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TANDEM MIRROR PHYSICS AND TMX*

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ABSTRACT

The Tandem Mirror Experiment (TMX) is being built at Livermore to test the principles of the new tandem mirror reactor concept. In this concept the fusion plasma is confined in a long solenoid terminated at each end by mirror machines of the magnetic-well type. High density plasmas are maintained in each of the mirror end cells by neutral injection at high energies (up to 1 Mev in a high Q reactor). The usual positive ambipolar potential that automatically develops in each mirror cell serves as an electrostatic barrier that confines ions in the solenoid for many collision times, and the very stable plasmas in these end cells "anchor" each flux tube, thereby assuring MHD stability of the system up to betas of order unity in the solenoid. The TMX will test these main features of the tandem mirror idea and will also investigate optimum means of suppressing loss cone instabilities in the end cells based on methods demonstrated in the 2XIIB experiment. The end cells will be similar in size and injected power to 2XIIB, but some injectors will operate at 40 kV. Expected parameters are $n\tau \sim 10^{11}$ cm^{-3} sec at ion energies of 20 keV in the end plugs and $n\tau \sim 1\text{-}3 \times 10^{11}$ cm^{-3} sec in the solenoid at ion temperatures up to 2 keV if auxiliary beam heating is applied to the solenoid. The solenoid field will be variable up to about 4 kG and the length is 5 meters. The facility is nearing completion (18 months construction time) and experiments are expected to begin early in 1979.

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Tandem Mirror Physics and TMX

The Tandem Mirror Experiment (TMX), now in the last stages of construction at the Lawrence Livermore Laboratory, is designed to test the principles of the new tandem mirror concept that should be able to achieve Q = 5 or more, where Q is the ratio of the fusion power produced to the neutral beam injection power necessary to sustain the plasma.[1,2] Although the tandem mirror geometry was first published by Kelley in 1967,[3] full importance of the concept has only emerged in the last two years. Kelley's objective was to reduce the deleterious effects of the ambipolar potential on mirror confinement in a large mirror central cell protected by two smaller mirror machines at each end. The new idea, developed independently at Novosibirsk and Livermore, goes further in turning the potential into an asset, as follows.*

Figure 1 shows the essential parts of a tandem mirror machine. Mirror coils of the baseball type are placed at either end of the solenoid. Beams of high-energy neutral atoms are injected into the baseball coils; the result is a high-density, mirror-confined plasma in each coil. A gas -- deuterium and tritium in a reactor -- is injected into the solenoid. Hot electrons that pass freely between the central solenoidal cell and the end cells ionize the injected gas, creating and maintaining a plasma in the central cell that has a lower density than the plasma in the end cells. The ions in the central cell are confined radially by the solenoidal magnetic field and longitudinally by the mirror machines at either end. Although continuous input power is required to sustain the plasma in the end cells, the overall Q can be high because the volume of the plasma in the central cell greatly exceeds that in the end cells.

The longitudinal confinement provided by the mirror machines results from a difference in the electrostatic potentials of the plugs and the

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* The following description is abstracted from B. G. Logan, "Energy Technology and Review," Lawrence Livermore Laboratory, July 1977.

solenoid, called a "potential well," that confines ions in the solenoid. To illustrate how this well is formed, we show in Fig. 2 the variations with distance along the axis of the tandem mirror system of the magnetic field strength and the various particle densities.

Because of their smaller mass and larger velocity, electrons tend to scatter and to escape along the magnetic field lines from the plugs and solenoid much faster than the ions. As a result (see Fig. 2), the electron density tends to drop slightly below the ion density in both the plugs and solenoid. This difference in density is maintained because both the plugs and the solenoid then develop enough positive charge with respect to the end walls of the system to keep the electron loss rate equal to the ion loss rate. Only a very slight difference between the ion and electron densities is required to set up large positive potential energies that are several times the electron temperature. This potential, called the "ambipolar potential," develops automatically in all mirror machines to confine the electrons. Since the positive potential increases with the density of the electrons, and since the electron density in the plugs is higher than that in the solenoid, in the tandem arrangement the plug plasmas are more positive than the solenoid plasma.

This potential difference between the plugs and the solenoid makes the potential barrier that confines ions in the solenoid. Depending on the plug-to-solenoid density ratio and the electron temperature (which determines the magnitude of the potential well), it can take a hundred ion-ion collision times before the ions overcome the potential barrier, leave the potential well, and leak through the plugs. (For example, in present-day experiments the electrons are confined some 1000 collision times by the ambipolar potential.)

The plugs also provide a sufficient average centering magnetic force to provide MHD stability of plasma in the solenoid. Without the plugs, the shape of the field at the ends of the solenoid would allow sideways motion of plasma -- an interchange instability.

In a fusion reactor burning deuterium and tritium in the solenoid, fusion alpha particles (helium-4) born in the solenoid plasma from the deuterium-tritium reaction can provide a large fraction of the heat input required to maintain the temperatures of the electrons and the solenoid ions. The rest of the required energy input to the solenoid plasma can originate with the energetic ions in the plugs. These ions lose energy to the electrons that pass freely between the end cells and the central cell. The electrons in turn transfer energy to the solenoid ions, which are cooler than the electrons. In this way, a large fraction of the neutral-beam power required to maintain the plugs is also used to heat the solenoid ions. It will also sometimes be advantageous to provide auxiliary heating of the electrons, by ECRH or other means, or heating of the ions, by neutral beams in the solenoid.

Because of the long confinement time of ions in the solenoid, the heat injected via the plugs goes a long way, sustaining a very large volume of plasma in the solenoid. The Q of this system is large because it is equal to the solenoid fusion power (which is proportional to the plasma volume in the solenoid) divided by the power of the neutral beams being injected into the plugs (the only external power input).

The purpose of the TMX is to provide a proof-of-principle evaluation of the tandem mirror concept as rapidly as possible. To do this, the experiment must:

(1) Demonstrate the establishment and maintenance of a potential well between two mirror plasmas.

(2) Show that high-β, minimum-B mirror plasmas (the plug plasmas) can provide MHD stability for a high-β plasma in the straight solenoid (β is the usual ratio of plasma pressure to the pressure of the confining magnetic field).

(3) Investigate the microinstability of the end plugs, in combination with the solenoid, in order to learn how to take maximum advantage of plasma flowing out of the solenoid in stabilizing loss cone instabilities (in particular, the DCLC mode).

(4) Investigate electron heat losses to the end walls.

To amplify on the third and fourth points, the theory of the DCLC mode developed in conjunction with 2XIIB experiments should apply to the mirror plugs of the tandem mirror system;[4] this theory was used to predict the baseline performance of TMX. An important objective of TMX experiments is to verify quantitatively the applicability of this theory to the tandem mirror and to implement further stabilization techniques now being investigated in 2XIIB. A corollary should be a significant reduction in electron heat losses. In 2XIIB, stability has been obtained by streaming cold plasma through the system. Since the ambipolar potential turns away most of the stream, a large excess of stream is needed to obtain the necessary penetration of stream through the hot plasma and this excess represents a large heat sink. In the tandem mirror, the stabilizing stream can be supplied by the plasma leaking out of the solenoid; the stabilization should be achieved more efficiently; and consequently electron heat losses should be small, as in an ideal, isolated mirror system. Moreover, according to theory, less stream is required as the plasma radius increases, and new data from 2XIIB appears to verify this point.

The principal question regarding MHD stability is the beta-limit due to the "ballooning" mode. Whereas the end plugs are magnetic wells and the solenoid is "neutral", the transition region where flux emerging from the end plugs joins the solenoid necessarily has bad curvature. The strong stabilization in the end plugs tends to "anchor" each flux tube and thereby prevent instability. However, as the beta increases, finally the plasma in the transition has enough energy to bend field lines and become unstable by itself. This is prevented so long as $\gamma < v_A/L_t$ where γ is the growth rate, v_A is the Alfven speed and L_t is the length of the transition region.[5] Roughly, this stability condition gives

$$\gamma \sim \frac{v_{th}}{L_t} < \frac{v_A}{L_t} \sim \frac{v_{th}}{L_t} \frac{1}{\beta^{\frac{1}{2}}} \qquad (1)$$

from which we see that the system should be stable up to $\beta \sim 1$. Detailed calculations also give a high beta threshold, in the range 0.5 or more depending on field line shape.[5]

Besides the beta limit, the main quantitative questions to be investigated in TMX are the temperatures and confinement time predicted by the theory, as follows. If the density in the plugs n_p is greater than that in the solenoid n_c, the requirement of quasi-neutrality establishes a potential difference ϕ_i between the two regions; this is how the ions are confined as described above. For a Boltzmann distribution of electrons, ϕ_i is given by

$$\phi_i = T_e \ln \left(\frac{n_p}{n_c}\right) . \tag{2}$$

Central-cell ions with energies < ϕ_i are confined in this axial potential well for a time τ_i required for them to diffuse upward in energy above the barrier height. For $\phi_i \gtrsim 2T_i$, where T_i is the ion temperature, τ_i is given by Pastukhov as [6]

$$\tau_i = \tau_{ii}\, g(R) \left(\frac{\phi_i}{T_i}\right) \exp \frac{\phi_i}{T_i} \tag{3}$$

where τ_{ii} is the ion-ion collision time, and $g(R)$ is a slow function of the central-cell mirror ratio R. Substituting eq. (2) into eq. (3) gives

$$\tau_i = \tau_{ii}\, g(R) \left(\frac{T_e}{T_i}\right) \ln \left(\frac{n_p}{n_c}\right) \left(\frac{n_p}{n_c}\right)^{T_e/T_i} . \tag{4}$$

This is the basic result for confinement in a tandem mirror that determines the temperature and density in steady-state and, from these, the Q of the system. The relevant quantities are:

$$P_{fusion} = \frac{1}{4} n_c^2 \left(\overline{\sigma v_{DT}}\right)_c E_n \cdot V_c \tag{5}$$

$$P_{injection} = 2 \cdot \frac{n_p^2 E_0}{(n\tau)_p} \cdot V_p \tag{6}$$

(two plugs)

$$P_{loss} = \frac{n_c}{\tau_i}\left(\phi_i + T_i + \phi_e + T_e\right) = \frac{n_c}{\tau_i}\left(10\text{-}12\ T_e\right) \qquad (7)$$

where subscripts p and c denote the end plugs and solenoid, respectively. These quantities represent the fusion power produced (neglecting power made in the end plugs); the power injected into the end plugs; and the power lost from the solenoid by ions and electrons leaking over their respective potential barriers.

In eq. (6), the hot ion lifetime $\tau_p \sim \tau_{ii} \sim \tau_d$ in the end plugs. Since $\tau_p \sim \tau_d$, most of the injection power contributes to heating the solenoid (via the passing electrons), as do alpha particles from DT reactions (if the alphas are well-confined). Equating heat inputs and losses, we obtain in steady-state

$$P_c + f_p\, P_{injection} = P_{loss} - f_\alpha P_{fusion} \qquad (8)$$

where P_c represents any auxiliary heating in addition to power injected into the plugs; $f_p = (\tau/\tau_d)$ and $f_\alpha \lesssim 0.2$ (since E_α = 3.5 MeV = 0.2 E_n). If $T_e \neq T_i$, we would require an additional energy balance equation to couple the ions and electrons.

Eq. (8) is the basis for predicting temperatures in TMX. The same relationship would determine temperatures in a reactor and hence the fusion reaction rate and Q. It is useful to write Q in two ways, as follows. First

$$Q = \frac{P_{fusion}}{P_{injection}} = \left\{\frac{1}{8}\,(n\tau)_p\,(\overline{\sigma v_{DT}})_c\,\frac{E_n}{E_0}\right\}\left\{\frac{n_c\ V_c}{n_p\ V_p}\right\} \qquad (9)$$

for P_c = 0. In this form, the main role of the power balance, eq. (8), is to determine T_i and hence $\left(\overline{\sigma v_{DT}}\right)$ in the solenoid. Equivalently, if eq.(8) is satisfied,

$$Q = f_p\,\frac{P_{fusion}}{P_{loss} - f_\alpha\ P_{fusion}} = f_p\,\frac{Q_0}{1 - f_\alpha\,Q_0} \qquad (10)$$

where

$$Q_0 = \frac{P_{fusion}}{P_{loss}} \simeq \left\{\frac{1}{4}\left(n\tau_{ii}\right)_c \left(\overline{\sigma v}_{DT}\right)_c \cdot \frac{E_n}{10\text{-}12\ T_e}\right\}\left\{\left(\frac{n_p}{n_c}\right)^{\frac{T_e}{T_i}} \ln\left(\frac{n_p}{n_c}\right)^{\frac{T_e}{T_i}}\right\} . \quad (11)$$

Comparing these equivalent expressions for Q with that for the standard mirror, we see that in each case the first factor in brackets has the form of "Q" for one collision time (of ions in the plug, in eq. (9), or in the solenoid, in eq. (10)) and hence not surprisingly these factors will turn out to be at most of order unity. The other factors express the improvement over the standard mirror. In the second expression, eqs. (10) and (11), the improvement depends primarily on the density ratio n_p/n_c which, according to eq. (2), determines the height of the potential barrier confining the ions. From this we conclude that a high value of Q requires a high value of n_p/n_c, typically of order $n_p/n_c \sim 5$ to 10 depending on the role of alpha heating (if alphas are confined, $Q = 5$ would represent "ignition" in the solenoid). The other expression for Q, eq. (9), displays the dependence of Q on V_c/V_p in order that the power needed to maintain the plugs be small compared to the power produced in the solenoid. From this we conclude that, since $n_p/n_c \sim 5 - 10$, a large Q also requires $V_c/V_p \sim 500 - 1000$. Finally, to obtain T_i in the thermonuclear regime (10's of keV) it is necessary that E_0 be many 100's of keV to avoid expelling ions from the plugs by the total potential $\phi_i + \phi_e \sim 10\ T_e$ (see Fig. 2).

Typical results are shown in Fig. 3, which plots Q versus n_p/n_c for a fixed injection energy, $E_0 = 1$ MeV. Values of V_c/V_p (also plotted) were in this case chosen to maximize Q at each value of n_p/n_c. As anticipated, in principle Q increases indefinitely as n_p/n_c and V_c/V_p are increased, but practical constraints will limit the actual Q achievable; probably $Q \sim 5$ to 10 is acceptable. The principal limitation is the density n_p that can be achieved in the end plug. As we have seen, n_p must be several times the density n_c in the solenoid in order to obtain a large potential barrier. On the other hand, n_c must not be too small ($\sim 10^{14}$ cm^{-3}) in order to achieve an interesting fusion power output per unit volume in the solenoid. Thus n_p in the end cells must be 10^{14} - 10^{15} cm^{-3} and, as noted above, the ion energy there must be 100's of keV in order that T_i reach useful values. This simultaneous demand for both high density and high ion energy requires both a high value of the magnetic field in the end plug (100-150 kilogauss) and a plasma beta around unity. On the other hand, the much larger solenoid where most of the fusion reactions occur is relatively uncomplicated - circular coils at fields of 25 kilogauss or less - and the solenoid is distinctly separated from the end plugs. Thus, the nuclear processes and heat recovery are well isolated from the more sophisticated plasma technology in the end plugs. This separation of functions is perhaps the most important aspect of the tandem mirror from the viewpoint of reactor design and development.

The addition of various auxiliary heating methods may considerably improve the tandem mirror performance. For example, according to eq. (4), for a given n_p/n_c the ion lifetime increases markedly if $T_e > T_i$ or, conversely, n_p/n_c could be less for the same τ_i. For this reason, direct heating of the electrons may be advantageous. Similarly, R.F. heating of ions in the end plugs may increase E_0 beyond the reach of neutral beams, or do so more easily.

For TMX to provide the groundwork for a tandem mirror reactor, the characteristics of the TMX plasma have been chosen as nearly in proportion to the corresponding reactor characteristics as possible. Table I compares parameters for a TMR at Q = 5 with TMX parameters for the "reference" case in which all input power is provided by the neutral beams in the plugs ($P_c = 0$) in eq. (8).[7] Table II presents TMX parameters with auxiliary neutral beams (2 20-KV beams in the solenoid) to increase T_i in the central cell.[7]

Table I.

Parameters for a conceptual tandem mirror reactor (TMR) with a system Q of 5 and for the LLL tandem mirror experiment (TMX). Parameters of the TMX are roughly proportional to those of the TMR; the confinement mechanism is similar.

Parameter	TMR	TMX*
Energy of neutral beams injected into the plug, keV	1200	40
Magnetic field in the plug, T	16	1.0
Ion density in the plug, particles/cm^3	8.5×10^{14}	5×10^{13}
Ion density in the solenoid, particles/cm^3	1.0×10^{14}	1.2×10^{13}
Electron temperature, keV	43	0.2
Potential barrier for electrons, keV	260	1.1
Temperature of solenoid ions, keV	30	0.08
Potential barrier for ions, keV	92	0.29
Ratio of ion confinement time to ion-ion collision time	100	140
Magnetic field in the solenoid, T	2	0.05
Ratio of plasma pressure in the solenoid to magnetic field pressure in the solenoid	0.7	0.5
Length of plasma in the solenoid, m	100	5.5
Ratio of plasma volume in the solenoid to that in the plugs	430	570

* For the case in which the plugs above heat the central cell via the electrons; higher ion temperatures can be obtained by neutral beam injection in the solenoid (Table 2).

Table II

Parameters with gas feed plus 20-keV neutral beams at 60A (incident).[a]

Parameter	Value
Electron	
Temperature, T_e	0.29 keV
Confining potential, ϕ_e	1.5 keV
Plug	
Ion current (trapped, per plug), $j_p V_p a$	5 A
Confinement product, $(n\tau)_p$	4.9×10^{11} $cm^{-3} \cdot s$
Central cell	
Electron density, n_c	1.9×10^{13} cm^{-3}
Maxwellian density, n_w	1.4×10^{13} cm^{-3}
Energetic tail density (from slowing-down beam), n_H	0.5×10^{13} cm^{-3m}
Maxwellian temperature, T_w	0.28 keV
Total average energy (including energetic tail), $\bar{E}_c$	2.0 keV
Confining ion potential, ϕ_i	0.28 keV
Maxwellian confinement product, n_w^2/j_{gas}	6.3×10^{10} $cm^{-3} \cdot s$
Overall confinement product, $(n\tau)_c$	$1.25 \times 10^{11} cm^{-3} \cdot s$
Radius, r_c	16 cm
Magnetic field, B_c	1.9 kG
Mirror ratio, R_c; R	10.5 (to mirrors); 5.3 (to plug midplane)
Beta, β_c	0.54
Maxwellian Larmor radius, ρ_w	1.7 cm
20-keV Larmor radius, ρ_{20keV}	15 cm
Total ion current, $qj_c V_c$	210 A

[a] 36 A attenuated in plasma. Plug parameters are the same as in Table I except as indicated. The term "Maxwellian" refers to the gas feed ion component; "energetic tail" refers to the beam ion component.

The TMX design draws heavily upon experience and technology in the 2XIIB experiment. The end plugs are nearly identical to 2XIIB in scale and injection power, but the field duration is longer (a few seconds in TMX), and some of the injectors operate at 40 kV.

Each plug has 12 injectors; of these, four inject 40-keV beams of neutral deuterium and eight inject 20-keV beams of neutral deuterium. Each injector delivers about 1 MW of power in a 25-ms pulse.

Eighteen coils are used on TMX (Fig. 4). Each plug consists of a baseball coil with the mirror fields augmented by two C-shaped coils located in the jaws of the baseball coil. Six large, ring-shaped coils create the solenoidal magnetic field. At each end of the solenoid, there are bar-shaped quadrupole magnets to provide a transition from the fan-shaped field of the plug coil to the cylindrical field of the solenoid. All coils are copper, water-cooled, and operate for a few seconds by dc power supplies. The dc power now available will limit the magnetic field strength of the two mirror systems to 1.0 T at the midplane. Fig. 5 shows the TMX machine as it will appear when complete.

Because the plugs were chosen to be of 2XIIB size, the overall scale of TMX is determined by the 1-m mirror-to-mirror length of each baseball coil. Adding a 5-m-long solenoid (for a high-Q tandem reactor the plasma volume of the solenoid must be large compared to that of the end plugs) and end tanks beyond the plugs to dispose of the plasma losses brings the total machine length to a little over 15m.

The TMX is located in the area previously occupied by the Baseball II experimental facility at LLL, which was shut down and removed to make room for TMX. Fig. 6 shows the construction site. A 0.6-m-thick concrete wall will completely surround the experiment to shield personnel from the possibly large neutron fluxes produced by deuterium-deuterium fusion reactions.

By using some existing facilities it has been possible to construct TMX in about 18 months at a total cost of about $11 million. We hope to complete the facility shortly and begin experiments early in 1979.

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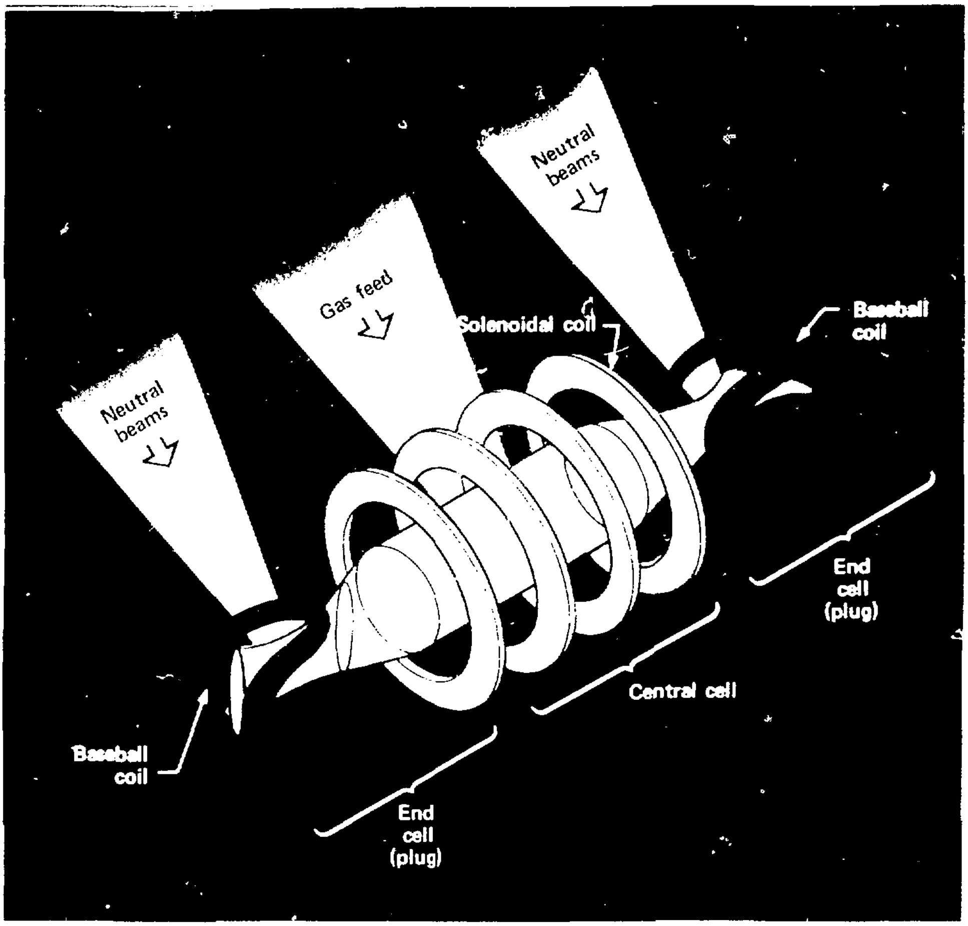

Neutral beams
Gas feed
Neutral beams
Solenoidal coil
Baseball coil
End cell (plug)
Central cell
Baseball coil
End cell (plug)

Figure 1.

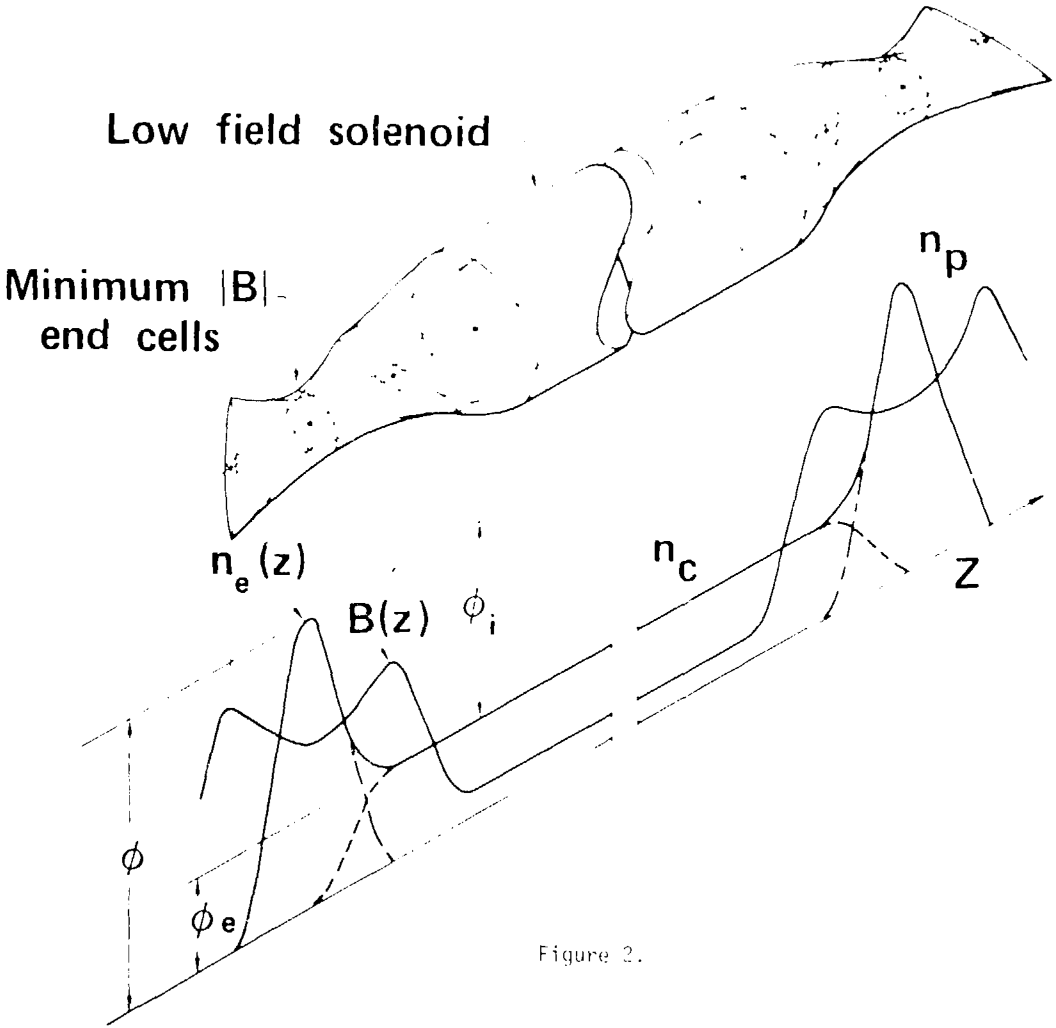
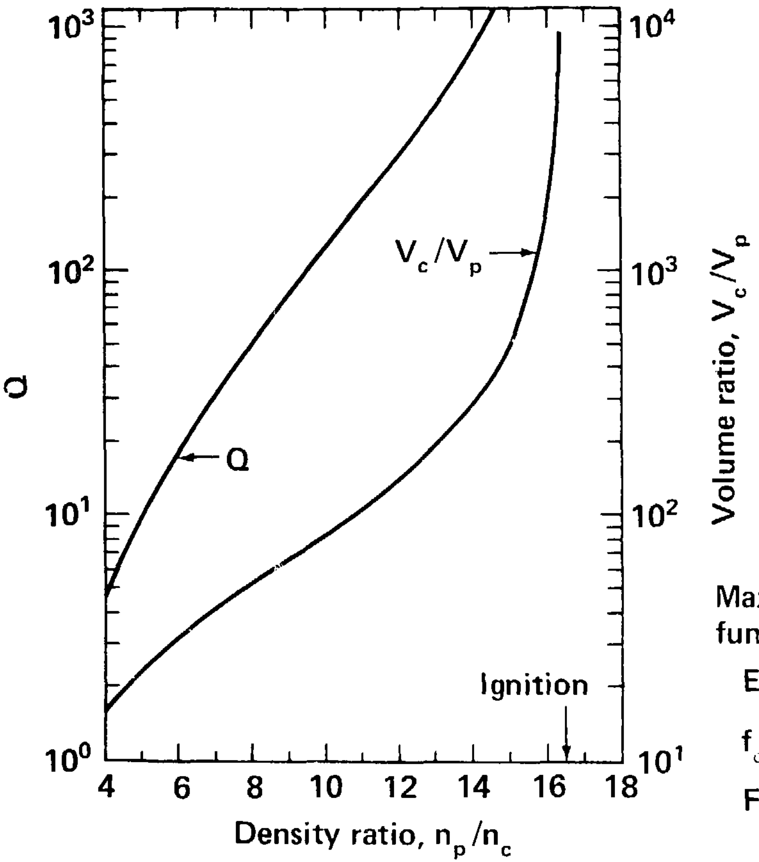

Low field solenoid
Minimum |B| end cells
n_p
$n_e(z)$
n_c
Z
B(z)
ϕ_i
ϕ
ϕ_e

Figure 2.



Maximum Q and volume ratio as a function of density ratio for

$E_{inj} = 1$ MeV

$f_\alpha = 1$

$F_{e\text{-}aux} = 0$

Figure 3.

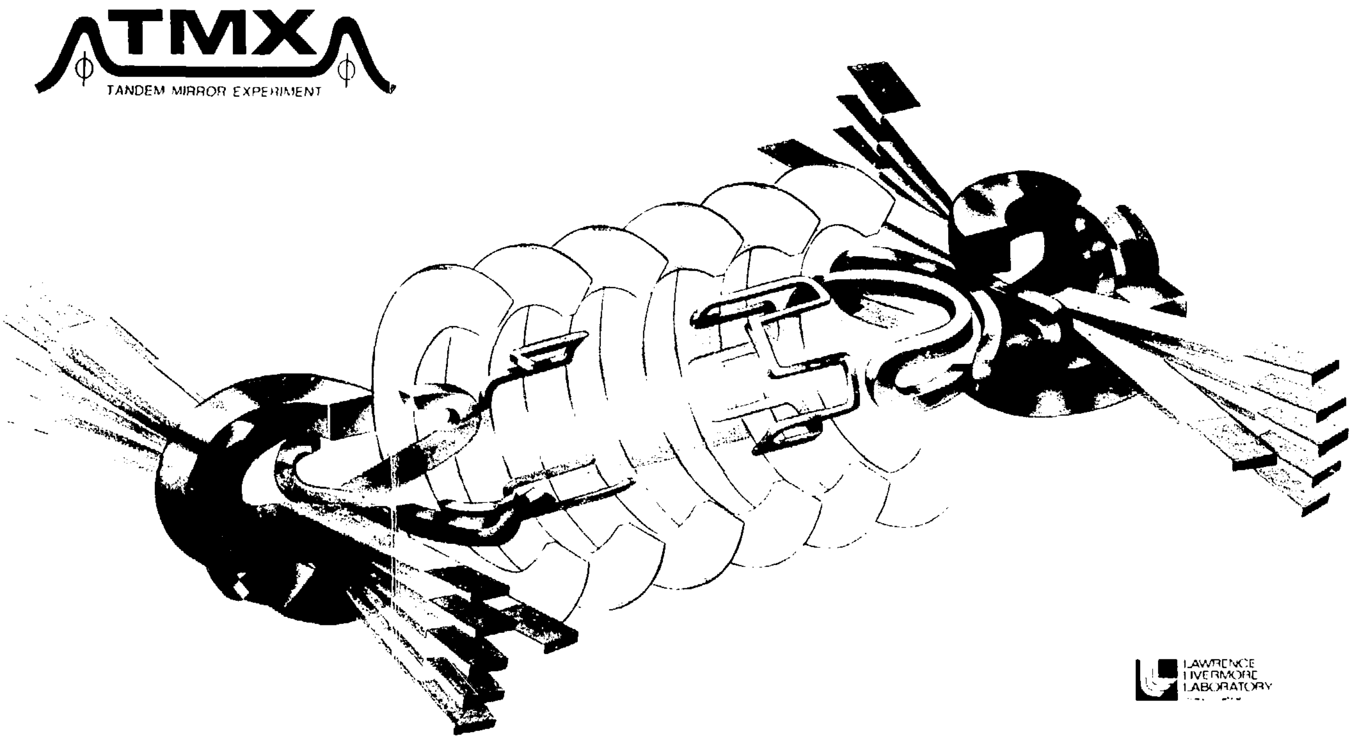
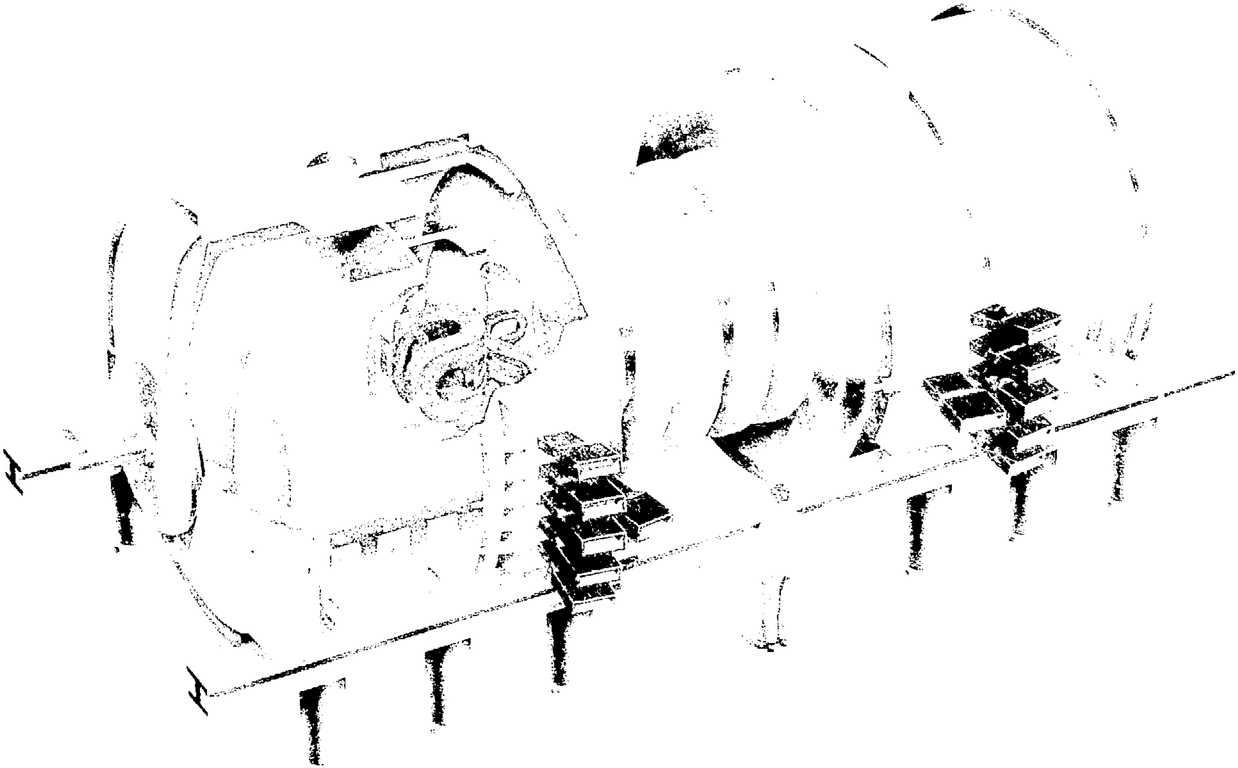

TMX
TANDEM MIRROR EXPERIMENT
LAWRENCE
LIVERMORE
LABORATORY

Figure 4.

TANDEM MIRROR EXPERIMENT



TMX

Figure 5.

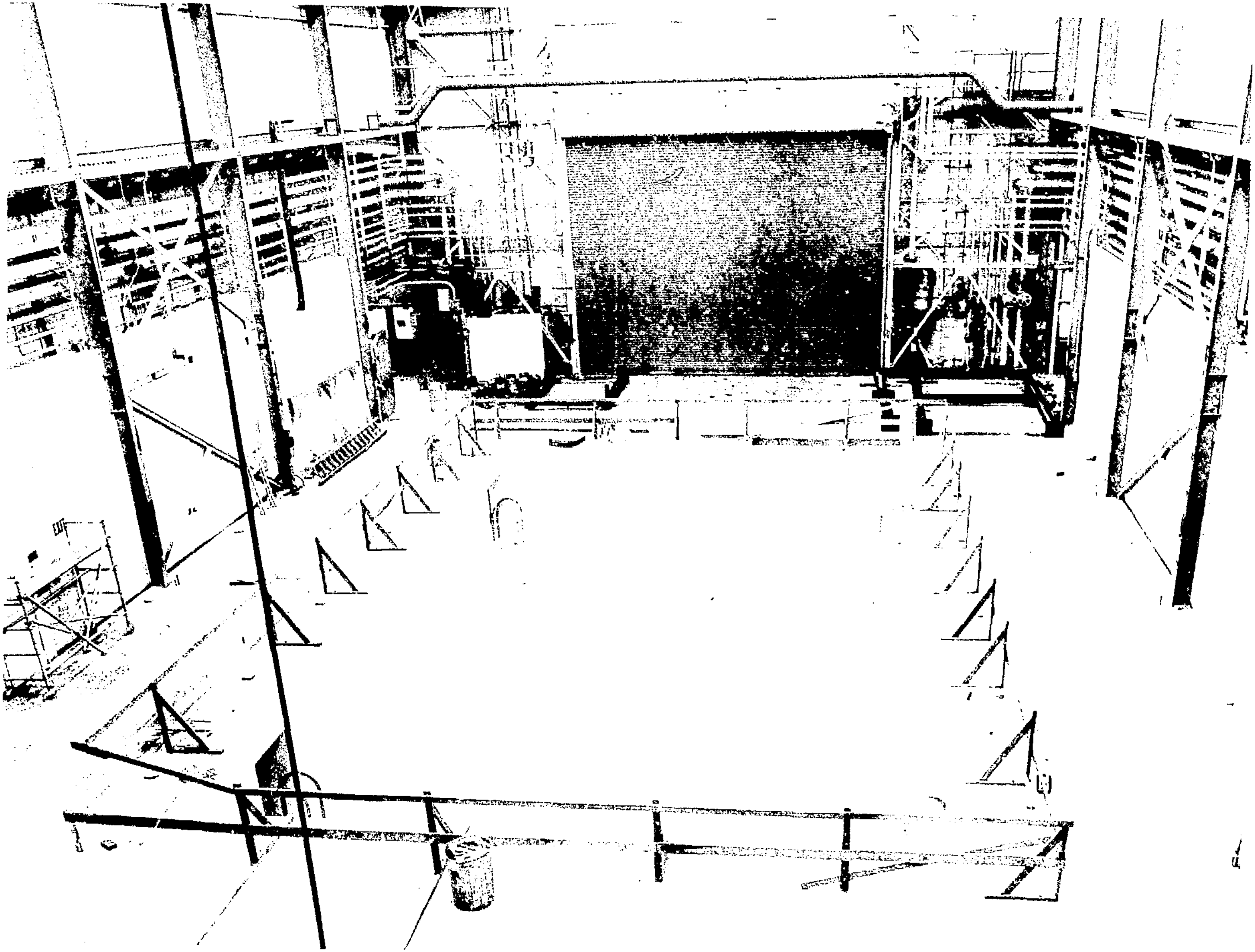


Figure 6.