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MAGNETIC MIRROR FUSION RESEARCH AT THE LAWRENCE LIVERMORE LABORATORY

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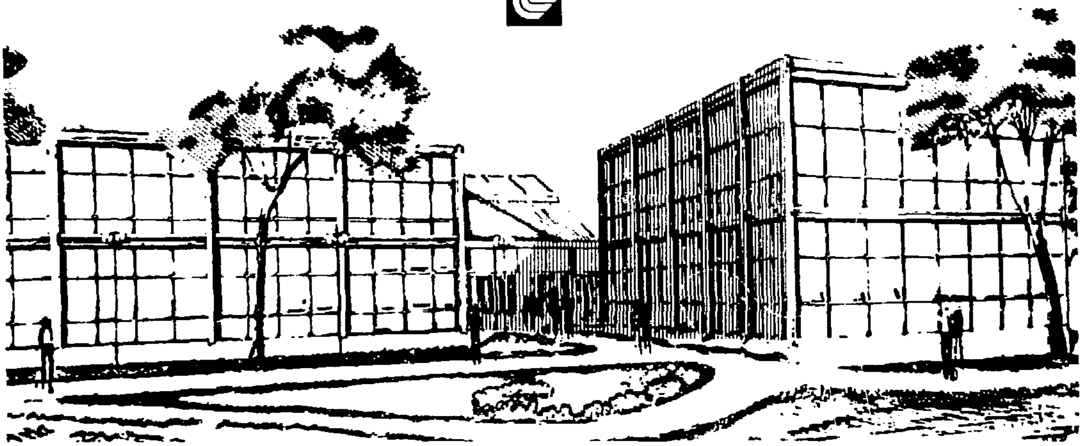

Magnetic Mirror Fusion Research at the Lawrence Livermore Laboratory*

R. F. Post

I) Introduction

I am very pleased to have been invited to participate in this conference commemorating the date of the 70th birthday of Academician Lev Artsimovich. Before beginning the technical part of my talk I would like to pay my special respects to his memory. I met Lev Artsimovich on many occasions and he always impressed me not only as a fine scientist but as a man who had the rare quality of being able to combine a sense of realism with a spirit of optimism. As I perceived him, he never minimized the difficulty of achieving fusion power, but he never doubted but that the problem would be solved - especially if fusion research could be carried out in a spirit of international cooperation. And indeed he did a great deal to encourage that kind of cooperation throughout his career. In this connection I particularly recall what he said in his presentation at the 1958 Geneva Conference: "This problem (fusion) seems to have been created especially for the purpose of developing close cooperation between the scientists and engineers of various countries, working at this problem according to a common plan, and continuously exchanging the results of their calculations, experiments and engineering developments."

I think Soviet scientists can be very proud of the role that Lev Artsimovich played in hastening the day when fusion power will be achieved.

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

II) Research Rationale of Livermore Mirror Program

As you know, the magnetic mirror fusion program has grown dramatically over the last several years. The total funding level for magnetic mirror research in the U.S. is exceeded only by that for the tokamak. The Lawrence Livermore Laboratory has been designated as the national "Lead Laboratory" for mirror research. As Lead Laboratory, the Livermore laboratory has responsiblity not only for carrying out the major U.S. effort in mirror research we are also deeply involved with university and industrial laboratories that perform related and supporting work. In my talk I will concentrate mainly on the effort at Livermore, although there is important mirror-related research being carried out at several other sites.

For many years mirror research at Livermore concentrated on a single goal: demonstrating that the magnetic mirror configuration could confine plasmas at fusion temperatures and at densities high enough to be useful for fusion power generation. We believe that we have succeeded in this task, which required the solution of many difficult problems both of a scientific and of a technical nature. To motivate what I will later have to say about our present program, I will briefly review that work.

As with most other approaches to magnetic fusion, the main scientific problems had to do with the understanding and control of plasma instabilities. In this we were very fortunate to have the benefit of the pioneering work in the USSR on the stabilizing effect of the magnetic well mirror field, carried out by Ioffe under the direction of and inspired by Academician Artsimovich. What was not known at the time those first experiments were performed in 1961 is how good the magnetic well principle really is in controlling MHD-like instabilities. As our experiments in the 2XIIB facility at Livermore have demonstrated, even a shallow magnetic well field can sustain plasmas with peak energy densities that equal or even exceed the energy density of the confining magnetic field. We feel that this demonstration of beta values approaching unity is a very important result, and one which we now understand both experimentally and theoretically.

Although the problem of MHD stability in mirrors was solved very early, it took us many years to understand and control the high frequency instabilities that are associated with the non-maxwellian nature of plasmas confined in mirror systems. Even now, while we believe we have an adequate theoretical understanding of both the nature of and the means for controlling these instabilities, we are not yet satisfied with the technical means that we are presently using to obtain this control and are working to improve these means.

I have mentioned the status of our work on the question of MHD and high frequency instabilities. Of equal importance in understanding the rationale of our research is the question of our technical means for achieving fusion plasmas. Here I believe we have come a long way, both in the matter of the achievement of fusion plasma parameters and in the ability to predict and extrapolate these techniques to still higher levels of performance. I am referring of course to the technique of high current neutral beam injection, which we pioneered at Livermore, together with the solutions to earlier problems of high vacuum and high plasma purity that we have by now achieved. We believe it is now possible to design with confidence neutral beams and vacuum systems that will permit us to achieve almost any plasma ion temperature and plasma particle density that we foresee as being needed in the future, up to ion temperatures of 100 kilovolts or more and plasma densities in excess of 10^{14} ions/cm^3.

It is because we have found workable solutions both to the scientific problems of plasma equilibrium and plasma instabilities and the technical problems of creating and sustaining fusion plasmas in mirror systems that we now are turning our full attention to what is essentially an economic question - how to improve the power amplification factor, Q, of a fusion system using magnetic mirrors.

Since the beginning days of mirror research this has been the most consistent criticism of the mirror approach - namely that its Q value would be too low to permit economic power generation - or perhaps to achieve any net power at all. Fortunately (as I view it) theory was never able to show that we <u>could</u> <u>not</u> succeed - but only that the situation was marginal. We feel that we have been living on the edge of that cliff in Q space for long enough - and that is one of the reasons we are now undertaking some new mirror approaches. These new approaches give promise of increasing the Q factor while still retaining essential features of the mirror approach. As you are probably aware the new approaches are the Tandem Mirror and the Field Reversed Mirror. I would like to spend the rest of my talk describing our work in progress or planned toward proving out these ideas.

III) The Tandem Mirror

I am sure that you are all familiar with the Tandem Mirror idea, invented by Dimov here in the Soviet Union and by Fowler and Logan in the United States. At Livermore we have constructed a major experimental facility, called TMX, to test the physics principles of the Tandem Mirror. My first slide shows a photograph of TMX as it appeared just before the completion of construction. We are now in the midst of bringing TMX into operation, and hopefully will be obtaining data soon.

Meanwhile there have been advances in our understanding of the theoretical issues of the Tandem Mirror. One of the important such issues is that of radial transport. David Baldwin, Ronald Cohen and Yung Lee have considered these issues, following the work of Ryutov and Stupakov here in the Soviet Union. They conclude, in agreement with Ryutov's and Stupakov's results, that both for our TMX and for a full-scale Tandem Mirror power plant the losses of thermal ions by radial transport can be reduced below the normal axial losses through the mirror plugs by using care in scaling. The next slide illustrates the regions where these scaling considerations enter. The simplest scaling has to do with the radius of the plasma itself, as in the tokamak. But the longitudinal scale length of the transition regions also must be considered. These are those field regions between the axially symmetric central solenoidal field and the fan-shaped field regions in the end cells. The length of this transition region and details of its shape are the important scaling parameters which influence radial transport. Our designs seem to be satisfactory from this standpoint for the thermal particles. But for a Tandem Mirror power plant the containment of the alpha particles is also an important issue. At Livermore Ron Cohen has recently performed some calculations that are encouraging in this respect. Briefly, he finds that for transition regions of reasonable length the alpha particles will start their life history well within the banana orbit regime, where radial losses will be tolerably small. Only after they have slowed down enough and given up most of their kinetic energy to the plasma (mostly through electron drag) will they enter the plateau regime and subsequently be lost much more rapidly than would be the case in the absence of resonant diffusion. The regimes involved are shown on the slide. We seem therefore to have the possibility of "having our cake and eating it": The alphas will deposit most of their energy, but after that then be lost, so that they do not accumulate and quench the reaction as had been feared.

There are other important issues in Tandem Mirror physics. One of these is the question of the stabilizaton of the Drift Cyclotron Loss Cone mode. Our present feeling is that this stabilization will come about effectively and automatically in TMX, owing to the plasma streaming that occurs naturally from the central solenoid region as the ions of the central plasma escape through the end plugs. Similarly, if a full-scale Tandem Mirror were to be operated with a relatively high central plasma density, that is in the so-called "two component" mode, as it might be employed in a fusion-fission hybrid system, we believe that streaming from the central region will stabilize the DCLC mode.

We are, however, not equally as sure about the stabilization of

Tandems where high Q values are required, such that the central plasma density is much lower than that in the mirror plugs. In this connection Don Pearlstein has been reexamining the stabilizing effects of inter-penetration or overlapping of the central and end plug plasmas and is finding that the stabilizing effects caused by overlap may be effective provided the end cell can be made very short (of order 10 to 20 a_i). In another investigation I have been examining, in a preliminary way, a process which I have called "ballistic damping". Here ions transiting through the end plugs from the central cell (or shot in from special low energy ion sources) gain energy resonantly from the DCLC wave and carry this energy out of the system, thereby limiting the growth of the mode. This general idea is also now being looked at by Berk, who plans to extend his earlier quasi-linear analysis of the DCLC mode to include such ballistic damping effects.

The final issue that I will mention in connection with the Tandem Mirror is the important one of the electron temperature and the cooling effects of heat conduction through the mirror. It is our present belief that the Tandem Mirror should not suffer from this effect to the degree it occurred in 2XIIB. There, there was the necessity to maintain a high streaming plasma density, owing to the steep radial density gradients in 2XIIB. That is, R_p/a_i, the plasma radius divided by the ion gyroradius, was about 3 in 2XIIB. As shown on the next slide, the theory of Berk, Baldwin and Pearlstein indicates that in such a case a relatively high fractional streaming plasma density within the hot plasma is required for stability. This in turn has required that we maintain a high density of cold plasma outside the mirrors, so that enough of it can penetrate the ambipolar barrier to satisfy the requirements for stabilization. The high density exterior plasma then represents a heat sink that tends to exchange energy with the central plasma by electron transport through the mirror.

We now have preliminary evidence obtained from 2XIIB before it was shut down for changes that our general picture of the radial scaling of stream stabilization is correct. By changing the operating parameters and shifting from deuterium to hydrogen in 2XIIB it was found possible to obtain data over a range of R_p/a_i values concerning the electron temperature and the $n\tau$ confinement factor, while holding beta approximately constant, and adjusting the streaming density so as to maintain stability. The next slide shows the variation of these parameters for R_p/a_i varying between about 2 and 6. The upward trends are quantitatively consistent with our expectations.

If we now couple these indications from 2XIIB with the possibility of eliminating the external streaming plasma sources as should be possible in TMX, we believe that the electron temperature in TMX should rise to substantially higher values than those we saw in 2XIIB at comparable plasma parameters, so that the ambipolar potential barrier will be correspondingly greater.

IV) The Field Reversed Mirror

I would like now to turn to a brief discussion of the other main element of the Livermore Mirror Program - the Field Reversed Mirror. We propose to create a field reversed state within mirror fields and then maintain this state by neutral beam injection. We believe that such field reversed systems would have many advantages for fusion power, including the possibility of highly compact plasmas producing a few megawatts of fusion power each. We realize that there are many serious scientific and technical questions to be answered before we can achieve such a goal, but we are encouraged by the results of experiments in the Soviet Union and in the United States which have achieved transient field-reversed states. We also have some encouragement from theory and from our computer codes, although the theoretical picture is by no means clear at this point.

The two main issues which we need to settle before we can expect to achieve our practical goals for the Field Reversed Mirror are 1) Initiating and sustaining a field-reversed equilibrium state and 2.) Insuring MHD stability of such states.

To solve problem number 1 we are proposing to use neutral beam injection as the main technique, augmented by other techniques as needed. We have already made an initial attempt to create field reversal in 2XIIB that we believe came close to achieving it. In these experiments the neutral beams were aimed tangentially so as to accentuate the trapped ion diamagnetic currents. The results of some of these experiments are shown on the next slide. Also shown is a comparison with the predictions of the Livermore "Superlayer" code that takes into account many but not all of the important features of the experiment, including neutral beam injection and electron drag. As you can see at the lower field of 4.35 kilogauss the agreement is reasonably good, and at high beam current a $\Delta B/B$ of approximately 1.0 was achieved, corresponding to completed exclusion of the magnetic field from the center region of the plasma. $\Delta B/B$ greater than unity is of course required for field reversal. At the high field we believe that the stream stabilization used was not adequate, which explains why the points fall below the Superlayer predictions.

The Superlayer code does not as yet include the effect of electron currents on reducing the ion diamagnetic effects. We believe that such electron currents are not important up to the point of field reversal, but that they may become important if we actually enter a state of field reversal. Baldwin and Fowler have estimated that if electron currents are taken into account we might require a factor of 3 or more in the product of neutral beam current and electron drag time in order to initiate field reversal than that presently predicted by Superlayer. They appeal to the so-called Okhawa current, assuming the presence of a few percent of higher Z ions, to depress the cancelling electron currents.

Since it is at present difficult for us to increase the neutral beam current in the upcoming Beta II (2XIIB reworked) experiments, we are planning to initiate field reversal by the use of a pulsed coaxial gun. This gun is based on a scaleup of some early work of Alfvén's group in Stockholm. The next slide shows qualitatively the ideas involved. But until we have tested the gun we will not know whether the plasma it produces is a suitable one for starting up a Field Reversed Mirror.

In addition to the experimental program on the Field Reversed Mirror, which we plan to carry out in both Beta II and in TMX, we have theoretical work underway on the issues of equilibrium and stability.

In some recent work D.C. Barnes and C.E. Selyer of the Los Alamos Laboratory believe that they have demonstrated that an elongated field-reversed plasma state, of the general shape created in the Los Alamos reversed field theta pinch, can be stable against MHD interchange modes. For stability they require both a properly shaped plasma and the presence of some plasma outside of the separatrix. It is possible that their result can help explain the apparently stable behavior of some reversed field theta pinches. However Newcomb at our Laboratory has criticized their treatment since they have considered only radial flute-like instability modes and did not consider certain axial displacements against which he claims their equilibrium would be unstable. It may be that the resolution of the problem will be found in including kinetic effects such as finite orbit stabilization, that are not included in the present MHD theories. It seems very important to me to pursue the experimental successes already achieved in the reversed field theta pinches to try to understand their stability and reconcile it with the theory.

At the other end of the scale from the MHD theory of equilibria is the theory of equilibria where the ion orbits are large enough to traverse the whole field reversal region. We have gained some insight into the physics of the Field Reversed Mirror by considering models where the ion distribution function is assumed to be a delta function in energy and canonical angular momemtum and then calculating the self-consistant orbits these ions execute in maintaining a field reversed state. Some of this work was reported in the Innsbruck meeting and at Erice in September. The next slide shows an example of self-consistent ion orbits in a long field-reversed layer. While the model is a special one, we have learned some possibly general results from studying it. One result is that it is not possible to achieve field reversal in a long layer unless the outer radius of the layer is larger than 2 times the orbit radius of the ion in the vacuum magnetic field. (That is, a/a_0 greater than 2 in the notation of the slide.) We would expect that the presence of even partial current cancellation by the electrons, as considered by Baldwin and Fowler, would increase this number. In fact, in their example the ratio is 4. On the other hand it seems apparent that the plasma radius cannot become too large compared to the ion gyroradius if we expect finite orbit effects to help maintain stability. We therefore, as has happened before in fusion research, may have a somewhat narrow range of parameters that must be adhered to in order to achieve both equilibrium and stability.

V) The Mirror Fusion Test Facility, MFTF

After TMX and Beta II our next major mirror experiment at Livermore will be MFTF. We are presently about 1 year into the constructon of this facility. Major contracts have been let for the construction of the neutral beam power supplies and for the vacuum chamber, and the winding of the 200 ton superconducting magnet has started. The next slide is an artist's drawing of the vacuum chamber and the magnet showing the size scale. You will notice that the magnetic axis is horizontal in this drawing. In our original proposal the axis was to be vertical. However, owing to increasing interest in the Tandem Mirror idea in the U.S. we received approval to redesign the support structure in order to make the axis horizontal, so that this magnet could later be used as one end cell for a large Tandem Mirror machine. We are now considering an even more ambitious step, to make MFTF into a Tandem Mirror from the beginning. The next slide shows an artist's concept of this proposed facility, which we are calling MFTF-B. If the decision is made to proceed with MFTF-B it would delay the completion of the facility from 1981 to the end of 1982.

MFTF-B would represent a major step for us toward a full-scale Tandem Mirror power plant. It would in fact be about as large physically as a hybrid fusion-fission system is projected to be based on our design studies of Tandem Mirror systems. The next slide shows some projected plasma parameters for MFTF and MFTF-B, together with their calculated Q values for DT plasmas. We do not plan to operate MFTF or MFTF-B with deuterium-tritium. Therefore the Q values given are those that would be expected, assuming that DT were to be used at the same plasma temperatures and densities.

It should be noted that if we decide to proceed with MFTF-B, it will not prevent us from pursuing the Field Reversed Mirror idea, assuming encouragement from experiments in Beta II and in TMX. Just as we plan to carry out field reversal experiments in TMX, we feel that MFTF-B will be a good facility in which to explore both the Tandem Mirror and the Field Reversed Mirror.

VI) Conclusion

In this brief talk I have attempted to give you an overall view of our progress and plans for pressing forward with mirror research at

Livermore. I have not had time to go into detail on any one subject, and I have left out of my talk many interesting investigations being carried out at University laboratories in the U.S. that augment and support our efforts at Livermore. We believe that the mirror idea and its new modifications, the Tandem Mirror and the Field Reversed Mirror, have great promise for fusion power and we hope that other efforts on mirror systems, such as those in the Soviet Union, will grow and will be able to profit from our work, and I am sure we will from theirs.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."

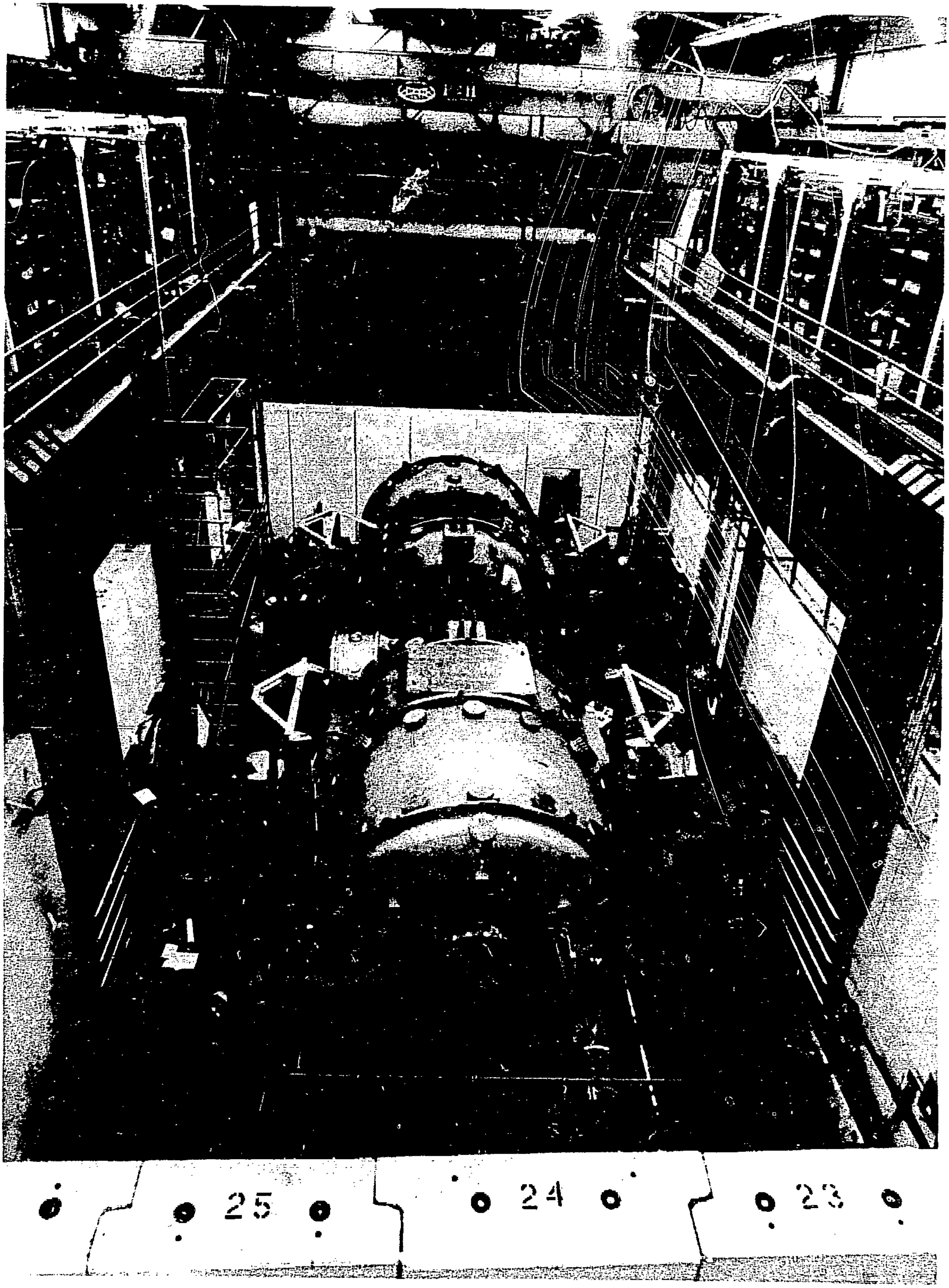
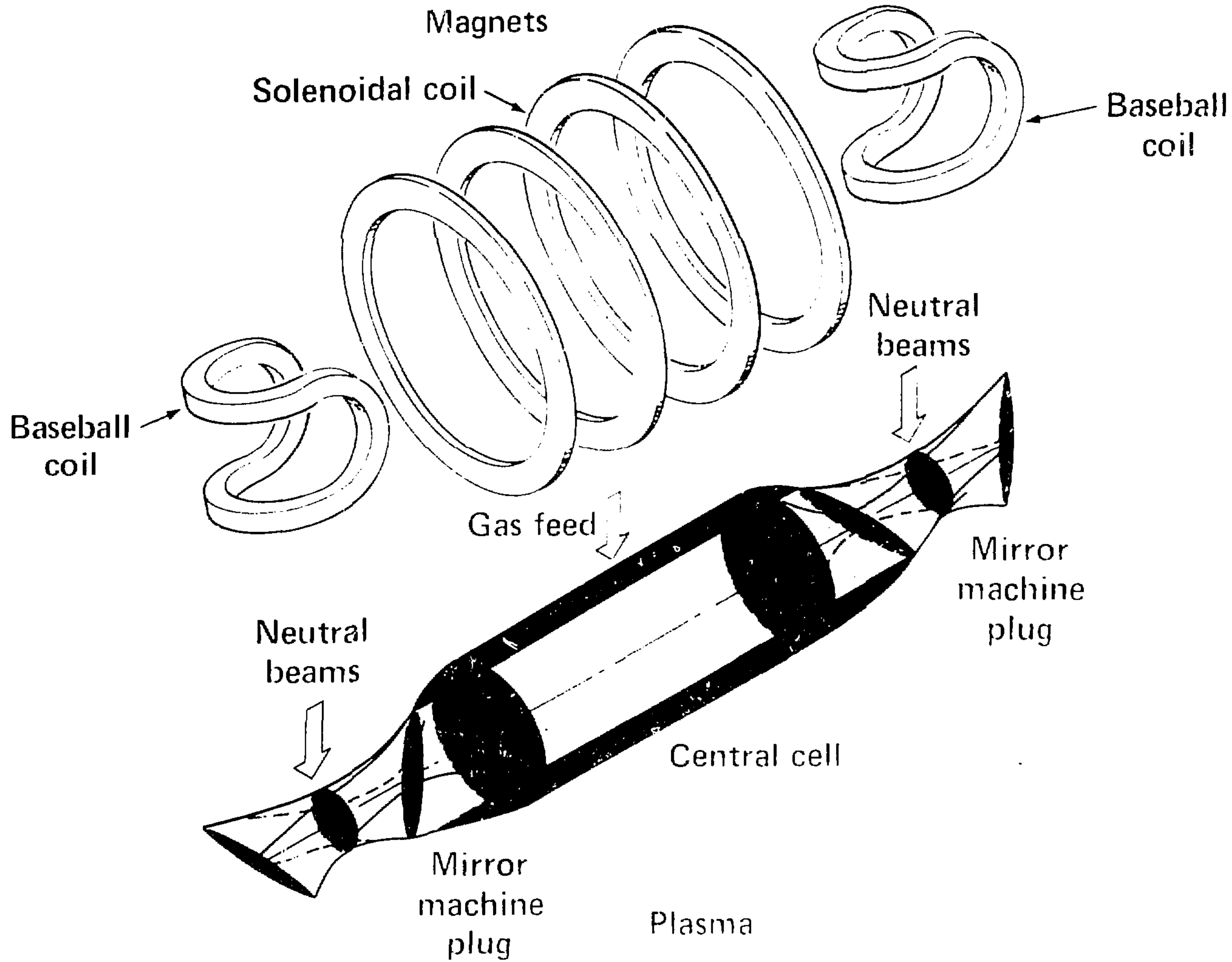


Figure 1

TANDEM MIRROR MACHINE



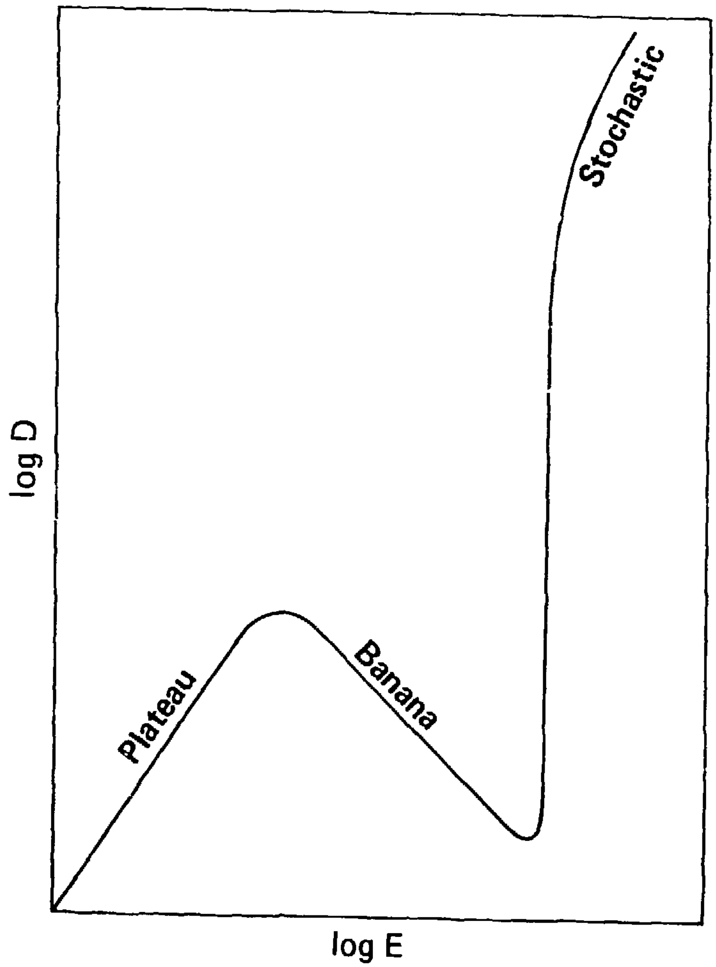


Figure 3

THEORETICAL MINIMUM-REQUIRED STABILIZING STREAM DENSITY VERSUS PLASMA RADIUS

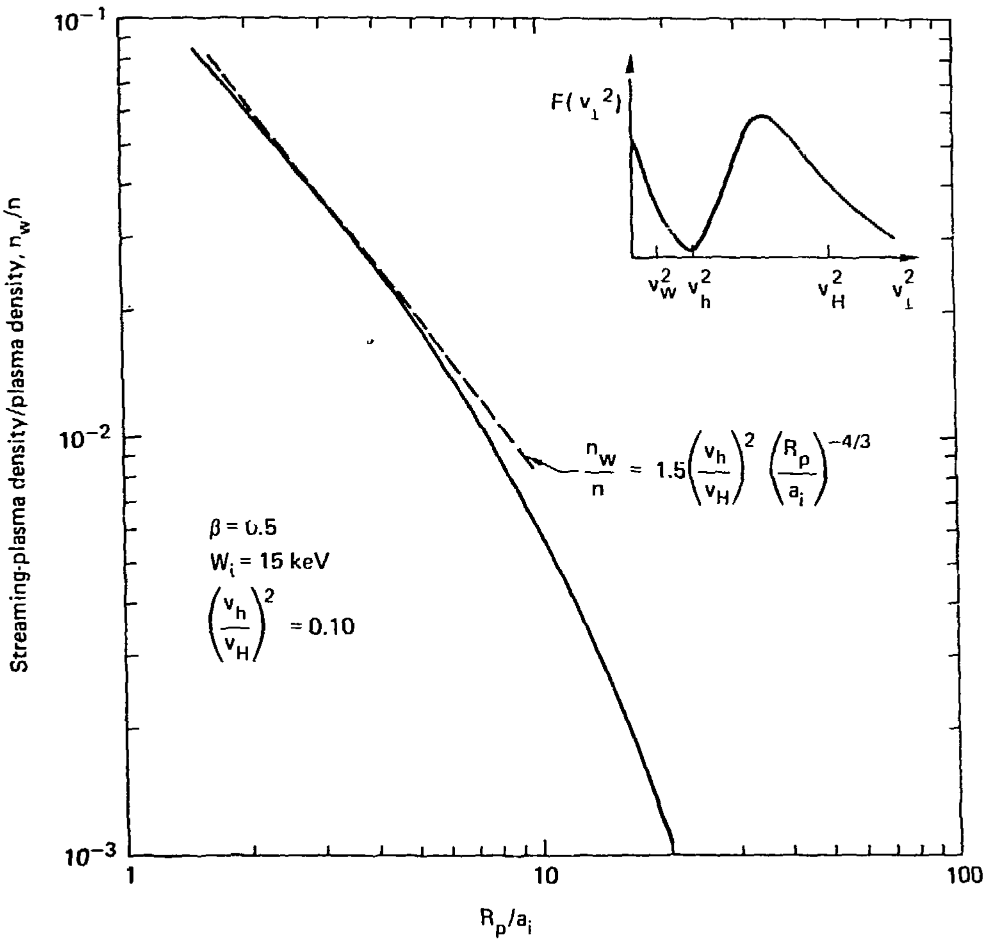


Figure 4

AT FIXED β, BOTH ENERGY CONFINEMENT AND ELECTRON TEMPERATURE INCREASE MONOTONICALLY WITH LARGER R_p

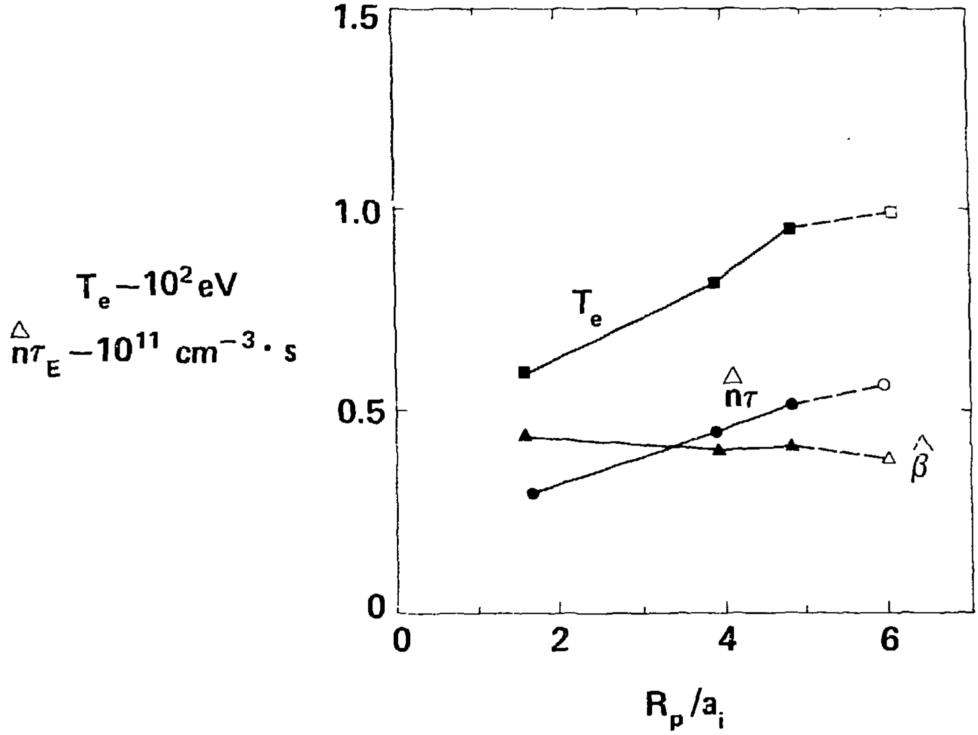


Figure 5

COMPARISON OF EXPERIMENTAL DATA WITH THE SUPERLAYER PARTICLE SIMULATION CODE

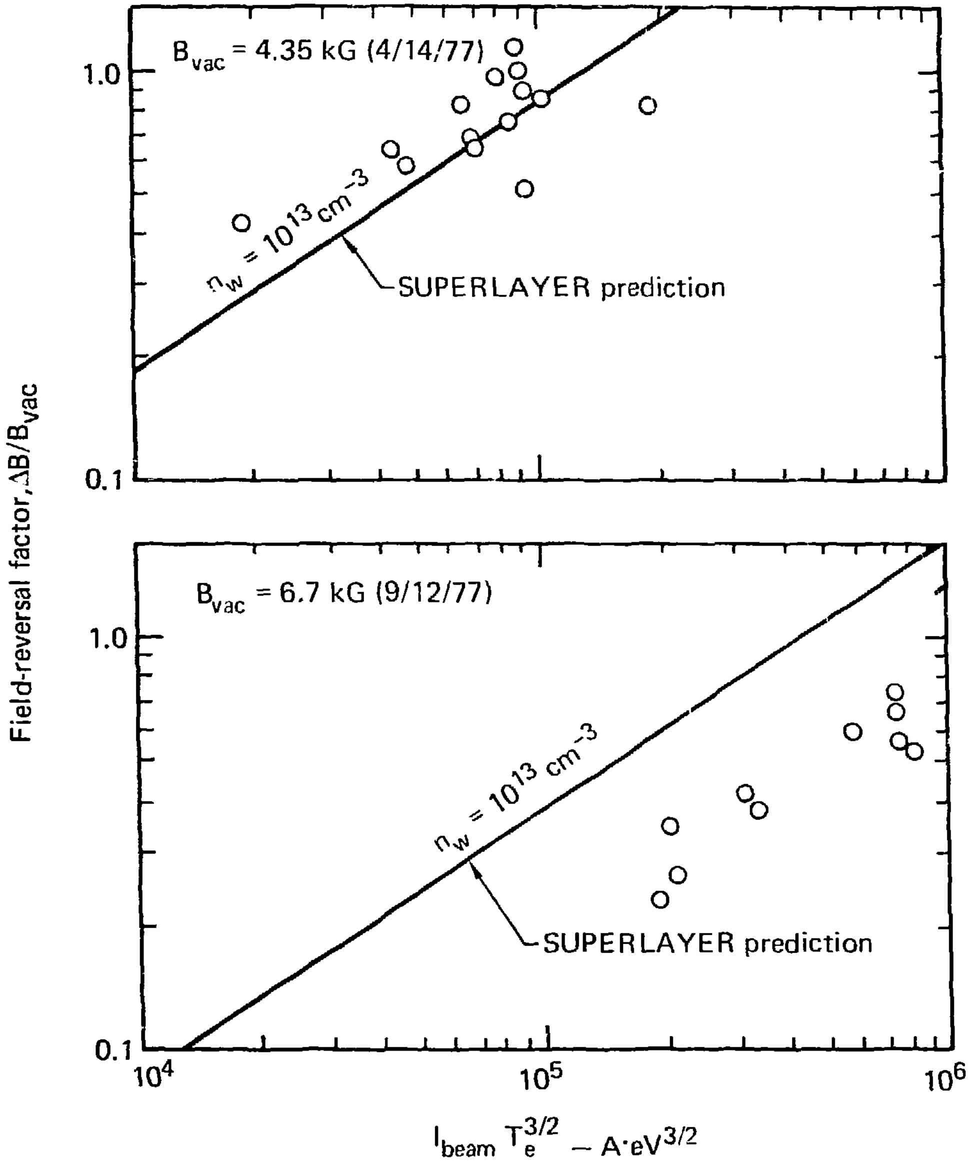
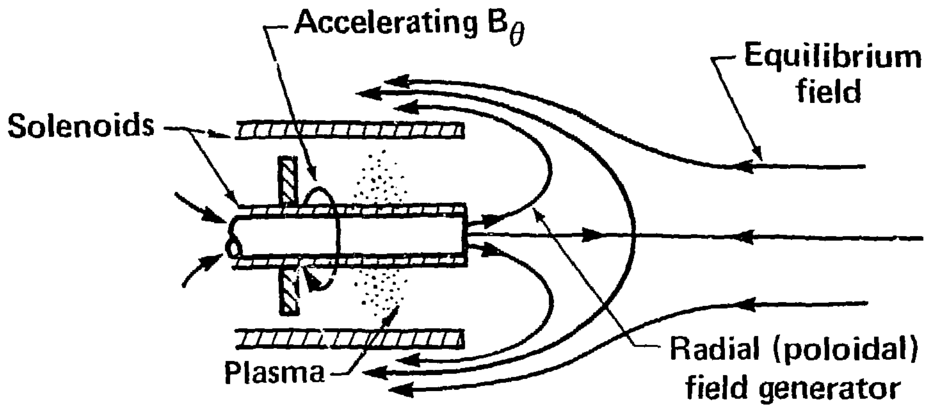
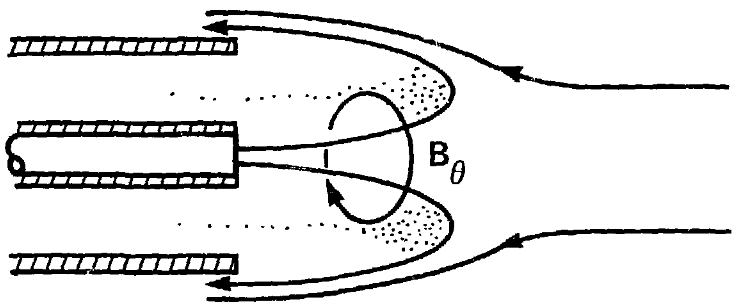


Figure 6

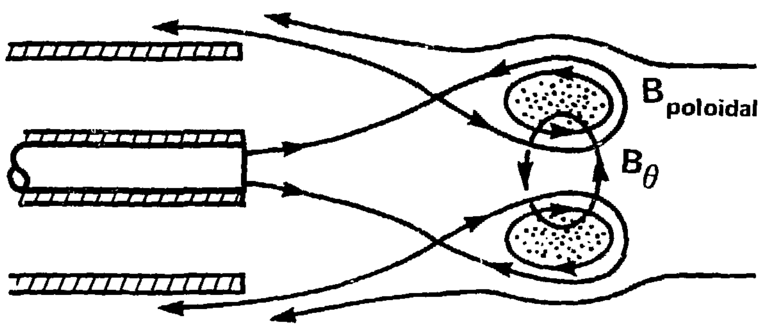
FORMATION OF FIELD-REVERSED PLASMA



(a) During acceleration



(b) Later



(c) Still later

Figure 7

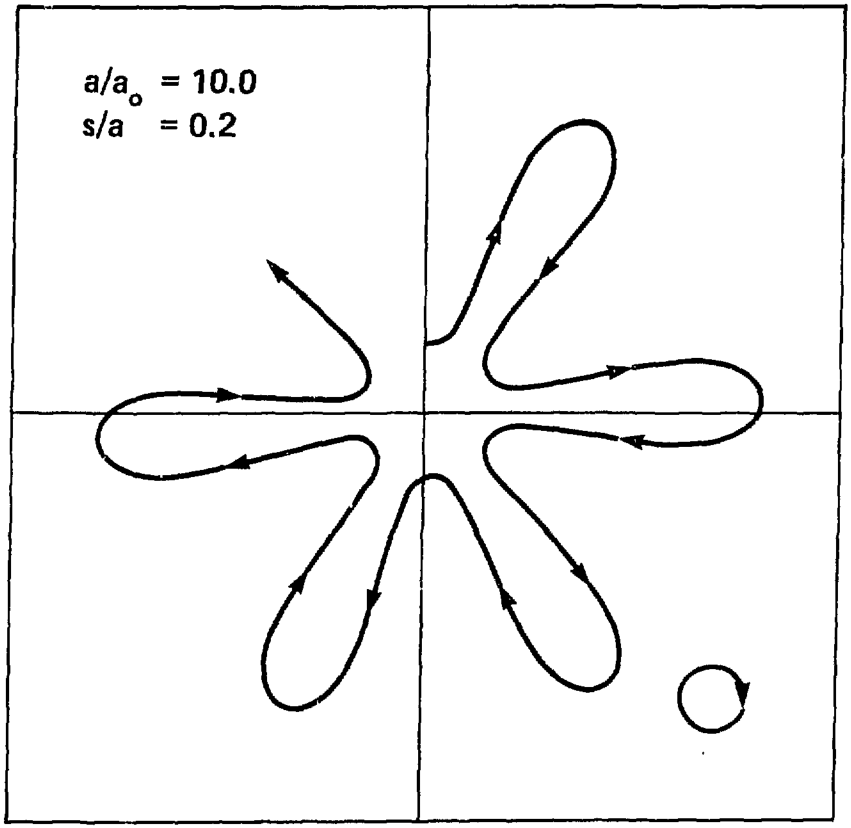
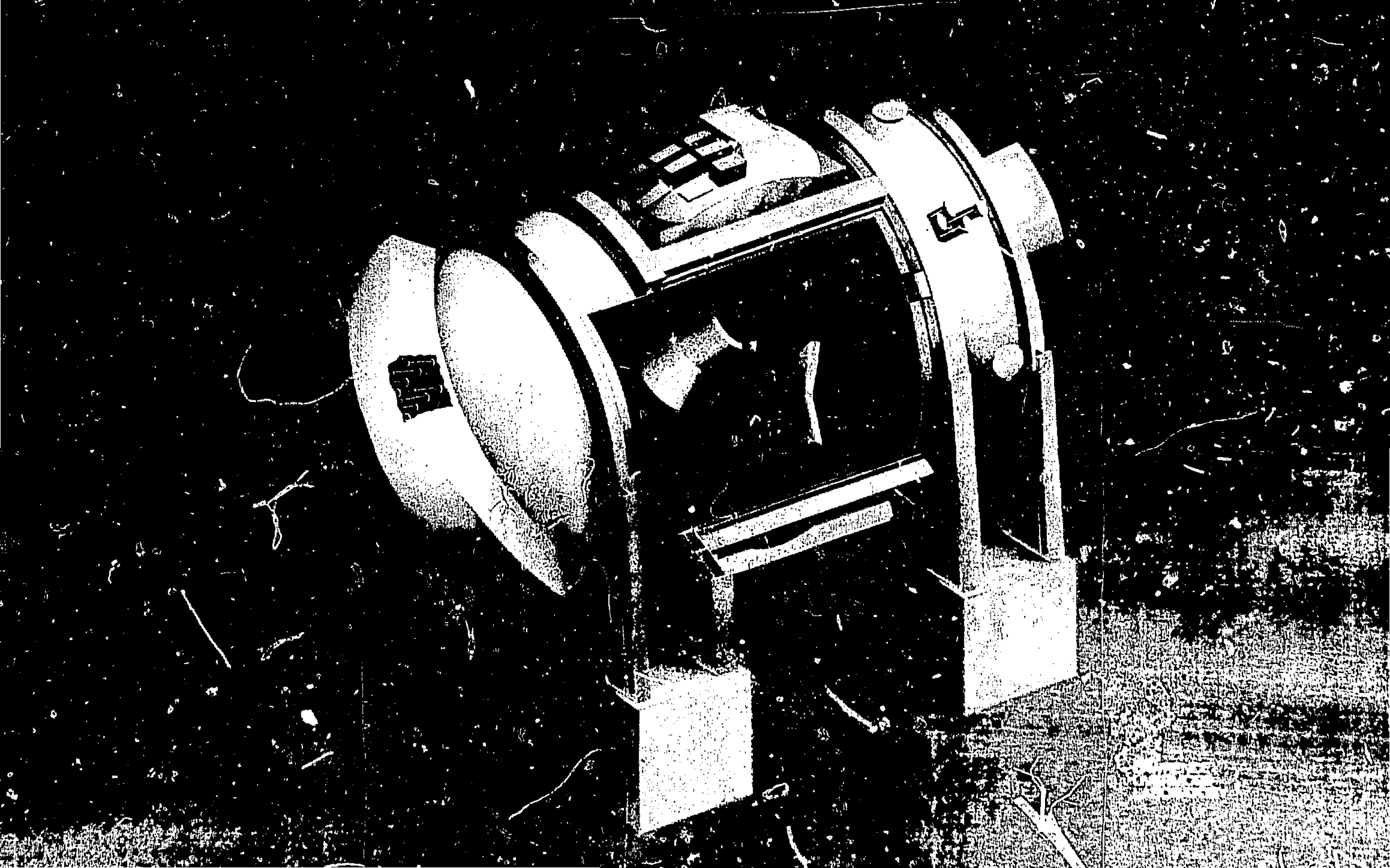
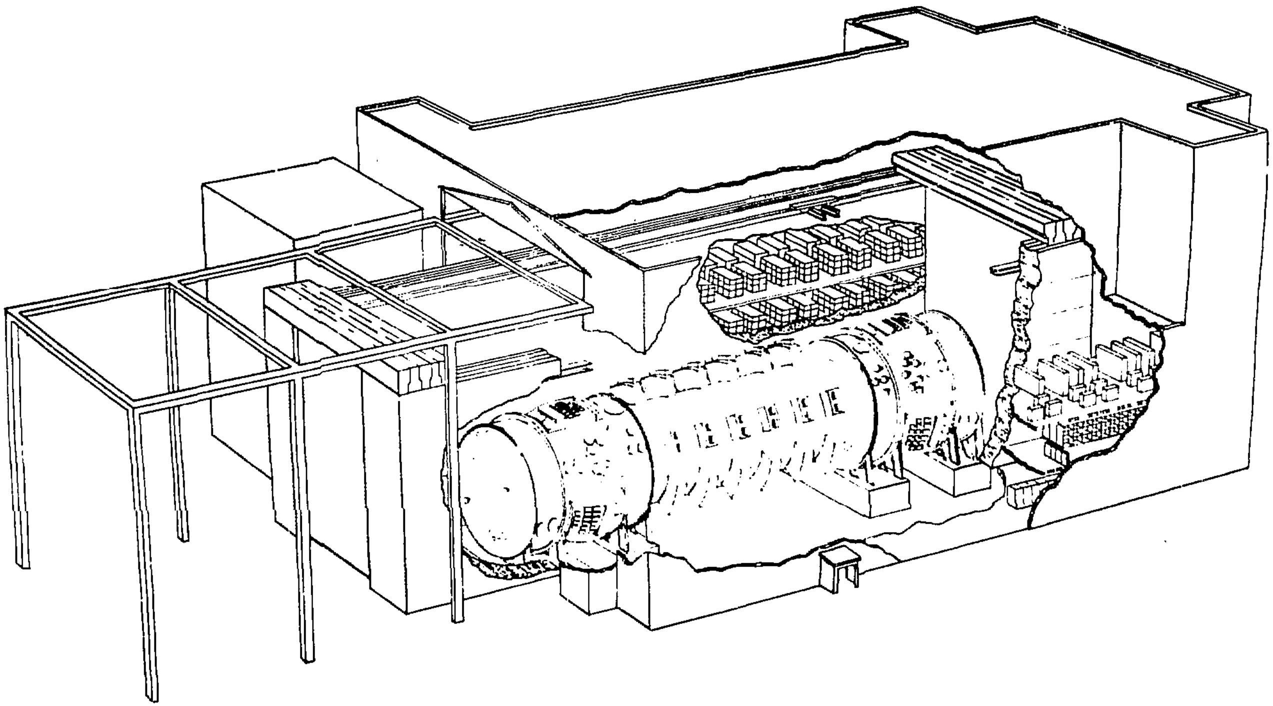


Figure 8

MIRROR FUSION TEST FACILITY – VACUUM VESSEL





MFTF B

Figure 10

MFTF-B PERFORMANCE

	MFTF	MFTF-B Stream Stabilized	MFTF-B Stable End Plugs
$n\tau$	10^{12} cm^{-3} sec	3×10^{12}	10^{13} - 10^{14}
Q*	0.05	0.2 (solenoid only; Q = 0.1 overall)	0.5 (up to $\gtrsim 1$ with beam improvements)

*Equivalent Q (= fusion power/beam power) for DT operation; actual operation will use pure deuterium.

Figure 11