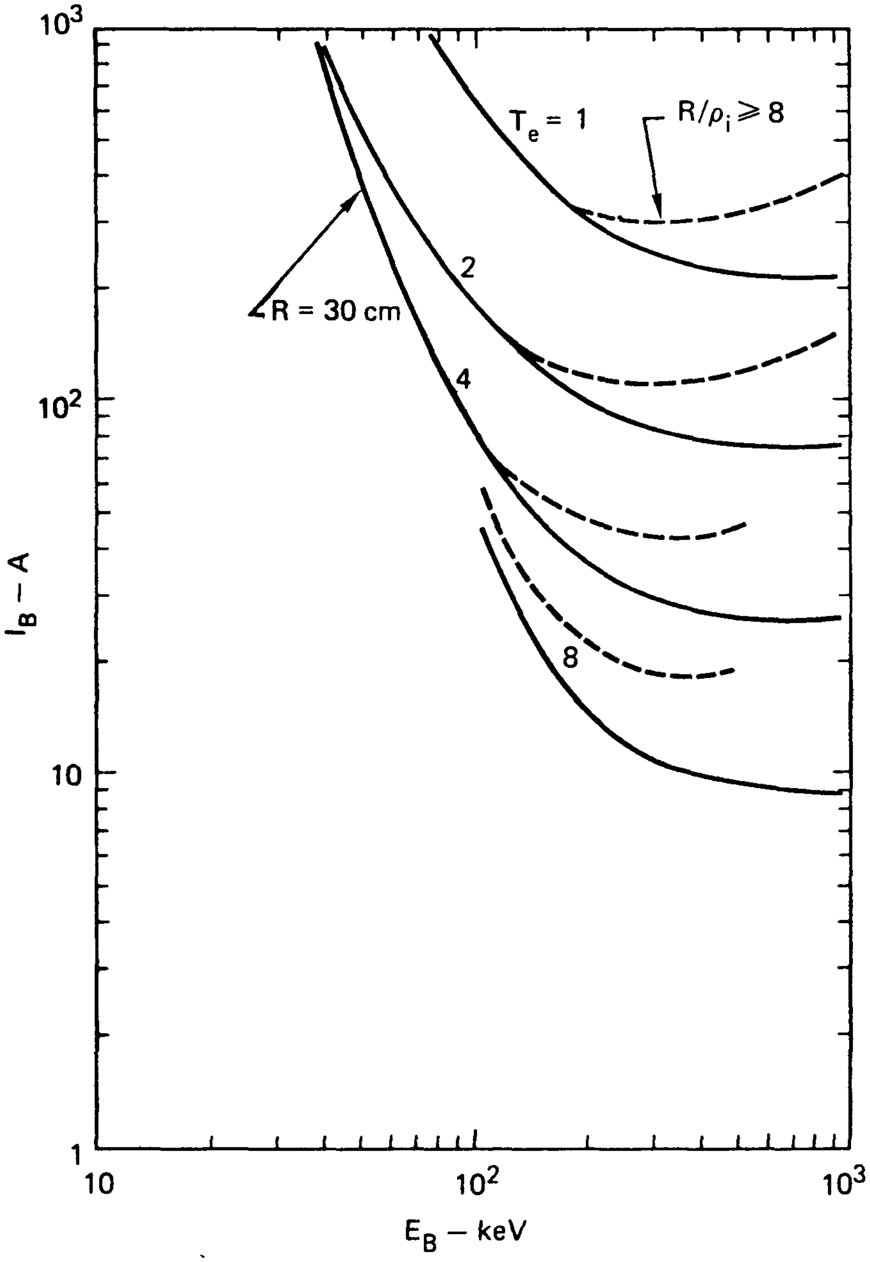

Figure 7. Neutral-beam current I_B required to sustain core density at $\beta = 0.5$ vs beam energy E_B. Solid curves are for constant core radius R = 30 cm; dashed curves maintain $R/\rho_i \geq 8$.

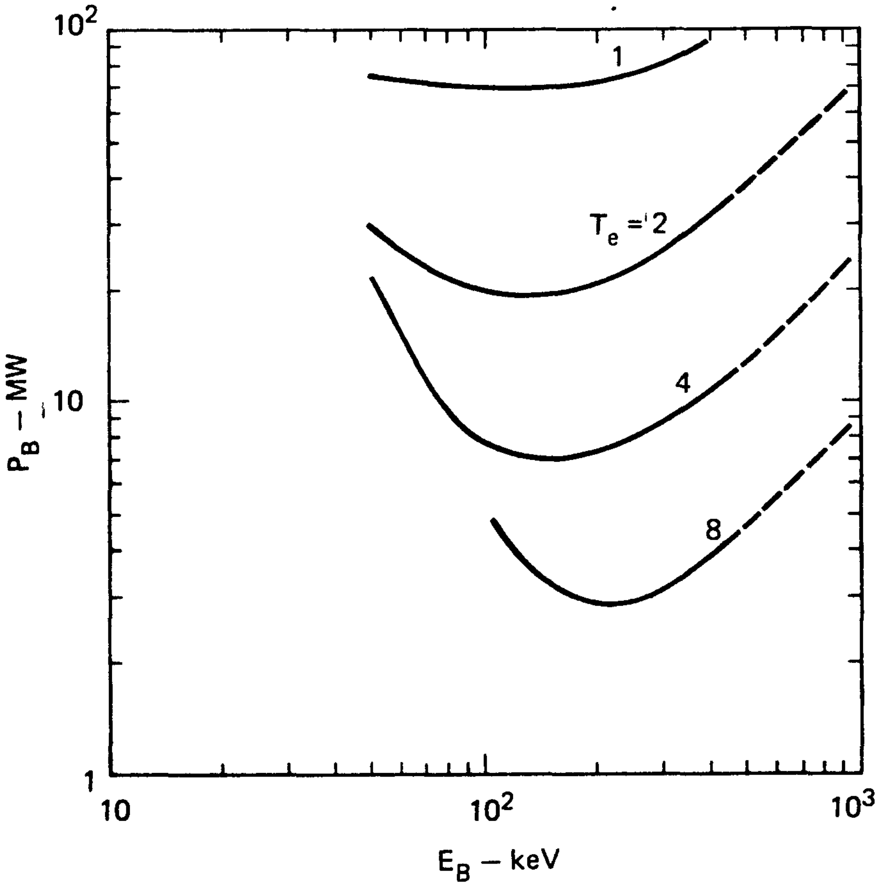

Figure 8. Neutral beam power P_B vs beam energy, E_B. Curves are for core radius constant at R = 30 cm.

CONCLUSIONS

Extension of the beam injection pulse to $\sim$30s in MFTF would enable us to test plasma sustenance in steady state, including the relevant technology required for mirror reactors. For this test, we require neutral-beam sources designed for steady-state operation with an option for either hydrogen or deuterium extraction.

Increasing the beam injection energy to the range of 200-300 keV could increase the confinement parameter by an order of magnitude (to $n\tau \approx 10^{13}\ \mathrm{cm}^{-3}\cdot\mathrm{s}$) above the MFTF base case. This upgrade is dependent on a successful flat-topping of the density profile, leading to an increase in T_e in accordance with our understanding of the DCLC stabilization requirements. Neutral-beam currents of 10 - 50 A incident on the plasma would be required, depending on the degree of success in raising T_e.

Following the MFTF construction completion date in late 1981, and planning for a year of initial operation to explore the base-case regime, our need for beam upgrade could be as early as 1983. We expect to refine and extend these studies during the present FY1978.

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