PREPRINT UCRL-81555

CONF-780946--1

Lawrence Livermore Laboratory

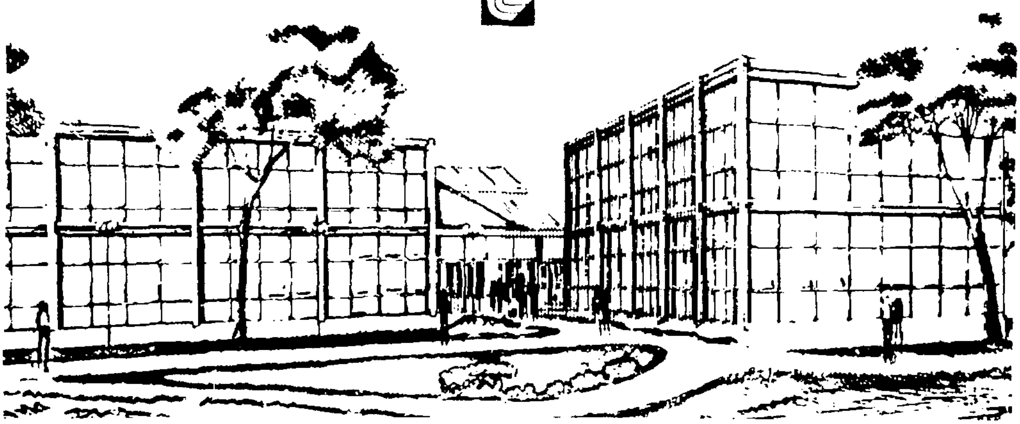
THE U. S. MIRROR PROGRAM

T. K. FOWLER

MASTER

August 10, 1978

This paper prepared for the Fourth International Conference on Driven Magnetic Fusion Reactors - Erice, Italy September 18-26,1978



Commission of the European Communities
Fourth International Conference on
Driven Magnetic Fusion Reactors
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THE U. S. MIRROR PROGRAM*

T. K. Fowler
University of California
Lawrence Livermore Laboratory
Livermore, California U.S.A.

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ABSTRACT

The mirror approach is now the principal alternate to the tokamak in the U. S. magnetic fusion energy program. The program is now focused on two new concepts that can obtain high values of Q, defined as the ratio of fusion power output to the neutral beam power injected to sustain the reaction. These are the tandem mirror and field reversed mirror concepts. Theoretically both concepts should be able to attain Q = 5 or more, as compared with $Q \sim 1$ in previous mirror designs. Success with either or both of these approaches would point the way toward fusion power plants with many attractive features. The linear geometry of mirror systems offers a distinct alternative to the toroidal tokamak. As a direct consequence of this difference in geometry, it is generally possible to build mirror systems in smaller units of modular construction that can probably be made to operate in steady-state. During the next 5 years the main mirror facilities in the U. S. will be the 2XIIB (renamed Beta II); a tandem mirror experiment called TMX; and the Mirror Fusion Test Facility (MFTF) scheduled to be completed in 1981 at a cost of $94 million. As a background for discussing this program and mirror reactor concepts in later lectures, the current status of mirror physics will be reviewed by comparing theory and experimental data in four critical areas. These are: adiabatic confinement of individual ions; electron heat losses out of the ends of the machine; the achievement of beta values of order unity; and stabilization of "loss cone" modes.

* This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

U. S. Mirror Program

The magnetic mirror approach is now the principal alternate to the tokamak in the U. S. magnetic fusion energy program. The mirror program is focused on two new concepts that can obtain high values of Q, defined as the ratio of fusion power output to the neutral-beam power injected to sustain the reaction. These are the tandem mirror and field reversed mirror concepts, discussed below (see Fig. 1). Theoretically both concepts might be able to attain Q = 5 to 10, as compared with Q ~ 1 in previous mirror designs.

The tandem mirror represents a return to the original mirror idea of a long solenoid terminated by mirrors that plug up the ends.[1,2] Most of the fusion power would be made in the solenoid. In the tandem mirror, the end plugs are mirror machines of the magnetic well type used in present-day mirror experiments (see Fig. 2). High density plasmas would be maintainted in these end cells by neutral injection at very high energies (perhaps as high as 1 Mev in a high-Q DT reactor). As is characteristic of mirror confinement, the end cells develop a strong positive ambipolar potential because electrons are less well confined by the magnetic mirror action than are the ions. Thus these dense plasmas in the end cells, charged positively to a potential of some hundreds of kilovolts, act as electrostatic barriers that confine ions in the solenoid for very many collision times. Though it is a new synthesis of the ideas, tne tandem mirror rests on a very solid base of mirror physics.

The field-reversed mirror, though more speculative, follows as a natural adjunct to the present experimental program. The field-reversed mirror is best thought of as just another mode of operating the ordinary mirror machine (see Fig. 3). It builds on the demonstrated fact that mirror machines can achieve very high values of beta of order unity[3] ($\beta = 8\pi p/B^2$ where p is the pressure and B is the magnetic field strength). Of course, high beta means that with a relatively weak field one can hold very high pressure. Thus it turns out that there would be a possibility of producing power at power densities that are a hundred or more times what would be possible in other magnetic fusion schemes. That is one virtue of high beta. The other possible virtue is that the diamagnetic plasma current at high beta may become so strong that the magnetic lines close, as shown in the figure. In this way the high beta plasma would plug up its own leaks since the plasma would now have to cross the closed magnetic lines in order to escape. Such a mode of operation would combine some of the good features of the mirror machine with some of the good features of the Tokamak, resulting in a rather compact and small reactor cell producing ten or twenty megawatts of fusion power in a plasma volume of a few litres.[4] One can imagine a reactor consisting of a string of five or ten such cells adding up to a hundred megawatts output.

During the next week you will hear much more about these ideas and our program to explore them. For the next five years the main mirror facilities in the U. S. will be the 2XIIB (renamed Beta II); a tandem mirror experiment called TMX ; --- and a large mirror device called the Mirror Fusion Test Facility (MFTF) at a cost of $94 million (see Fig. 4). Machine parameters are shown in Fig. 5 . All of these facilities will be located at Livermore. Smaller mirror experiments are being carried out at MIT and the Los Angeles and Irvine campuses of the University of California, as well as related work on field reversal at Cornell, Los Alamos and the Naval Research Laboratory. The tandem mirror concept, independently developed at Novosibirsk and Livermore, has caught worldwide attention. Besides TMX, a tandem mirror experiment called Gamma 6 is already in operation at Tsukuba University in Japan and experiments are under construction at the University of Wisconsin (Phaderus) and Novosibirsk (Ambal 1).

Why this resurgence in mirror research when tokamaks are doing so well? I think there are three reasons. First and foremost is the data from the 2XIIB experiment that has achieved betas greater than unity and the highest ion temperatures -- 10 to 23 Kev -- of any major approach to fusion, both magnetic and inertial (Fig. 6). Second, perhaps, is the greater promise of the new ideas discussed above. Third is a persisting perception that, if they could work, mirror machines might make better reactors (see Fig. 7).

As you know, mirror machines are of the linear, or "open", type in which field lines escape out the ends. There are profound differences between toroidal and linear systems that are direct consequences of the difference in geometry. As we shall see, whereas the physics of tokamaks and other toroidal devices has been dominated by the need to limit radial transport and to increase the plasma beta, linear mirror systems are inherently high-beta devices in which transport in velocity-space (changes of ion energy and direction of motion) is the dominant concern. The second important difference between toroidal and linear systems is the perceived greater simplicity of engineering design afforded by the linear geometry. This could be an important factor in the ultimate course of fusion reactor development. Thirdly, depending on how successful mirror confinement can be, it should be possible to develop smaller power plants based on linear mirror systems (as little as 100 MW output in some cases, as we saw above) as compared to the minimum-size economical toroidal system. Smaller plants could be deployed sooner in order to gain valuable on-line experience in the course of developing fusion power. Fourth, mirror reactors can probably be operated in steady state, again leading to great simplifications in engineering. Finally, the possible use of fusion to breed fissile fuel is a natural application of linear mirror systems that make the most of their assets with least demands on Q. This latter point will be dealt with extensively in later lectures.

Still, the perceived advantages of mirror reactors can never be realized if they won't work. How well do we understand mirror confinement? This is the topic I wish to deal with for the remainder of this lecture as a background for the lectures that follow. I will treat four topics: adiabatic orbits; heat loss through the electrons; high beta; and microinstabilities caused by the mirror loss cone. These four areas form the foundation of mirror physics.

I will first treat adiabatic orbital motion, that is, how individual particles are confined (in particular, the ions). I am sure that most of you are familiar with the concept of the magnetic moment $\mu = mv_\perp^2/B$ as an adiabatic invariant. However, perhaps you are not as familiar with just how accurate this concept is, how well this is understood and what the consequences are for ion confinement in mirror devices.

As one might guess, since the conservation of μ follows from averaging over the cyclotron rotation, corrections have the form[5]

$$\frac{d\mu}{dt} = A \cos \theta \tag{1}$$

where θ is the azimuthal position of the particle spinning at a frequency ω_c as it moves along the field line (z direction),

$$\theta(z) = \int \frac{dz}{v_\parallel} \, \omega_c(z) \quad . \tag{2}$$

On integrating Eq. (1) between turning points, one obtains a result for the change $\Delta\mu$ in one transit of the form

$$\frac{\Delta\mu}{\mu} = A \exp(-L_m/a_i) \tag{3}$$

where a_i is the Larmor radius and L_m is the scale length over which the field strength doubles in value. In the absence of collisions among the particles, it can be shown that the above changes in μ occur in a bounded and periodic manner if $\Delta\mu$ is small enough, in which case a single particle could be confined forever. This condition, known as super-adiabaticity, typically requires $\Delta\mu/\mu < 0.01$.[6] Otherwise, μ can be expected to vary stochastically by a random walk with steps of order $\Delta\mu$ in a transit time $L/v_\parallel$, where $L \sim 2L_m$ is the distance between reflection points. The time τ required for significant changes in μ by this stochastic process is

$$\tau = \left(\frac{\mu}{\Delta\mu}\right)^2 \frac{L}{v_\parallel} \quad . \tag{4}$$

Unless other processes cause losses in a still shorter time, τ would be the lifetime of the particles. Because of the exponential behavior of $\Delta\mu$ in Eq. (3), τ tends to be large, corresponding to thousands or even millions of transits across the machine.

How well this theory fits the facts is shown in Fig. 8. On the left is a comparison of the calculated change $\Delta\mu$ in one transit time with numerical calculations of exact orbits for typical cases.[6] On the right is data from the Baseball I experiment, showing the onset of losses because of non-adiabatic confinement as predicted.[7] As you see, the agreement is very good.

I would next like to discuss electron heat losses out of the ends of a mirror machine. This is a topic of great concern since, while the ion temperature is 10 Kev and more in our experiments, the electron temperature is typically 100 eV and it is this that largely determines the heat confinement time since ions cool off by colliding with the electrons. The point I wish to make is that the experimental results are as they should be under the present circumstances. According to mirror theory, the electrons are confined electrostatically by an ambipolar potential ϕ that forces the electrons to leak at the same rate as the ions. Hence, in an isolated plasma free of impurities and direct contact with the end walls, the power drain through the electrons should be

$$P_{electrons} = \eta I \, T_e, \qquad (5)$$

where I is the ion current escaping out the ends and $\eta = (e\phi + T_e)/T_e$ should be 4 to 6 according to the theory, depending somewhat on details. The other important ingredient determining T_e is the rate at which electrons are heated by the ions, taken in the theory to be the classical collision rate calculated by Spitzer. How well this picture is confirmed is shown in Fig. 9. On the left is data from 2XIIB showing directly that the rate of energy transfer from the ions to the electrons occurs at the classical Spitzer rate; there is no "anomalous" transfer.[8] On the right is data from 2XII showing that in an isolated and clean plasma, the electron heat loss agrees rather well with expectations (the data indicates $\eta = 8$).[9] More recently higher electron temperatures, T_e = 140 eV, have been obtained in 2XIIB using up to 7 MW of neutral beam heating.[3]

Turning to high beta, as an example I now show results obtained in our experiments attempting to reach field reversal in 2XIIB (Fig. 10).[3] As already noted the beta in these experiments actually exceeds unity, which is possible here because the plasma length and diameter are comparable. Even so, though we did not quite reach field reversal, we believe the limiting factor was end losses in competition with the amount of neutral beam input rather than anything having to do with beta itself.

In general beta was still increasing with beam current at the maximum current available (500A). In our best results, we inferred a 90% depression of the magnetic field on axis in fair agreement with a computer simulation of the experiment using the Superlayer code. One interesting feature is the fact that most of the mirror ratio confining the plasma in the axial direction is provided by the plasma current itself; the plasma "digs its own well". I should perhaps remind you that these remarkable results are quite consistent with the MHD theory of stability of plasmas in a mirror machine of the magnetic-well type developed in the 1960's, which has become the standard geometry in 2XIIB and other mirror experiments.[10]

Finally, I come to microinstabilities caused by the loss cone. The greatly improved understanding and control of microinstabilities is perhaps the single most important accomplishment in the mirror field. Attention is now focused largely on the so-called drift-cyclotron mode (DCLC) that was both observed and suppressed in 2XIIB and appears to be the principal instability phenomenon to be reckoned with in mirror design, including the end plugs of a tandem mirror.[11]

From among the many aspects of this research, I have selected two key points to discuss. First is the concept of warm plasma stabilization first proposed by Post some 10 years ago.[12] This is, we believe, the means by which the DCLC mode is suppressed in the 2XIIB experiment. The DCLC mode is caused by the "ambipolar hole" in the ion velocity distribution; that is, that part of the loss cone representing the absence of low energy ions expelled by the ambipolar potential. Hence replacing ions in the ambipolar hole by streaming cold ions through the hot plasma should suppress the instability. This is the idea of warm plasma stabilization. Since electrons accompanying this streaming ion current carry away power (by the same formula as eq. (5)), it is important to know how much streaming current is required. Since $e\phi \approx T_e$, it turns out that the "warm" density n_w required to fill the ambipolar hole is $n_w \approx (T_e/E_i)n$ where E_i is the mean energy of the hot ions and n is their density. These ions flow out at a speed $(\phi_i/m_i)^{1/2} \approx (T_e/m_i)^{1/2}$ and hence the required streaming current per unit volume scales as:[13]

$$I_s \propto n_w \left(\frac{\phi}{m_i}\right)^{\frac{1}{2}} \propto n\left(\frac{T_e}{E_i}\right)^{3/2} \quad . \tag{6}$$

As is shown in Fig. 11, the minimum stream required to suppress instability in 2XIIB agrees with this scaling and the proportionality constant is within a factor of 2 or so of that predicted by a simple theoretical model.[14] In the tandem mirror, I_s can be provided by the outflow of plasma from the solenoid through the mirror machines that serve as end plugs. As TMX was designed according to this principle using theoretical values for I_s, the above results bode well for TMX experiments.

According to theory, the DCLC mode is weakened as the plasma radius R_p increases in ratio to the Larmor radius a_i and as a consequence of this the predicted warm plasma density n_w (and streaming current I_s) needed for stability decreases as R_p/a_i increases.[5,15] The MFTF is designed on this principle. Recent measurements in 2XIIB just reported at the Innsbruck meeting seem to support this theory up to the values $R_p/a_i \sim 4$ in deuterium and 6 in hydrogen that could be achieved in 2XIIB (albeit at reduced $\beta \sim 0.4$ because of the increased volume). This data is shown in Fig. 12. The theoretically predicted n_w is shown on the left.[5] On the right is the data for T_e and $n\tau$ versus R_p/a_i for a fixed β compared to calculated values relating T_e to the predicted n_w (and I_s).[3] Though somewhat inferential, the agreement is encouraging. Note that, according to this theory, the end plugs of a Tandem Mirror Reactor should be stable if $R_p/a_i \sim 15$-20 in the end plugs even without any warm plasma stabilization. This is an important point in attaining a high Q system since at high Q there would be too little leakage out of the solenoid to provide much stabilizing warm density in the end plugs. It should be possible to test this point at moderate densities in MFTF.

While I do not mean to convey a misimpression that we understand everything about mirror machines, I hope you will agree that the results I have presented do represent an impressive body of knowledge about the key points and that the mirror fusion concepts we will discuss in coming lectures are worthy of your attention. I wish for you and us a most fruitful meeting.

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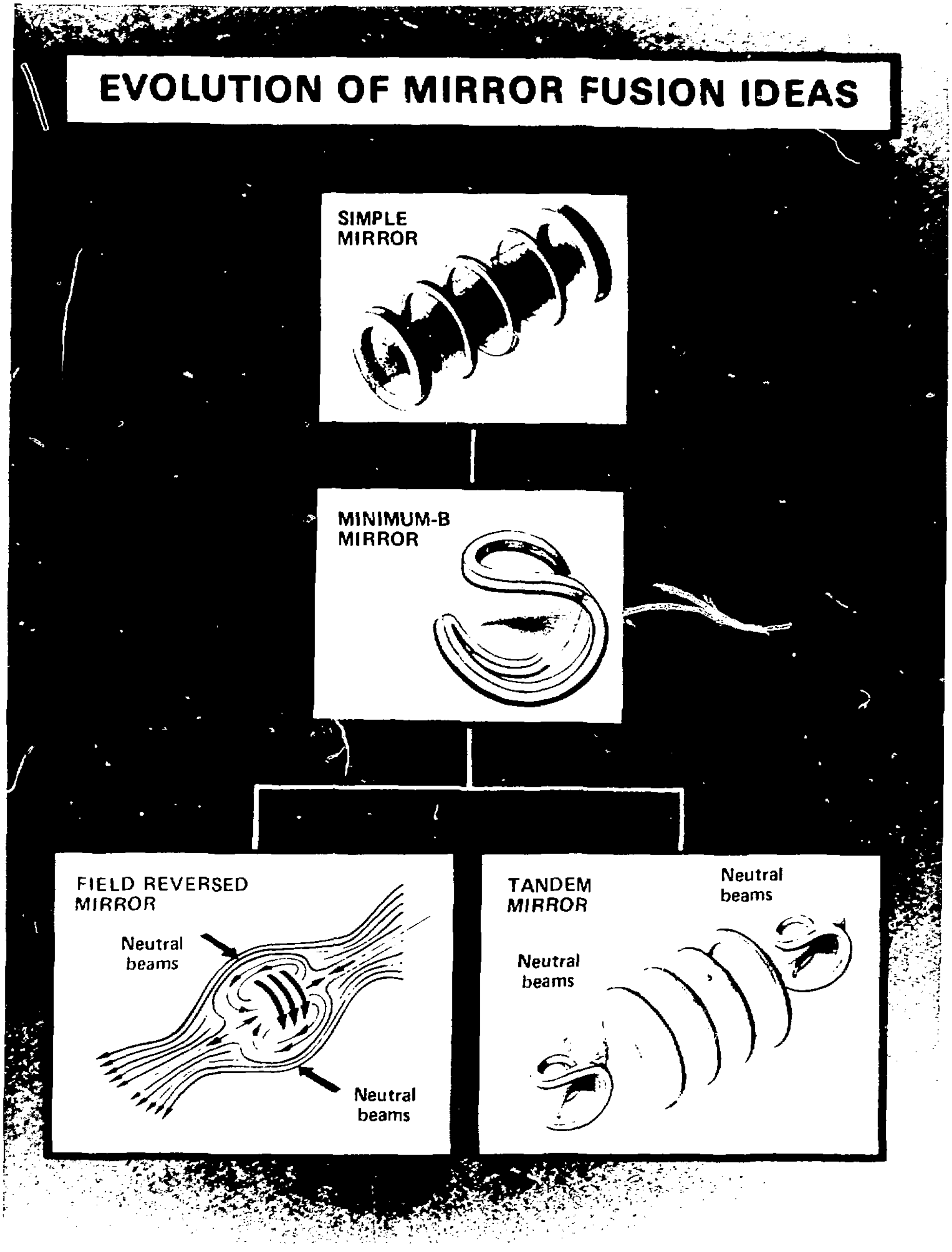

EVOLUTION OF MIRROR FUSION IDEAS
SIMPLE MIRROR
MINIMUM-B MIRROR
FIELD REVERSED MIRROR
Neutral beams
Neutral beams
TANDEM MIRROR
Neutral beams
Neutral beams

Figure 1.

TANDEM MIRROR MACHINE

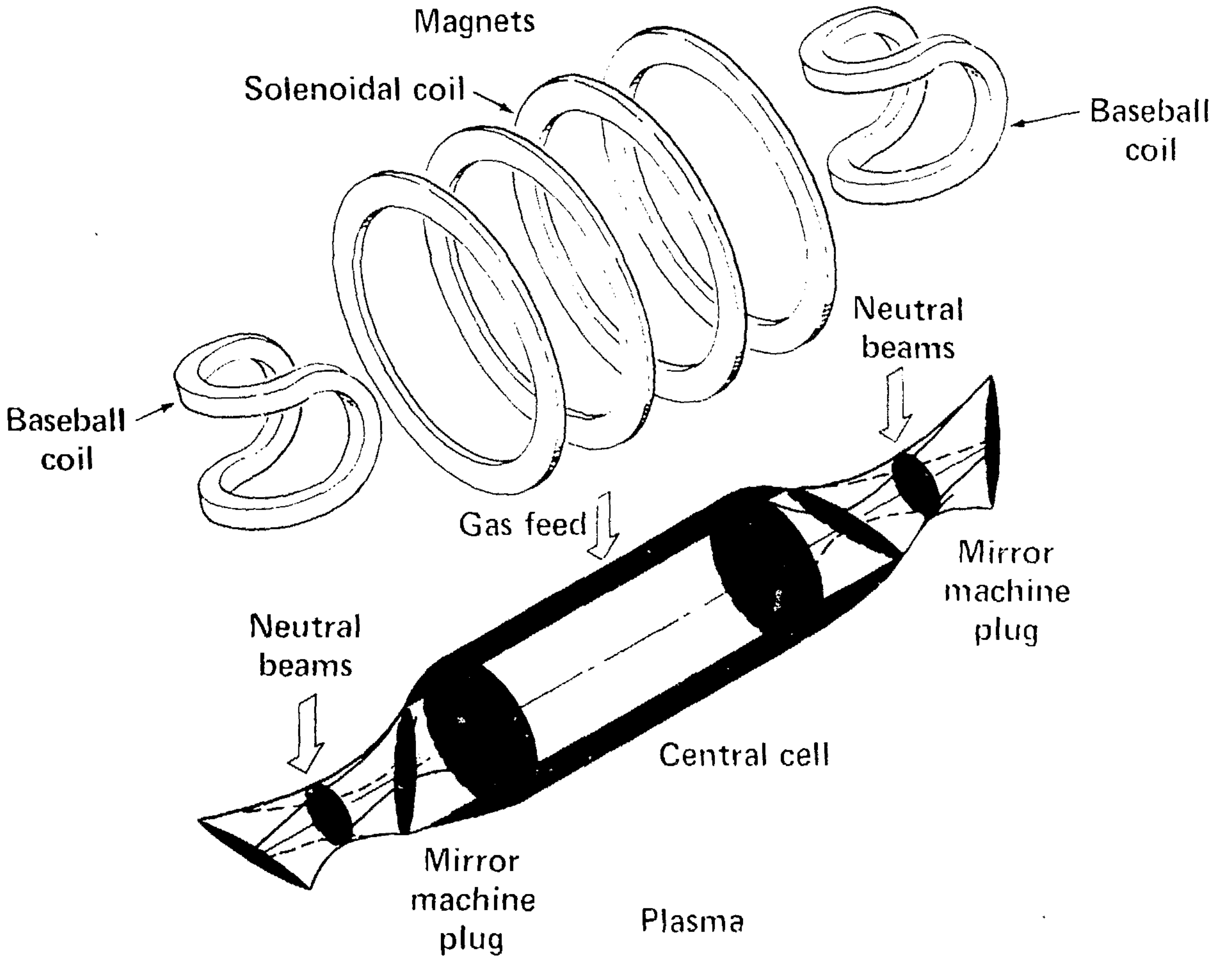
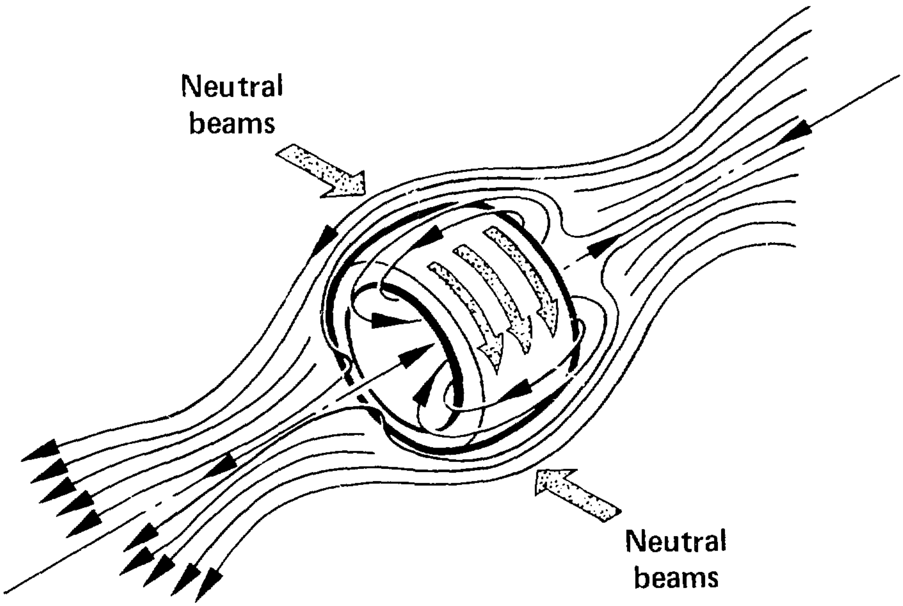


Figure 2.

THE FIELD REVERSED MIRROR REACTOR WOULD CONTAIN MULTIPLES OF A BASIC CELL



Parameter	Value
Vacuum field	50 kG
Plasma length	20 cm
Plasma radius	6 cm
Beam energy	$\leqslant$200 keV
Fusion energy gain (Q)	5 to 9
Fusion power	19 MW/cell

1/78

Figure 3.

MIRROR FUSION TEST FACILITY

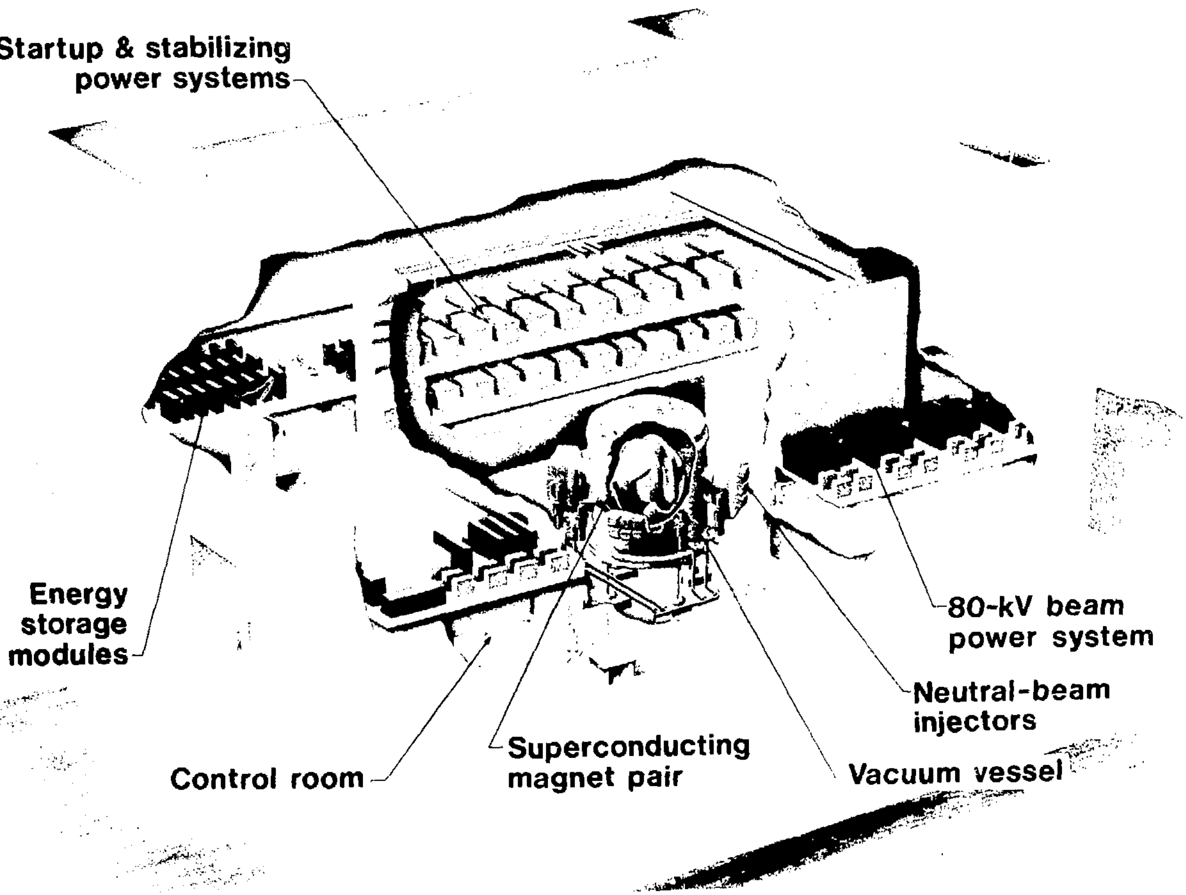


Figure 4.

MIRROR FACILITIES

	2XIIB	TMX (end plugs)	MFTF
Magnetic field (midplane)	7 kG	10 kG	20 kG
Field duration	10 msec	Seconds	Super conductor
Length between mirrors	1.6 m	0.9 m	3.2 m
Injection current	600 A	550 A	750 A
Beam accelerating voltage	20 kV	40 kV	80 kV
Beam duration	10 msec	25 msec	500 msec
Date operational	Operating	Oct 1978	Oct 1981

Figure 5.

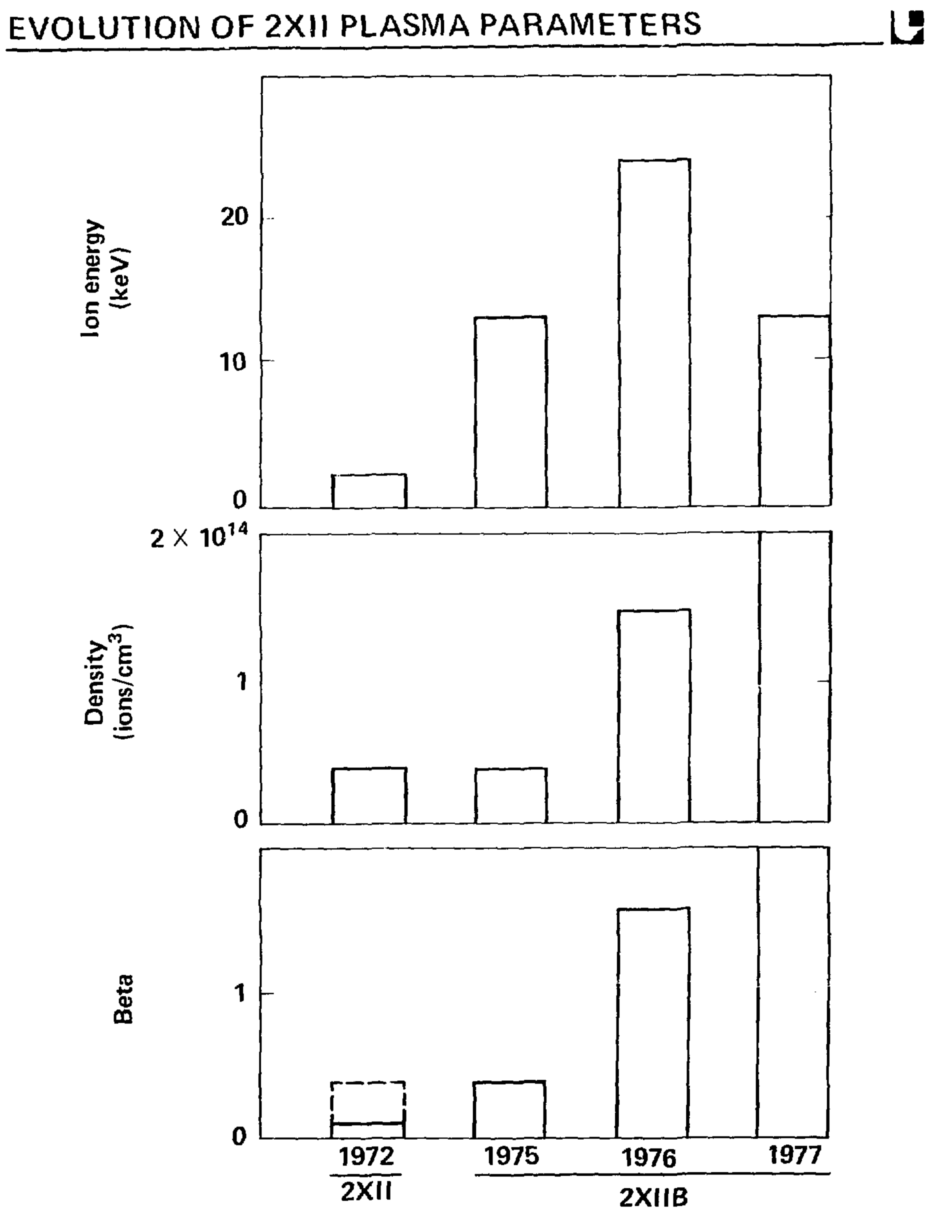
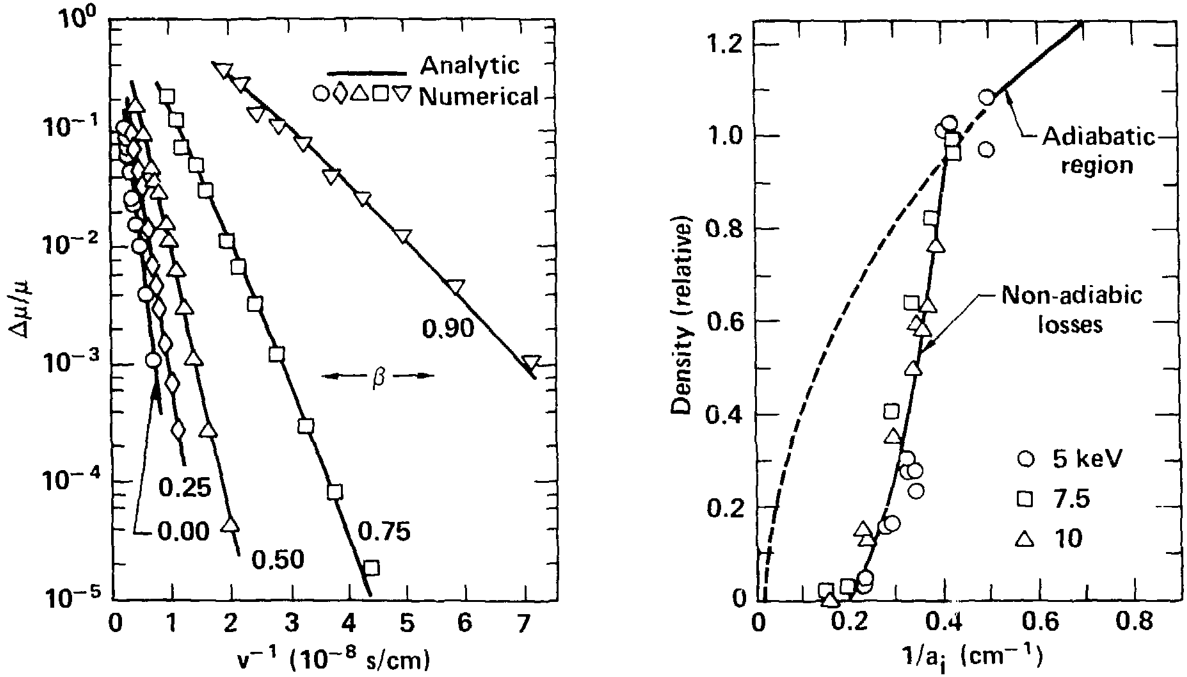

EVOLUTION OF 2XII PLASMA PARAMETERS
Ion energy (keV)
20
10
0
2 × 10^14
Density (ions/cm^3)
1
0
Beta
1
0
1972
1975
1976
1977
2XII
2XIIB

Figure 6.

POTENTIAL ADVANTAGES OF MIRROR REACTORS

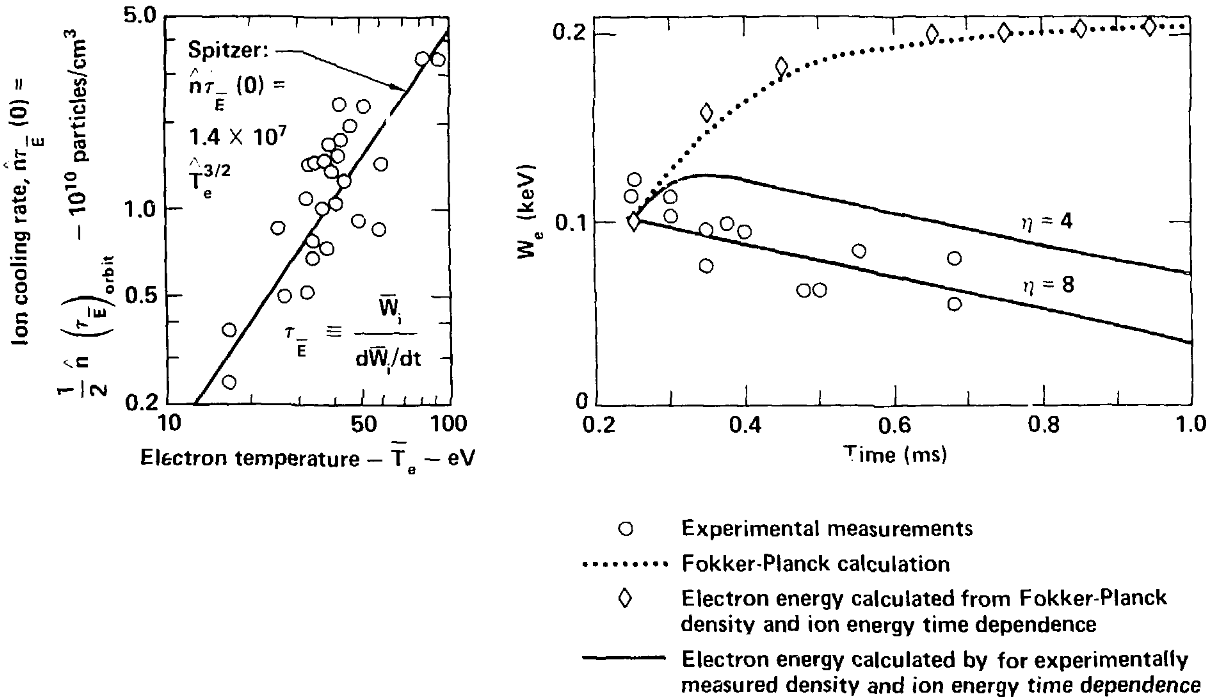
- High beta
- Linear geometry
- Relatively small unit size
- Steady state

Figure 7.



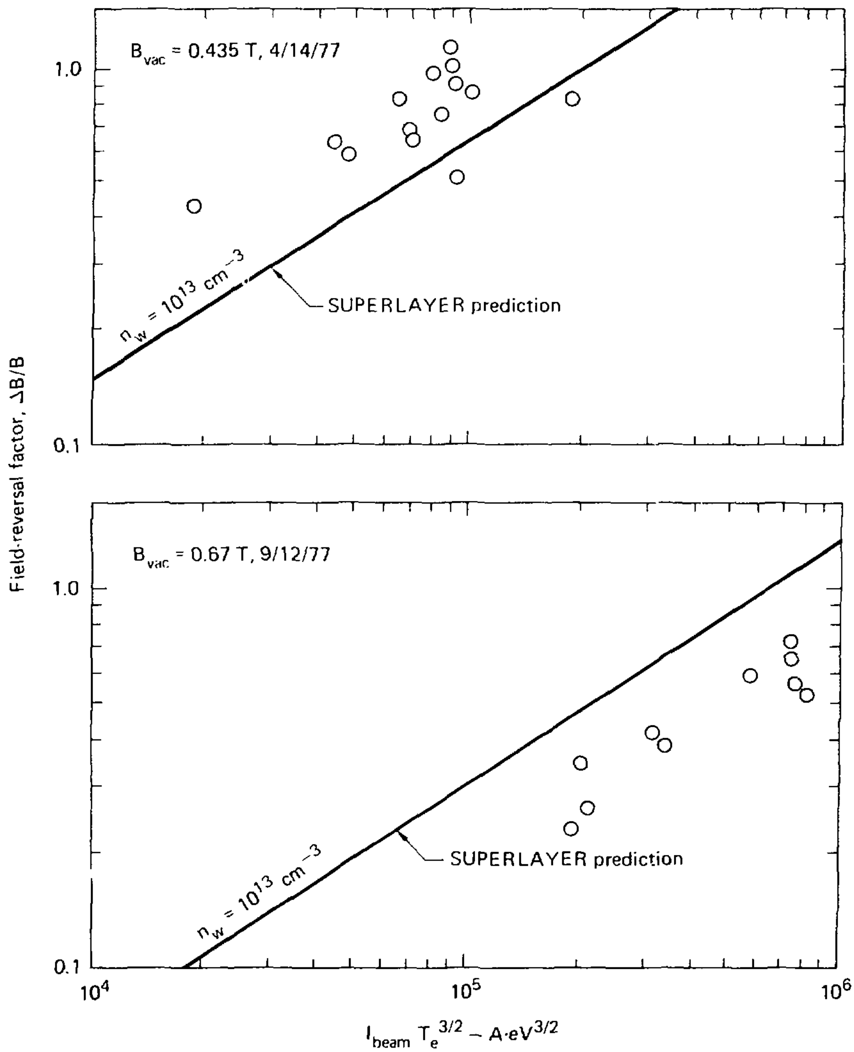
Analytic
Numerical
0.90
β
0.25
0.00
0.50
0.75
Δμ/μ
v⁻¹ (10⁻⁸ s/cm)
Adiabatic region
Non-adiabic losses
5 keV
7.5
10
Density (relative)
1/a_i (cm⁻¹)

Figure 8.



Ion cooling rate, $\hat{n}\tau_{\bar{E}}(0) = \frac{1}{2}\hat{n}\left(\tau_{\bar{E}}\right)_{orbit}$ – 10^{10} particles/cm^3
5.0
1.0
0.5
0.2
10
50
100
Electron temperature – $\bar{T}_e$ – eV
Spitzer:
$\hat{n}\tau_{\bar{E}}(0) =$
1.4×10^7
$\hat{T}_e^{3/2}$
$\tau_{\bar{E}} \equiv \frac{\bar{W}_i}{d\bar{W}_i/dt}$
W_e (keV)
0.2
0.1
0
0.2
0.4
0.6
0.8
1.0
Time (ms)
$\eta = 4$
$\eta = 8$
Experimental measurements
Fokker-Planck calculation
Electron energy calculated from Fokker-Planck density and ion energy time dependence
Electron energy calculated by for experimentally measured density and ion energy time dependence

Figure 9.



B_{vac} = 0.435 T, 4/14/77
1.0
0.1
$n_w = 10^{13}$ cm^{-3}
SUPERLAYER prediction
Field-reversal factor, ΔB/B
B_{vac} = 0.67 T, 9/12/77
1.0
0.1
$n_w = 10^{13}$ cm^{-3}
SUPERLAYER prediction
10^4
10^5
10^6
$I_{beam}\ T_e^{3/2}$ – A·eV$^{3/2}$

Figure 10.

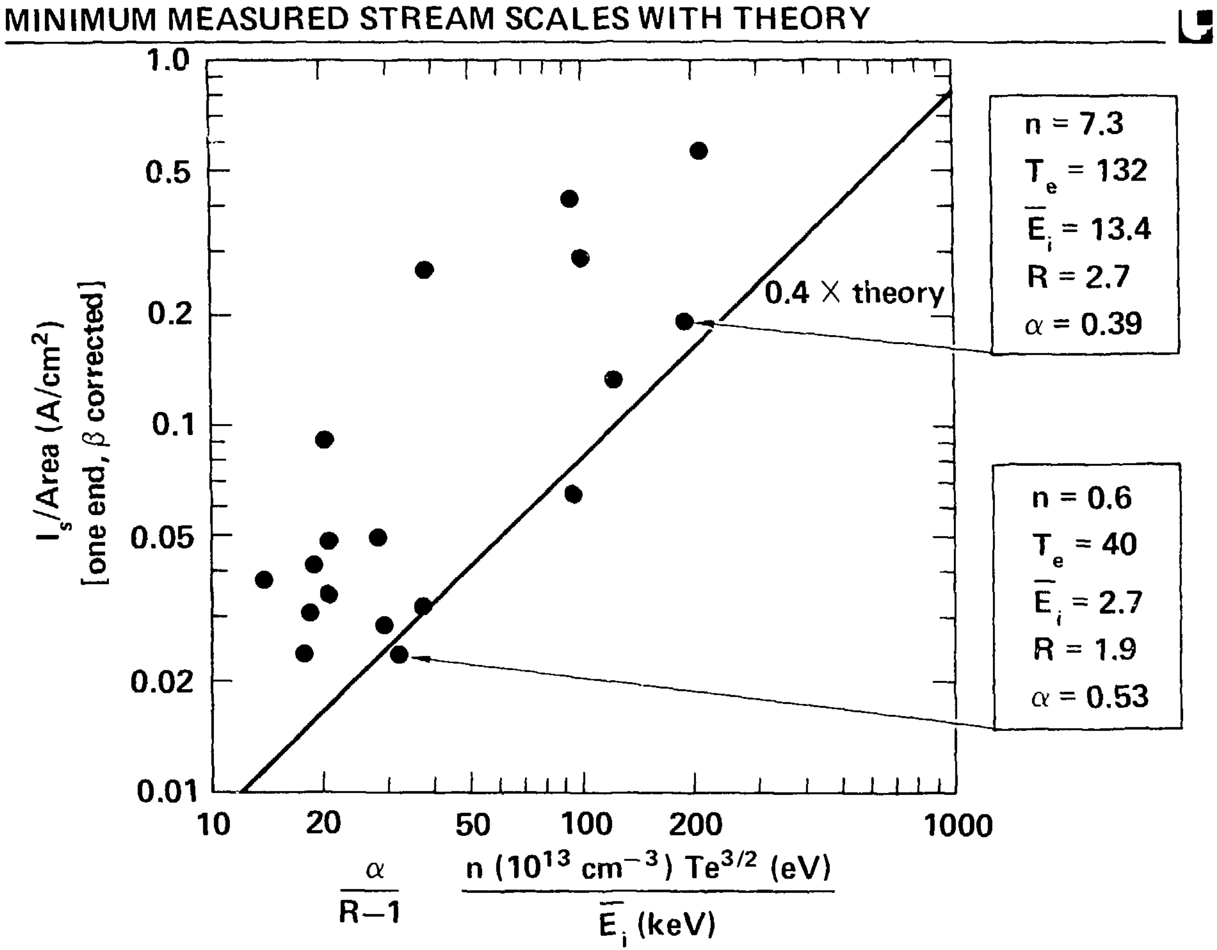
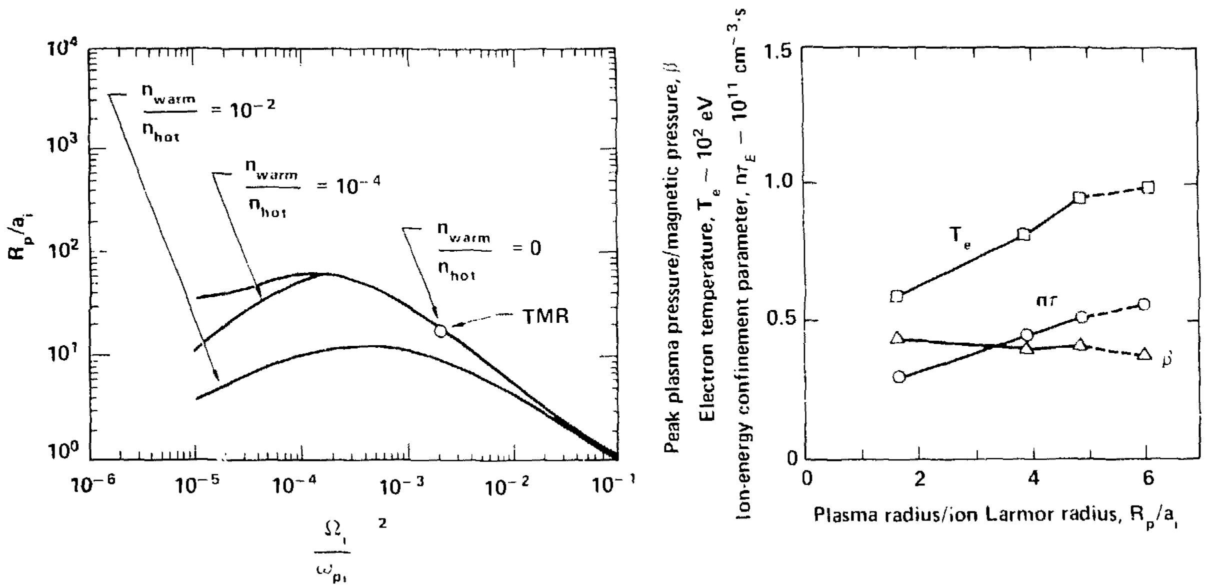

MINIMUM MEASURED STREAM SCALES WITH THEORY
1.0
0.5
0.2
0.1
0.05
0.02
0.01
I_s/Area (A/cm^2)
[one end, β corrected]
10
20
50
100
200
1000
$\frac{\alpha}{R-1}$ $\frac{n\ (10^{13}\ cm^{-3})\ Te^{3/2}\ (eV)}{\bar{E}_i\ (keV)}$
0.4 × theory
n = 7.3
T_e = 132
$\bar{E}_i$ = 13.4
R = 2.7
α = 0.39
n = 0.6
T_e = 40
$\bar{E}_i$ = 2.7
R = 1.9
α = 0.53

Figure 11.



R_p/a_i
$\frac{n_{warm}}{n_{hot}} = 10^{-2}$
$\frac{n_{warm}}{n_{hot}} = 10^{-4}$
$\frac{n_{warm}}{n_{hot}} = 0$
TMR
$\left(\frac{\Omega_i}{\omega_{pi}}\right)^2$
Peak plasma pressure/magnetic pressure, β
Electron temperature, T_e — 10^2 eV
Ion-energy confinement parameter, $n\tau_E$ — 10^{11} cm^{-3}·s
T_e
$n\tau$
β
Plasma radius/ion Larmor radius, R_p/a_i

Figure 12.