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LLL Mirror Fusion Program: Summary

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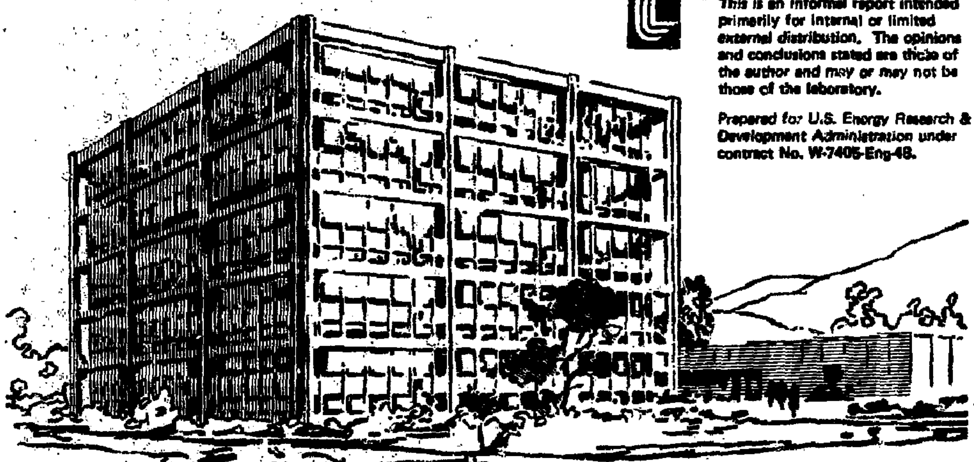

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LLL MIRROR FUSION PROGRAM: SUMMARY

During 1976, new Mirror Program plans have been laid out to take into account the significant advances during the last 18 months. The program is now focused on two new mirror concepts - field reversal and the tandem mirror - that can obtain high Q, defined as t e ratio of fusion power output to the neutral-beam power injected to sustain he reaction. Theoretically, both concepts can attain Q = 5 or more, as compared to Q = 1 in previous mirror designs. Experimental planning for the next 5 years is complete in broad outline, and we are turning attention to what additional steps are necessary to reach our long-range goal of an experimental mirror reactor operating by 1990.

Highlights of the events that have led to the above circumstance are listed in Table 1, and experimental program plans are outlined in Table 2.

The main facilities of the experimental program for the next 5 years are the 2XIIB, the MX Facility recently approved by ERDA as an FY 1978 line item, and the Tandem Mirror Experiment (TMX). Parameters for these facilities are compared in Table 3. Note that Baseball II has been shut down to provide resources for TMX. The long-range objectives of Baseball II, and also of the previously proposed 2XC, can eventually be met by experiments in the flexibly designed end mirror cells in the TMX facility. Field-reversal experiments could also be carried out in the end cells of TMX.

Anticipated results from the experimental program are listed in Table 4. Besides the actual accomplishments in terms of plasma densities, temperatures, and lifetimes, there are certain physics questions to be answered for each of the new concepts.

A tandem mirror reactor would consist of a long solenoidal magnet terminated at each end by conventional mirror cells that act as electrostatic "end plugs" to prevent plasma leakage out the ends of the solenoid. For the tandem mirror, there are two classes of physics questions. The first class of questions peculiar to this geometry - the formation of the electrostatic barriers and MHD stability in the solenoid - can be studied in experiments of modest size. The TMX, with end plugs similar to 2XIIB, is designed for this purpose.

The second class of tandem mirror questions concerns the conventional issues of mirror confinement in the end plugs - mainly instability caused by the "loss-cone" velocity distribution. Stability of the end plugs may be favorably modified by the partial penetration of the plugs by thermalized plasma from the solenoid. This point will be studied in TMX. But for the most part, questions of end-plug stability can be studied in a single mirror cell. Much progress has already been made in 2XIIB, but because of its small size, this experiment (and TMX) can only provide limited data on the main prediction of the theory. Namely, loss-cone instability should diminish to insignificance as the plasma radius increases in relation to the ion gyroradius. Experiments in MX could provide a definitive test of this theory.

For field reversal, the issues are, first, to obtain the field-reversed configuration by neutral injection, and second, to determine its MHD stability properties. The field-reversed state is an entirely different mode of operation of the mirror machine. Whereas conventional mirror operation is "open-ended", with magnetic lines passing into and through the plasma volume, the field-reversed state resembles a tokamak (or toroidal Z-pinch). The plasma volume assumes a toroidal, doughnut-like shape, and the plasma diamagnetic current becomes strong enough to cause magnetic lines to close on themselves within the toroidal plasma volume. In this configuration, there need be no loss cone - the plasma can assume a Maxwellian velocity distribution - but MHD stability is an important question that is difficult to calculate in the appropriate limits.

We have demonstrated by computer simulation that, with sufficient neutral-beam injection current, the plasma makes a smooth transition from open-ended mirror confinement to the toroidal field-reversed state if the beams are aimed off-axis, as shown in Fig. 1. We refer to this as "tangential injection", to distinguish it from "symmetric injection" (also shown) that produces the conventional mirror-confined plasmas of interest as tandem mirror end plugs. In principle, either plasma configuration can be obtained in a single mirror device, depending on which injector arrangement is employed. Experiments with tangential injection are presently under way in 2XIIB, with encouraging but inconclusive results thus far. It is hoped that field reversal will be conclusively demonstrated in 2XIIB, either in the present system or in a later modification with twice as many injectors (by FY 1980).

Even if field reversal is achieved in 2XIIB, there will likely remain issues of scale size for the field-reversal concept as there are for the tandem mirror. For the tandem mirror, we have seen that the issue of scale is loss-cone instability in the end plugs that should improve with increasing plasma radius. For field reversal, the issue is MHD stability, which may deteriorate with increasing plasma radius. In either case, MX could provide a definitive test.

Thus for both the field-reversal and the tandem-mirror concepts, success depends on issues of scale that may only be fully resolved in MX. This possibility is reflected in the program plan of Table 2, which shows experiments in MX as being a necessary input to a decision to begin construction of a DT reactor in FY 1984 based on either concept. (A fusion-fission system or a FERF remain as possible options, but we are focusing attention on a pure-fusion DT system here.) For either high-Q mirror concept, the basic design data would be provided by MX and the preceding smaller experiments. But the reactor itself would have a magnetic geometry quite different from the initial MX magnet (either the tandem geometry or, for field reversal, a series of cells). The plan therefore anticipates the need for modifying the MX Facility design and construction to serve as a physics prototype of the reactor design. Though not yet known in detail, these modifications would be expected to reuse most of the major MX components, including the neutral-beam power supply, cryosystem, and controls.

Favorable experimental results and theoretical advances could speed up this schedule. Two results pointing in that direction could yet come from 2XIIB in FY 1977. These are indicated in Table 4, labeled "best expectations."

One such possibility, concerned with conventional mirror scaling and tandem mirror end plugs, is to inject the beams so as to obtain a flattened density profile with negligible radial density gradient at the axis ($dn/dr^2 = 0$ there). This should suppress the dominant loss-cone instability (DCLC mode) near the axis so that classical confinement would obtain there and the electron temperature on-axis would rise markedly. This experiment in 2XIIB is planned toward the end of FY 1977. Positive results would provide a striking confirmation of mirror stability theory and imply a significant improvement in the performance of TMX and MX with injection arranged to create $dn/dr^2 = 0$ near the axis.

The second possibility concerns field reversal. The degree to which field reversal improves confinement depends on the fraction of the plasma residing on closed lines and on its radial extent (measured in ion gyroradii). If field lines are closed only in a small fraction of the plasma volume (partial field reversal), or if MHD stability limits the plasma radius to a very few gyroradii, field reversal will result in only a small improvement in confinement. Under the best of circumstances, most of the magnetic lines close within the plasma, and confinement is then limited only by diffusion across the closed lines as in a toroidal device. In the latter case, the confinement product $n\tau$ should improve another order of magnitude in 2XIIB (10 ms at a density of $10^{14}cm^{-3}$), and MX with its larger size could attain $n\tau$ as large as $10^{13} - 10^{14}cm^{-3} \cdot s$.

The actual situation should be clear by the time TMX is operating, and thus we see FY 1979-80 as a period of crucial decisions for the Mirror Program. These decisions will influence the actual course of mirror reactor development in the 1980's and the role that MX and modifications of MX will play in it.

A parallel circumstance exists for the mainline tokamak program. It is now appreciated that economic viability of the tokamak reactor depends on the parameter β, defined as the ratio of plasma pressure to the magnetic energy density ($\beta = 8\pi\ nT/B^2$). There are two possible means of increasing β in tokamaks from present values around 1% to the value around 10% needed for a reactor. One is forcing the toroidal cross section into an elongated shape, to be tested in the Doublet III facility at General Atomic. The other is a new "flux-conserving tokamak" concept that will be tested on a modification of the Ormak facility at Oak Ridge. These tokamak experiments also should produce results by FY 1979-80, in time to influence the major TFTR tokamak program at Princeton. Both MX and TFTR should become operational by FY 1982.

We believe that the Mirror Program has now been brought to a position competitive with tokamak. 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 possible to build mirror systems in small units of modular construction. Both the field-reversal and tandem-mirror concepts exemplify this point. If the field-reversal concept succeeds, it should be possible to build a self-contained reactor cell producing about 10-MW output. A reactor would consist of a chain of these, but development could be carried out on a few cells at a time. For the tandem mirror reactor, the long linear structure of the main solenoidal section offers similar opportunities for modular development. Sections of the solenoid could be exchanged and upgraded many times during the lifetime of an experimental facility. Exploring and exploiting these properties of mirror reactor systems is one of the important tasks before us as we continue planning for the 1980's.

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RECENT HIGHLIGHTS IN THE MIRROR FUSION PROGRAM

July 1975	2XIIB plasma stabilized, lifetime increased 10-fold, mean ion energy of 13 keV
July–Dec 1975	Theory of 2XIIB stabilization developed; predictions of this theory guide MX design.
Oct 1975	Simple method of "startup" in a DC magnetic field demonstrated – neutral injection on a cold plasma stream
Feb 1976	High β achieved (peak $\beta \sim 1.2$ to 1.6); raises hope for field reversal concept
March–Sept 1976	MX proposed, favorably reviewed and approved by ERDA
July–Dec 1976	Tandem mirror idea for high Q reactor introduced, favorably evaluated at LLL, and TMX proposed
Dec 1976	New attempt to obtain field reversal yields 50% greater diamagnetic signal and electron temperature increases from 60 eV to 180 eV; still being evaluated

Table 1

LLL PLANS TO DEVELOP FIELD REVERSED MIRROR AND TANDEM MIRROR CONCEPTS

FIELD REVERSED MIRROR		TANDEM MIRROR
Attempt field reversal in 2XIIB	FY 77	End plug stability studies in 2XIIB
	Complete TMX fab	
Prepare 1200A injection in 2XIIB	FY 79	Proof of principle – Demonstrate potential well – MHD stability
Second try for field reversal in 2XIIB; Begin design of DT reactor and Phase II mods of MX	FY 80	Begin design of DT reactor and Phase II mods of MX
	Complete MX fab	
Field reversal experiment in MX; begin Phase II mods in parallel	FY 82	End plug stability studies in MX; begin Phase II mods in parallel
Begin constructing experimental reactor	FY 84	Begin constructing experimental reactor
"10 MW" per cell	FY 90	"100 MW"

Table 2

LLL MIRROR FACILITIES

	2XIIB	TMX (end plugs)*	MX
Magnetic field (midplane)	7 kG	10 kG	20 kG
Field duration	10 msec	Seconds	DC (superconducting)
Length between mirrors	1.6 m	0.9 m	3.2 m
Injection current	600 A maximum	550 A maximum	750 A (sustaining beams)
Beam accelerating voltage	20 kV (some 40 kV)	20 kV (some 40 kV)	80 kV
Beam duration	10 msec	25 msec (first beam set)	500 msec (later, seconds)
Date operational	Operating	Oct 1978 (proposed)	Oct 1981 (proposed)

*TMX is a *tandem* mirror geometry with two mirror cells as "end plugs" connected by a low-field solenoid. Parameters above are those for each end plug.

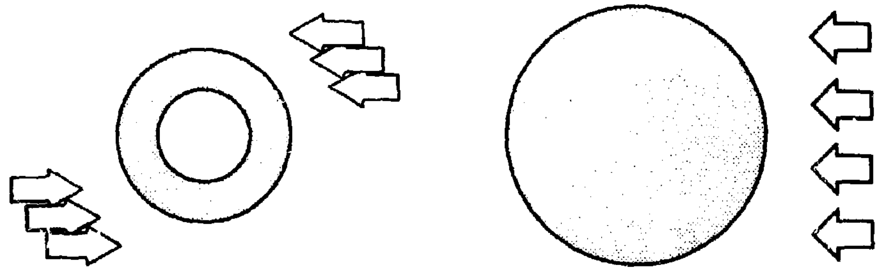
Table 3

ANTICIPATED RESULTS IN MIRROR EXPERIMENTS

	Minimum expectation	Best expectation
2XIIB		
Mirror scaling (end plugs)	$n\tau \sim 10^{11}$ (already obtained)	On axis if $dn/dr^2 \sim 0$: $T_e \sim 0.8$ keV $n\tau \sim 3 \cdot 10^{11}$
Field reversal	Obtain partial field reversal $n\tau \sim 10^{11}$	$n\tau \sim$ few $\cdot 10^{11}$
Field reversal at twice the current	Second try at obtaining field reversal (FY 1980)	$n\tau \sim 10^{12}$ (larger volume)
TMX		
	$T_e = 0.2$ keV $n\tau = 10^{11}$ in the solenoid	On axis if $dn/dr^2 \sim 0$: $T_e \sim 0.35$ keV $n\tau \sim 7 \cdot 10^{11}$ in the solenoid
MX		
Mirror scaling (end plugs)	$T_i = 50$ keV $T_e = 1$ keV $n\tau = 10^{12}$	On axis if $dn/dr^2 \sim 0$: $T_e = 3$ keV $n\tau = 2 \times 10^{12}$
Field reversal	Obtain partial field reversal $n\tau \sim 10^{12}$	$a/\rho_i \sim 5$ $n\tau \sim 10^{13} - 10^{14}$

Table 4

BEAM INJECTION CONFIGURATIONS TO STUDY FIELD REVERSAL AND TANDEM MIRROR END PLUGS



Field reversal

Beams perpendicular to magnetic axis, aimed to create a compact plasma volume of toroidal (doughnut) shape

Tandem mirror

Beams perpendicular to magnetic axis, symmetric about the axis, and aimed to fill a large volume (plasma radius equal to many Larmor radii)

Fig. 3

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