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STATUS REPORT ON MIRROR ALTERNATIVES

W. C. Condit, T. K. Fowler, and R. F. Post

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LAWRENCE LIVERMORE LABORATORY
University of California Livermore, California 94550

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STATUS REPORT ON MIRROR ALTERNATIVES

Abstract

The present status of studies at Lawrence Livermore Laboratory (LLL) directed toward exploring variants on the basic magnetic mirror confinement concept is described. These studies have emphasized those ideas that could lead most directly to improvements in

the scientific and economic viability of fusion reactors based on the mirror concept, within the general context of the extensive body of specialized physics and technology that has been developed in the course of the Mirror Program.

1. Introduction

As outlined in Ref. 1, the Lawrence Livermore Laboratory (LLL) Mirror Program is primarily directed toward a steady-state fusion reactor based upon a superconducting Yin-Yang magnet, neutral beam injection, and direct conversion. In addition, a portion of our theory and design efforts is aimed at exploring improvements in this system and also alternative concepts employing the mirror confinement principle.

In these exploratory studies, we have mainly considered those ideas that use the physics and technology already being developed in the program. Thus, some ideas can be tested directly in the 2XIIB and Baseball II-T experiments and the proposed MX

experiment. In other cases, we have in mind the possibility of further modifications of 2X a year or two hence, and later perhaps a major experiment on the scale of MX and using the same 160-MW beam power supply, cryogenic facilities, and controls

Thus, largely by utilizing facilities that would already exist in the mainline program, promising new mirror ideas could be pursued at a relatively small additional cost. In most cases, the largest new expenditure would be a new magnet set; for reference, the MX magnet itself is only 10% of the total cost of the MX facility.

2. Studies in Progress

The following is a list of five categories of exploratory mirror ideas that have received the most attention in recent months:

- *Means to improve Q .* This includes Fokker-Planck studies to optimize injection parameters as well as additional machine components aimed at improving the ratio of fusion power to injected power, denoted by Q .

- *Field reversal.* This concerns the possibility that plasma currents in the mirror machine can be made to form a stable, closed pattern of magnetic lines, similar to the Astron or reversed-field, theta-pinch configurations.

- *Field optimization and simple mirrors.* This concerns mirror field designs that might be simpler and less expensive than the Yin-Yang, while preserving magnetohydrodynamic (MHD) stability.

- *Mirror-torus hybrids.* This concerns toroidal geometries that also involve mirror confinement in an essential way (for example: the Ion Bumpy Torus (IBT)).

- *Long linear machines.* This includes the two-component mirror concept, multiple-mirrors, and long solenoids.

The status and present evaluation of each of these study categories are outlined in Table 1. More details appear in the sections that follow.

Table 1. Summary and present evaluation of mirror alternatives studies

Category	Problems	Available theoretical tools	Applicable near-term experiments	Present evaluation
Means to improve Q	Detailed balance of gains and losses	Mainly Fokker-Planck codes	1. 2XIIB, Baseball II-T, (2 limits)	Should continue theoretical study: might increase Q by ~ 50% and decrease mirror reactor cost proportionately.
Field reversal	1. MHD stability 2. Startup	1. SUPERLAYER code revised for neutral injection 2. Stability analysis	1. Cornell Astron: Kurtmullaev experiment 2. Possibly 2XIIB 3. High-intensity ion sources	Should actively pursue: has greatest potential for small, cheap reactor, though still great uncertainty in physics. Needs development of intense ion sources.
Field optimization and simple mirror	1. MHD beta limit 2. Heat loss by 'line tying'	1. 3D equilibrium code 2. Stability analysis	2XC and certain aspects of 2XIIB	Should build 2XC: could substantially reduce reactor cost and magnet development.
Mirror-torus hybrids	1. MHD beta limits 2. Field design	1. Field design codes 2. Point model energy-balance code	1. 2XC (to model a single mirror cell) 2. Elmo Bumpy Torus (EBT) 3. TORNAC, MIRICLE	Ion Bumpy Torus (IBT) may be promising if simple mirror cell can be made to work.
Long linear machines	1. Large size because of heat leakage at the ends	1. MARTENI code 2. Analytical models	1. 2XIIB in two-component mode 2. Multiple-mirror experiments (UCB, Novosibirsk)	The size still seems to be large.

3. Means to Improve Q

In our mirror reactor designs, Q is calculated from the two-dimensional Fokker-Planck code with classical coefficients. Previously, good agreement has been obtained between classical Fokker-Planck calculations and Baseball II data with 1- to 2-keV injection under fully stable conditions at low density.* Besides Q, the code now also calculates β (in the "long, thin" plasma limit) and the axial density profile, all as functions of the mirror ratio, the beam energy, and the angle of injection relative to the midplane. Optimum parameters are chosen to minimize the overall cost per kilowatt output. The main leverage on Q in these calculations is the vacuum field mirror ratio, R_{vac} . However, assuming the peak mirror field to be fixed, the power output drops rapidly as R_{vac} increases. The optimum occurs around $Q = 1$ for this model.³ Increasing Q from 1 to 2 with no change in R_{vac} and β would cut the plant cost almost in half for a given

power output and reduce the projected cost per kilowatt to around \$1400/KW.³

It is entirely possible that Q is underestimated by our present calculational models. In the past, it had been assumed that high β would decrease the scattering loss rate because the net mirror ratio would thereby be increased. As it has turned out, an essential feature of our present model by which these effects are calculated is that Q is almost independent of β .⁴ This is due to the fact that achieving high β with the presently-used theory requires beam injection near enough to the loss-cone angle so that improvements in Q are negated. However, the 2XII-B data has called this model into question (see Appendix A). The model is based on the joint conditions of stability to the MHD mirror mode and an equilibrium calculated in the limit of weak field curvature (the long, thin limit). In the 2XII-B machine, the plasma $\beta = 0.4$ or more, although the vacuum mirror ratio over the actual plasma length is less than 1.1. This disagrees with the results for the long, thin limit and suggests the possibility that in the "short, fat" case the limit on β with injection nearly

*By including a charge-exchange term representing the measured gas density (comparable to scattering losses), the calculated and measured end losses² agreed within 5% for Baseball II runs with good vacuum conditions (well within uncertainty).

perpendicular to the magnetic field may be significantly greater than that presently predicted. If so, the classical Q value for a given vacuum mirror ratio would be higher, accordingly.

Several other possibilities for improvements in Q are under study. For example, there is preliminary evidence that a spread in beam energies would help (thus far beams are assumed monoenergetic). We have also briefly examined the effects of augmented rf heating at ion resonance ($k_{\parallel} \approx 1$), which acts somewhat like compressional "clamping" in the Toroidal Fusion Test Reactor (TFTR). Dawson and co-workers have shown that ion cyclotron waves can raise $T_{\parallel}$ and decrease $T_{\perp}$.⁵ A related idea not requiring rf equipment is a mode of operation in which the neutral beams

are slowly pulsed on and off, during which slow axial expansion that decreases $T_{\parallel}$ competes with the increase in $T_{\perp}$ by scattering. This possibility is discussed in Appendix B. Still another possibility, discussed in Section 6, is the recirculation of escaping electrons through a toroidal loop in order to improve the electron heat confinement (MIRICLE).

While none of the above ideas has yet reached maturity, these ideas indicate promising avenues to explore. Furthermore, other ideas will no doubt come along. Meanwhile, the stability criteria in order that the classical results be valid are undergoing intensive reassessment, and diffusion coefficients to represent any residual turbulence are being incorporated in the Fokker-Planck code.

4. Field Reversal

Two reversed-field configurations might be considered. One resembles Astron, in which a ring of very energetic ions encircling the axis would create the field configuration that confines the plasma. Since this configuration is one orbit in diameter, ion energies of many MeV are required in order to obtain a useful volume. This approach is now being pursued at Cornell.⁶

Lovelace has published a theory of the stability of this configuration.⁷

Here, we shall discuss another possibility, which we will call the reversed-field mirror configuration, in which the plasma itself produces field reversal. Created and sustained by neutral injection, it would simply be a different operating mode of the standard mirror machine, but one in which Q would be expected

to be enhanced by virtue of toroidal confinement. The configuration, shown in Fig. D-1, resembles a reversed-field theta pinch, or (since the plasma seems to prefer a fat-doughnut shape) a diffuse, toroidal, Z-pinch with no stabilizing field. Thus, in this configuration, while one hopes for largely toroidal confinement, we would actually abandon the strong toroidal field that, while it helps to make a tokamak stable, at the same time constrains it to be a low-beta device.

CONFIGURATIONAL STABILITY

At first sight, one would expect a reversed-field configuration such as we describe to be unstable. A recent piece of experimental evidence has a bearing on this subject.⁸ Kurtmullaev and co-workers believe that they have created just such a state by first making a reversed-field theta pinch ($T_i = 100$ eV) that then contracts to a fat doughnut with reversed field and appears to persist stably for 50 ms. They stress the importance of a strong multipole "barrier" field in their setup to prevent blowup during the contraction phase and a careful adjustment of parameters to insure that the final doughnut is fat enough to fill the tube.

Anderson and Newcomb at LLL have analyzed this experiment in some detail and find that it should have been unstable as judged by strict MHD theory (zero Larmor radius). They neglect the barrier field in their analysis.

Presuming that Kurtmullaev and his group have interpreted their experimental results correctly, we now believe that the most probable explanation is finite-orbit stabilization, together with an aspect ratio near unity (see Appendix C). In essence, finite-orbit effects could provide internal rigidity if the aspect ratio also restricts azimuthal wavelengths to be a few times the minor diameter. An exception is the mode of transverse displacement as a rigid body, which should be stabilized by minimum-B (the multipole field).

If a low aspect-ratio is essential, the configuration could only be achieved in a mirror machine or a solenoid (e.g. a theta pinch). That is, the major axis must be free of obstructions (no ohmic heating, toroidal windings, etc) in order that the low aspect ratio can be attained.

Finite orbit stabilization implies a restricted plasma volume, with a radius of only a few ion Larmor radii. The implications of this for plasma confinement and reactor economics are

discussed briefly in Appendix D. At first cut, it appears that the system could produce a few times 10 MW per metre of length at attractive capital costs, and might be well suited to modularized reactor construction.

CREATING FIELD REVERSAL BY NEUTRAL INJECTION

It appears to be fundamental that, in a static field, field reversal can only be initiated by orbits encircling the axis, and this is borne out in our SUPERLAYER code runs. On the other hand, once the reversed-field configuration is achieved, further injection of ions with small orbits not encircling the axis could in principle produce diamagnetic currents maintaining the status quo. This suggests starting up such a system at low field so that all orbits encircle the axis initially, and then programming the injection to maintain the reversed-field configuration as the field slowly increases to its steady-state value. We are now attempting to simulate this approach with the SUPERLAYER code.

Initial efforts to achieve field reversal in 2XIIB with injection currents of over 300 A have not succeeded, despite favorable predictions by the code. In the code, we have found that injection symmetric to the axis does

not produce reversal, whereas injecting orbits concentric to the axis does. However, in the experiment the maximum result was $\beta \approx 0.4$ in both cases. The reason appears to be a strong recurrence at high density of the same microinstability [drift cyclotron loss cone (DCLC)] that dominates confinement in the absence of the stabilizing plasma stream needed at lower density.

Because of the difficulties thus far in trying to create reversed fields, we consider the startup problem to be the critical-path item. Learning from the Cornell Astron experience, we should therefore consider seriously the development of very rapid neutral injection in order to achieve the desired configuration before micro-instabilities characteristic of the nonreversed state can intervene.

A near-term solution to this problem might be a plasma gun. A gun capable of injecting 10^{18} particles at 10 keV in a period of few microseconds has been described by Cheng.⁹

This gun would be adequate to produce field reversal in 2XIIB from a single unit. Neutralization of gun plasmas has been extensively studied at LLL, but these techniques have not yet been applied to Cheng's gun design. Also, while the gun-produced plasma appears to be well

focused, the actual beam quality must be measured more accurately to determine whether it meets requirements.

Recently, Prono has obtained encouraging though preliminary results with a new ion source concept that should work in the energy range of 100 keV or more and that could be the basis of a pulsed neutral injector delivering a thousand or more times the current obtained from present sources (see Appendix F). Thus far, ions have not been extracted; this is the next experiment. If these tests give positive results (for example, concerning beam quality), this new source should be developed as rapidly as possible both for the purposes

discussed here and for wider usage in CTR research.

Otherwise, since the magnet design does not appear to be a critical issue, research on the reversed-field mirror configuration would likely follow as a matter of course using the mainline facilities through the MX phase.

However, the reversed-field possibility does give added impetus to the development of less costly magnet designs, as discussed in the next section. The combination of field reversal and a low-cost, simple-mirror magnet could well be that tour de force that would make a small, cheap, mirror fusion reactor feasible.

5. Field Optimization and Simple Mirrors

The direct contribution of the Yin-Yang magnet to the cost of the present DT mirror reactor reference design ranges from 15% to as high as 25%, depending on what type of support structure turns out to be necessary. A simpler design compatible with MHD stability could reduce these direct costs considerably and might allow greater flexibility in the design of other components that would further improve upon the capital cost picture. Moreover, a simpler coil system

would surely save time and money in the development phase.

We propose to utilize 2XC in experiments toward these ends. The 2XC, now proposed to be built in FY 1977, would be a further modification of the 2X facility. Only the magnet and vacuum chamber would be replaced, while all 2XIIB power supplies, neutral beams, diagnostics and controls would be reused. Thus, the cost would be quite modest (see Appendix G).

The 2XC magnet would consist of two independent coil sets as sketched in Fig. G-1. The outer "cee-shaped" magnets would be used to spoil the minimum-B field created by the inner Yin-Yang pair and therefore would permit the experimenter to create a wide variety of field shapes ranging from unstable configurations to minimum-B and gradations between. An important theoretical tool to be used in these optimization studies is the LLL three-dimensional equilibrium and MHD stability code that is now operational and giving first results at finite beta.

One of the important questions along these lines is the possibility of returning to the simple mirror stabilized by line tying. Recently,

LLL prepared a report on the current status of this problem.¹⁰ The report suggests that, unless feedback is added, a plasma at the ends in sufficient contact with the walls to provide line-tying across the whole machine cross section would necessarily present an unacceptable heat leak (except in the two-component mode). Since then, other possibilities have been considered in which line tying would occur only over a thin surface where the hot plasma ($\Delta p \approx 0$ inside) would be in contact with a shell of low-temperature plasma that would provide the necessary contact to the ends. Many questions remain, some of which may be answered in 2XIIB experiments.

6. Mirror-Torus Hybrids

Several promising mirror-torus hybrid possibilities are already being pursued, such as the Tormac at Lawrence Berkeley Laboratory (LBL) and the Elmo Bumpy Torus (EBT) at Oak Ridge National Laboratory (ORNL). While we plan to follow closely the work of other laboratories in this area with the possibility of cooperative work in the future, we have no immediate plans.

We find that a major issue is the relatively large cost of all but the simplest toroidal configuration. For this reason, a bumpy torus composed of simple mirrors, such as EBT, is especially attractive. As a complement to the EBT employing electron cyclotron heating, it may be possible to base such a configuration on neutral injection and stability of mirror-confined hot ion components

stabilized by line tying to limiters at the plasma surface, as discussed above. If so, the first step would be an experiment with a single, simple-mirror cell. Alternatively, 2XC could provide the data. Then, if a single cell could be stabilized, one could proceed directly to construct such an Ion Bumpy Torus (IBT) based on neutral injection. Again, by sharing mainline mirror program facilities, costs to develop this new configuration need not be prohibitive.

In reaching our conclusions on mirror torus hybrids, we have examined several different geometries. Following the work of Chris Watson at Culham,¹¹ we have re-examined a toroidal configuration of linked, minimum-B mirrors. A rough parameter analysis is given in Appendix H. Knowing the relatively high cost of Yin-Yang magnets, we first looked into simpler shapes, but in the end we agreed with Watson that back-to-back Yin-Yang magnets provide the best means of leading the diverging flux from one mirror cell into the next. However, the cost is high because of the high field and high ellipticity of the connecting toroidal

sections. Consequently, capital costs for such a reactor appear to be high, though within a reasonable range for future power needs. Intermediate experiments would be expensive. To be meaningful, a minimum experiment would probably be the equivalent of a dozen Baseball II machines.

We have also examined the possibility of a two-component mirror system in which a "simple" toroidal return would contain a dense Maxwellian component threading through a single, minimum-B mirror cell. Again, matching the diverging flux bundles to the toroidal loop proved to require an extra pair of Yin-Yang windings, and this single-cell case also requires very high values of n_T in the toroidal section (see Appendix H).

Besides the above concepts in which the toroidal nature is dominant, McNamara and Hall have suggested that a small toroidal loop be used to recirculate electrons at a density 10% or so of the hot plasma density.¹² The motive is to produce a small improvement in Q (see Section 3). Cornell has proposed carrying out such an experiment (MIRICLE).

7. Long Linear Machines

Primarily motivated by the two-component mirror concept, we have examined several magnetic configurations that might serve as a fusion engineering research facility (FERF) in a relatively small size and project to reactors in large sizes. In the two-component mirror, a dense, tritium, Maxwellian plasma flows freely along the axis of a mirror system that confines hot deuterons supplied by neutral injection.

This class of ideas poses fewer stability issues than any of the foregoing concepts. Concerning microinstability in particular, the 2XIIIB experiments are very encouraging on this point, and experiments more specifically applicable to the two-component regime are planned for the future.

A major problem is a requirement for high beam power to do convincing experiments. A full two-component experiment in 2XIIIB is expected to yield an $n\tau$ about 10 times less than that already achieved. Following the

simple two-component approach, a breakeven experiment would require a gigawatt or more of beam power (but only for a few milliseconds).¹³ Another problem is the field design to maintain MHD stability in the mirrors at the end of a long, thin column; however, line tying might serve.

Again, we are watching developments in this area with interest, but have no immediate plans beyond what can be done in existing experiments. For now, we are maintaining much the same position with respect to multiple mirrors; some members of the LLL staff are studying reactor applications of multiple mirrors, and we cooperate with the U.C. Berkeley group in this area.¹⁴ We are also following with interest the work of Dawson and others on end plugs that could reduce the length of long solenoid reactors (with mirrors only to confine the ion beams injected for heating).

8. Summary

The main-line mirror program at LLL defines an approach to fusion power that we feel possesses many advantages. In this report, we

have discussed some present thinking on ways to more fully exploit these basic advantages through modifications motivated by physics or economic

considerations. The approaches discussed range from simple optimization of the magnet coils to speculations on the possibility of producing mirror-confined, reversed-field, plasma configurations. That we can contemplate such a wide range of possibilities

is a consequence of the inherent flexibility of the mirror approach. We feel that this flexibility, this availability of options for improvement, is a most important asset in achieving the goal of a viable fusion reactor at the earliest possible date.

Appendix A: Comparison of Experimental and Theoretical Limits on Beta

M. E. Rensink

Theoretical estimates of the beta limit in 2XIIIB have been based on the MHD (zero-gyroradius) stability condition for the mirror instability, where

$$G(\epsilon) = e^{-\epsilon} \left[I_0(\epsilon) - I_1(\epsilon) \right],$$

and

$$\epsilon = \frac{1}{2} (k_{\perp} a_i)^2$$

$$I_0, I_1 = \text{Bessel functions.}$$

$$B + \frac{dp_{\perp}}{dB} > 0,$$

and on the long, thin plasma equilibrium model,

$$P_{\perp} + \frac{1}{2} B^2 = \frac{1}{2} B_{\text{vac}}^2.$$

For highly anisotropic velocity distributions as deduced from experimental measurements of the axial density profile or from Fokker-Planck calculations, this theoretical model predicts

$\beta_{\text{max}} = 0.20$, whereas experimental observations yield $\beta_{\text{max}} = 0.40$.

This discrepancy may be partially explained by the fact that the theoretical model does not include the effects of finite gyroradius and field-line curvature.

The modification of the mirror instability beta limit by finite gyroradius effects has been treated by Furth.¹⁵ For an infinite, homogeneous plasma with ion distribution characterized by two unequal temperatures ($T_{\perp} \gg T_{\parallel}$) the beta limit is given by

$$\beta_{\text{max}} = \frac{1}{G(\epsilon)} \left(\frac{T_{\perp}}{T_{\parallel}} \right),$$

Here $k_{\perp}$ is the perpendicular wave-number of the instability and a_i is the ion gyroradius. In the zero-gyroradius limit, we have

$G(\epsilon) \xrightarrow{\epsilon \rightarrow 0} 1$, and the maximum stable beta is

$$\beta_{\text{max}} \approx \frac{T_{\perp}}{T_{\parallel}}.$$

In a finite-gyroradius plasma of finite radial extent, one has

$$k_{\perp} a_i \geq a_i / R_p,$$

where R_p is the plasma radius; therefore, in 2XIIIB where $a_i / R_p \sim \frac{1}{2}$, we may have $\epsilon \sim 1/8$, and the beta limit becomes

$$\beta_{\text{max}} \approx 1.25 \left(\frac{T_{\perp}}{T_{\parallel}} \right),$$

a 25% increase due to finite gyroradius. In a more extreme situation where $k_{\perp} a_i \sim 1$, the maximum beta is increased by almost a factor of 2 over the zero-gyroradius result. The

precise form of the ion velocity distribution is an important factor in these beta estimates. For example, the two-temperature Maxwellian analyzed by Furth gives $\beta_{\max} \approx T_{\perp\perp}/T_{\parallel}$ whereas a normal-mode loss-cone distribution¹⁶ gives $\beta_{\max} \approx 2 T_{\perp\perp}/T_{\parallel}$. The finite-gyroradius corrections need to be calculated for more realistic ion distribution functions.

A modification of the mirror instability beta limit by field-line curvature effects has been given by Rose.¹⁷ For an infinitely long homogeneous plasma of finite radius R_p with ion distribution characterized by two unequal temperatures ($T_{\perp} \gg T_{\parallel}$), the beta limit is

$$\beta_{\max} = \left[1 + \frac{\lambda K_0(\lambda)}{2 K_1(\lambda)} \right] \frac{T_{\perp\perp}}{T_{\parallel}},$$

where

$$\lambda = k_{\parallel} R_p$$

K_0, K_1 = Bessel functions.

Here $k_{\parallel}$ is the parallel wavenumber of the instability. In the long,

thin plasma limit $k_{\parallel} R_p \ll 1$, this reduces to the simple criterion

$$\beta_{\max} \approx \frac{T_{\perp\perp}}{T_{\parallel}}$$

In a plasma of finite axial extent (hence, finite parallel wavelength), one has

$$k_{\parallel} R_p \geq R_p/L_p,$$

where L_p is the axial scale length, so that in 2XIIIB where $R_p/L_p \sim \frac{1}{2}$, the beta limit would become

$$\beta_{\max} \approx 1.14 \frac{T_{\perp\perp}}{T_{\parallel}}$$

In the case of a spherical plasma where $R_p/L_p \sim 1$, the value of $\beta_{\max}$ would be increased by about 35% relative to the long, thin plasma result. The curvature for the equilibrium field lines has not been included in this analysis, but it is likely that this will produce an additional stabilizing effect on the mirror instability.

Appendix B: Q-Enhancement by Programmed Neutral Injection

R. F. Post

INTRODUCTION

Suppose that programmed neutral injection can be used to create a sequence of high- β equilibrium states in a mirror system where the distance between the mirroring points for the previously trapped particles increases with time. This action corresponds to reflection from receding mirrors, resulting in a loss of parallel energy from each particle upon reflection, i.e. cooling of $W_{||}$ by longitudinal expansion. During the time this process can be maintained, the rate of loss of particles through the mirrors will be reduced as a result of slowing of the rate of diffusion into the loss cone (which is caused by increasing $W_{||}$). Simultaneously, the reacting volume will increase as more and more particles are injected and thereby dig a longer and longer mirroring region by virtue of their localized $p_{\perp}$.

We wish to estimate the order of magnitude of the quantities involved to see if a significant reduction in end losses (hence a lengthening of mean residence time of the ions) could be expected. If so, one could expect an enhancement

of the Q value of the system through increasing the probability of reaction of the average ion before its loss. Two circumstances help here:

- Collisional diffusion involves three spatial coordinates, whereas particle losses are most directly to be associated with an increase in only one of the three ($W_{||}$).
- The large γ -factor associated with one-dimensional expansion preferentially removes $W_{||}$, as compared to a two- or three-dimensional expansion process.

ESTIMATE OF REQUIRED EXPANSION TIME SCALE

We shall assume that a significant effect will be observed if the rate of decrease of $W_{||}$ by longitudinal expansion equals or exceeds the mean rate of population of $W_{||}$ through collisional diffusion, taking into account that diffusion into the $W_{||}$ component is generally required for loss to occur. This condition can therefore be written approximately as

$$|\Delta W_{||}| \cdot v_R \geq \left| \frac{dW_{||}}{dt} \right| \approx \frac{1}{3} \left(\frac{W}{\tau_E} \right) \quad (B1)$$

Here v_R is the rate of reflection of particles from the outwardly moving mirrors, each reflection resulting in a reduction in $W_{||}$ of magnitude $\Delta W_{||}$; and τ_E is the usual ion-ion collisional relaxation rate for diffusion in energy (a la Spitzer).

From an elementary calculation, we find that

$$\Delta W_{||} = 2 M v_{||} v_m, \quad (B2)$$

where v_m is the velocity of recession of the mirroring points. Also

$$v_R = \frac{v_{||}}{L(t)}, \quad (B3)$$

where $L(t)$ is the (time-varying) distance between the mirroring points.

As usual we can write

$$n\tau_E = K W^{3/2}; \quad (B4)$$

$$\text{i.e.,} \quad 3\tau_E = 3 K W^{3/2}/n. \quad (B5)$$

Inserting Eqs. (B2), (B3) and (B5) into Eq. (B1), we obtain

$$\frac{2 M v_{||}^2 v_m}{L(t)} \geq \frac{W \cdot n}{3 K W^{3/2}}; \quad (B6)$$

i.e.

$$\frac{4 W_{||} \cdot v_m}{L(t)} \geq \frac{n \cdot W}{3 K W^{3/2}}.$$

Note that the condition becomes easier to satisfy for these particles that have gained $W_{||}$, thus leading to

a tendency to clamp their parallel energy.

If we write $\dot{L} = 2 v_m$,

$$\text{then} \quad \frac{\dot{L}}{L} \geq \frac{1}{6} \left(\frac{n}{K W^{3/2}} \right) \left(\frac{W}{W_{||}} \right), \quad (B7)$$

$$\text{or} \quad \frac{\dot{L}}{L} \geq \frac{1}{6} \frac{1}{\tau_E} \left(\frac{W}{W_{||}} \right). \quad (B8)$$

Integrating the equality

$$\frac{L}{L_0} = e^{ct} \approx 1 + ct + \dots; \quad (B9)$$

$$c = \frac{1}{6\tau_E} \left(\frac{W}{W_{||}} \right),$$

from this it follows that the required condition is, approximately,

$$\frac{L}{L_0} \approx 1 + \frac{1}{6} \left(\frac{t}{\tau_E} \right) \left(\frac{W}{W_{||}} \right). \quad (B10)$$

In other words, if the length between the mirror points doubles on a time scale shorter than a few times τ_E , a major influence on collisional end losses should be observed. Alternatively, one might hope to compete with a loss rate that is enhanced over classical rates by employing axial expansion rates that occur on about the classical loss-time scale.

The above calculations simply indicate that a significant influence on end-loss rates could be hoped for with programmed neutral injection (or some similarly acting process) that causes the mirroring points to recede

from each other on a time scale that might be as long as a few times the classical energy exchange rate. To find the Q enhancement actually achievable would require a transient Fokker-Planck code run. One might guess that an overall factor of 2 gain (integrated reaction yield divided by integrated beam energy input) is possible.

The process of axial expansion proposed involves exchanges of energy

with the confining field. To the extent that these exchanges are reversible, at the end of the process, when the reflection points will presumably collapse back toward the midplane, energy will be transferred to parallel particle motion and to the magnetic field. Presumably, these phenomena can be utilized to advantage in the direct conversion processes associated with the reactor operation.

Appendix C: Analysis of the Kurchatov Reversed-Field Experiment

C. W. Hartman

Kurtmullaev and his co-workers are studying a long-lived toroidal Z-pinch formed by the relaxation of a reversed-field θ -pinch⁸ (see Fig. C-1). In addition to the usual θ -pinch, a pulsed, octupolar "barrier" field is applied to prevent plasma contact with the walls during programmed field reversal. The barrier field may also affect the stability of the toroidal Z-pinch. has been determined experimentally : no toroidal flux is trapped in the pinch.

The toroidal pinch has the following parameters: $R \approx r_p \approx 3$ cm, axial length $Z_p \approx 2r_p$, $B \leq 0.45$ T, $T_e \leq 500 - 1000$ eV, $T_i \leq 100 - 200$ eV, and $n \leq 10^{15}$ cm⁻³. It is long lived only if the current layer is sufficiently diffuse and its diameter is sufficiently large, and then it lasts up to $\tau \leq 50$ μ s. Since this lifetime corresponds to several hundred transits of sound across r_p , MHD stability is apparently achieved. Also, since the lifetime corresponds to 10 or possibly more Bohm times, micro-instability is apparently weak.

Although Newcomb's energy-principle analysis of hydromagnetic

stability of a purely poloidal-field toroidal pinch does not yet preclude stability, indications are that stable states are unlikely. To explain the observed stability, other effects may be important, especially finite ion gyroradius and possibly barrier field trapped in the plasma.

To the extent that the toroidal pinch can be approximated by a straight Z-pinch, three ideal MHD instability modes are predicted:¹⁸ sausage instability, kinking of the whole column, and internal kinking. The necessity of achieving a diffuse current layer to obtain long life suggests reduction of the sausage mode growth rate as predicted by the theory, where stability occurs if $-d(\ln p)/d(\ln r) < 4\gamma/(2+\beta\gamma)$, $\beta = p/(B^2/2\mu_0)$. Near the boundary, where the stability condition is violated, finite-Larmor-radius (FLR) or line-tying effects may give stability. The absence of kinking of the whole column is perhaps credibly explained by the diffuse nature of the pinch, by nearby walls, and/or by the small aspect ratio R/r_p . This leaves internal kinking modes ($m = 1$)

with radial localization as the remaining MHD instability. As shown in Ref. 18, internal kink modes are present in the central region where $\beta \geq 1$, and they are not stabilized by a diffuse pressure profile. This persistent instability also appears in tokamaks if $q < 1$ in the interior.

A rough estimate of ion Larmor radius for the experiment can be obtained by noting that if I is the pinch current and $S = r_p/a_i$, then

$$I(A) = 1000 S T_i^{1/2} \text{ (eV)};$$

and from the Bennett relation,

$$I^2(A) = 10^{-9} n(\text{cm}^{-3}) r_p^2(\text{cm}) (T_i + T_e) \text{ (eV)},$$

so that S is given by,

$$S^2 = \frac{n r_p^2}{10^{15}} \frac{T_e + T_i}{T_i}.$$

Taking $r_p \approx 3 \text{ cm}$, $n \approx 5 \times 10^{14}$, and $T_e/T_i \approx 5$, gives $S \approx 4$ for hydrogen.

To estimate the importance of FLR effects on stability, allowance must be made for the noncircular cross-section (see Fig. C-1) and for the

fact that the internal $\beta > 1$ region has dimensions smaller than r_p . Roughly speaking, however, an equivalent S is probably in the range 1 to 10. Since the internal kink modes are localized radially, $k_{\perp} \geq k_r$ and values of $k_{\perp} a_i \approx k_r r_p S$ may be of order unity; thus leading to FLR stabilization.

No adequate stability theory is available for Z-pinches or for the small aspect ratio toroidal pinch of the experiment for which β and the ion gyroradius are both large and where strongly unstable fluid modes are present. For weakly unstable systems with low β , FLR stabilization occurs roughly when $\omega^* \approx \gamma$, where ω^* is the diamagnetic drift frequency, and γ is the fluid growth rate. The $m = 1$ kink instability has $\gamma \approx k_z V_{\text{Alfven}}$, and since $\omega^* \approx k_z V_{\text{sound}}$, a_i/r_p stability of kink modes is by analogy suggested when $a_i/r_p \geq V_A/V_S \approx 1/\sqrt{\beta}$. This possibility has been noted earlier¹⁹ in connection with the absence of kinking in the plasma focus.

PLASMA CONFINEMENT IN A PULSED SYSTEM WITH A COMPACT TOROIDAL CONFIGURATION

A.G. Saikov, G.A. Solovtsov, A.G. Kalyutin, B.Kh. Kurtsmullayev,
Ya.V. Lashin, A.I. Malyutin, A.I. Markin, A.P. Proshchikov,
V.L. Senenov

Kurchatov Institute of Atomic Energy, Moscow, USSR

Some hopeful results of shock heating and stable confinement by a purely poloidal field were obtained with times being substantially longer than rise times of characteristic MHD-instabilities [1]. Further development of these experiments is presented in this work.

The experiments were carried out with a Q-pinch device ($B = 4,5$ kG, $D = 1$ cm) with a reversed bias field $B_{\theta} = 0,5-2$ kG. It is well-known, that plasma expansion to walls at the initial stage of discharge results in a number of unwanted effects [2]. Pulsed plasma pressure out from the wall by means of a barrier field during this stage seems to be the most dramatic way to remove this disadvantage. Such barrier field is provided by longitudinal bars placed on the surface of the cylindrical plasma volume (Fig. 1). In the same figure an example will be shown, designed for fluxes B_z and B_{θ} reconnection controlling and longitudinal plasma contraction programming (similar to [3]).

The same aim can be reached by use of a quasi-stationary (here called) barrier field on the first half-cycle of the main discharge. Plasma compression and heating take place at parallel fields B_z and B_{θ} occur at the beginning of the second half-cycle, at the expansion stage, but plasma is effectively retained near the wall by a stationary barrier field. A crowbar on the second half-cycle provides the confinement of the toroidal plasma obtained.

In all cases studied it is possible to distinguish two main stages of the process as follows: formation, heating and onset of a toroidal equilibrium structure, and II-confinement, accompanied by longitudinal and radial plasma pulsations due to resistive pulsations in an external shock field (Fig. 2a, b). Note that resistive pulsations, associated with the use of probes at relatively long confinement times are likely to be reduced by the use of a probe with $(\delta \sim 1 \text{ cm})$ and permanent plasma motions, which are typical of a low-current pinch. At operating density $n_0 = (1-3) \cdot 10^{14} \text{ cm}^{-3}$ and $B_z = 4,5$ kG, a typical axial peak pressure of $nB(2\pi r) \sim 10^{17} \text{ erg/cm}^2$ is obtained. A closed magnetic structure is formed at the first stage ($\sim 5 \text{ nsec}$). The time to generate B_z (atomic magnetic) is shown in Fig. 3. A later analysis shows the electron temperature T_e (X-ray measurements), which at its maximum (at $\sim 5 \text{ nsec}$) amounts to $0,5 \text{ keV}$. In further pictures taken on a TV electronic image converter, in a relatively wide range of conditions the formation of an azimuthally symmetric plasma cylinder with an annular current sheath of regular form was observed (Fig. 4, a).

In the presence of a barrier field framing photographs show without plasma column compression on the first half-cycle ($0,5 \text{ nsec}$) and a successive radially-diverged plasma retardation by the barrier field (Fig. 4, b). When the external field passes zero, the probes on the axis show a relatively large trapped field (Fig. 2, b).

The second stage is rather sensitive to initial conditions, plasma configuration and size; this greatly affects the life-time of the closed magnetic structure.

Intensive radial compression of plasma (as a rule at $B_z > B_{\theta}$ or at relatively high density $n_0 > (0,5-1) \cdot 10^{15} \text{ cm}^{-3}$) affects adversely, leading to rapid disappearance of an antiparallel field geometry ($\sim 10 \text{ nsec}$).

The confinement time of the closed magnetic structure (up to $\sim 10 \text{ nsec}$) is observed when plasma column diameter is relatively large ($D_p/D = 0,5-0,8$) and current sheath is greatly diffused being

of the order of plasma radius. In conventional experimental scheme those requirements led to the necessity of shifting the crowbar to the point, lying substantially below the maximum of the pulsed magnetic field B_z . This resulted in a plasma pressure decrease by an order of magnitude. Use of a passive (stationary) barrier field didn't allow to avoid this difficulty, since the crowbar on the second half-cycle reduced, to large extent, a confining field. A pulsed barrier field ($B_{\theta} \sim 6 \text{ kG}$, $T \approx 3 \text{ nsec}$) to solve the problem of stable confinement simultaneously providing substantial increase of energy content in a plasma.

Measurements of the azimuthal component B_{θ} indicated at the absence of a force-free configuration, so that in current sheath $j \neq l$.

It should be noted, that the closed magnetic structure life-time observed is rather hopeful for a "Q-pinch with liner" application in a quasi-spherical case [4] where required time is $\sim 10^{-6} \text{ sec}$.

The authors express their gratitude to K.F. Velikhov for fruitful discussions."

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Fig. 1. Schematic diagram of installation

Fig. 2. Magnetic probe signals: a) antiparallel fields B_z and B_{θ} , $n_0 = 3 \cdot 10^{14} \text{ cm}^{-3}$. 1 - probe is on the axis outside the toroid, 2.50 cm; 2 - probe is on the axis inside the toroid, 2.50 cm; b) crowbar is on the 2nd half-cycle, 1.2 - magnetic field inside the toroid, 2.50 cm on the axis with stationary barrier field.

Fig. 3. Time variation of ion temperature, $n_0 \sim 2 \cdot 10^{14} \text{ cm}^{-3}$

Fig. 4. a) End view of discharge, interval between frames $t = 0,3 \text{ nsec}$. Antiparallel fields B_z and $B_{\theta} = 1 \text{ kG}$. b) Radial plasma and current sheath position, obtained from a picture ren. Crowbar is on the 2nd half-cycle, $B_{\theta} = 1 \text{ kG}$, with stationary barrier field.

Fig. C-1. Reproduction of Ref. 8.

Appendix D: Reactor Potential of Reversed-Field Mirror Configuration

W. C. Condit and T. K. Fowler

In Section 4 of the main text, it was suggested that a reversed-field configuration in a mirror machine might be stabilized by finite-orbit effects, together with an aspect ratio near unity (see also Appendix C).

Assuming this as a working hypothesis, we have considered briefly what a reactor might look like.

The concept is sketched in Figs. D-1 and D-2. In the absence of a quantitative theory, let us assume a/ρ_i to be a small integer (10 or less) and $R_p/a = 1$ to 2, where ρ_i is the ion Larmor radius, and R_p and a are the major and minor radii of a (short) cylindrical plasma "doughnut". The plasma density will be nonuniform, represented by a parameter $f = n^2/n_0^2$. The fusion power per unit length would be

$$\frac{P}{L} = \frac{f}{4} n^2 \cdot \overline{\sigma v} \cdot E_{\text{nuc}} \cdot \pi \cdot [(R_p + a)^2 - (R_p - a)^2]. \quad (D1)$$

Substituting $E_{\text{nuc}} = 17.6$ MeV, $2n T_1 = \beta B^2/8\pi$, and writing lengths in units of the deuteron ρ_i , with a

$$\text{constant } K = \frac{M_D}{2} \cdot E_{\text{nuc}} / 128 \pi q^2 = 57.2 \times 10^{16} \text{ keV/cm:}$$

$$\frac{P}{L} = K \cdot f \cdot \beta^2 B^2 \left(\frac{a}{\rho_i}\right)^2 \frac{R_p}{a} \frac{\overline{\sigma v}}{T_1}. \quad (D2)$$

For a Maxwellian distribution, $\overline{\sigma v}/T_1$ for DT reactions is constant at $2.2^* 10^{-17} \text{ cm}^3$ per keV's for T_1 between 15 keV and 35 keV to within 10%. Then, in this range and taking $a/\rho_i = 10$, $R_p/a = 2$, $\beta = 1$, and λ and $f = 8/15$ for a parabolic profile, we obtain

$$8.3 \frac{\text{MW}}{\text{m}} < \frac{P}{L} < 33 \text{ MW/m} \quad (D3)$$

$$\text{for } 2.5 \text{ T} < B < 5.0 \text{ T.}$$

While it has disadvantages, the lower field is to be preferred for beam injection reasons: assuming the beams will be aimed tangent to the radius at the field null (R_p), the thickness of the plasma traversed by the beam is $2\sqrt{5}a$ for $R_p = 2a$. We shall choose the product of thickness and density to lie between $1.5^* 10^{16}/\text{cm}^2$ (the FERF value from Ref. 20 for 60-keV injection) and $2^* 10^{16}$ (for 200-keV injection, per Ref. 13). At 2.5 T,

we get the following parameters for

$$T_e = T_i = 30 \text{ keV}, \beta = 1:$$

$$\begin{aligned} T_e &= 30 \text{ keV} \\ B_0 &= 2.5 \text{ T} \\ n_{e0} &= 2.6 \cdot 10^{14} / \text{cm}^3 \\ \rho_D &= 1.41 \text{ cm} \\ a &= 14.1 \text{ cm} \\ R_p &= 28.3 \text{ cm} \\ 2\sqrt{5} n_e a &= 1.65 \cdot 10^{16} / \text{cm}^2 \end{aligned} \quad (D4)$$

This value of $2\sqrt{5} n_e a$ is convenient for beam penetration. Stronger fields and lower temperatures would make beam penetration more difficult. Higher temperatures, coupled with moderate increases in B_0 (say B_0 proportional to $\sqrt{T_i}$) would leave the density and the dimensions unchanged, yet increase the power per unit length proportionally to $\sqrt{v}$ from Eq. (D2). As will be shown below, this will require higher wall loadings. However, the higher temperature reduces technological problems (mainly vacuum problems) related to charge exchange, so the actual parameters selected for a reactor would be a compromise between wall loading and other considerations. Finally, the diffuse plasma profile, mentioned in Ref. 8, will permit additional field (and density) increases, and ostensibly will make the vacuum problems easier.

The wall radius must be placed two alpha gyroradii beyond the

plasma boundary at $R_p + a$ — this gives a wall radius of 64 cm. At a fusion power of 8.3 MW/m, the wall would have a neutron flux of 1.7 MW/m^2 for the 2.5 T case, a convenient level at which to operate.

We imagine a reactor as consisting of a number of independent modules. An example set of machine parameters for a single module, based on Eq. (D4), is given in Table D-1. Note there, and in Fig. D-1, that we have incorporated a multipole field provided by Ioffe bars. In the table, the Ioffe bar current corresponds to the conservative assumption that the Ioffe field is a quadrupole with a field strength equal to the main field at a radius of $R_p + a$. It remains to be seen whether such a field is actually needed in the steady state, and, if so, how strong it must be.

An alternate set of parameters, with higher temperature and somewhat higher wall loading, is given in Table D-2. Note that these parameters yield a higher power output. These were arrived at by scaling up the magnetic field and temperature (as described after Eq. (D4) above) and taking advantage of the small but noticeable increase in beam penetration for higher-energy injection. We have omitted the Ioffe bars from

this parameters set, because, again, we are not convinced that they are essential.

Whether such modules could form the basis of an economical reactor is now under study. A preliminary estimate indicates that the economics will be favorable if no Ioffe bars are needed, but marginal for the Ioffe currents shown in Table D-1. The system might consist of one or more linear chains of independent mirror cells linked end to end. To maintain a neutron flux of a few MW/m^2 , the first wall radius would be 0.5 to 1 m. Thus, one might imagine a single

cell about the physical size of MX ($L = 3.6$ m), but with circular coils. It is obvious that the combination of simple coils and enhanced plasma confinement should have a favorable impact on reactor economics.

The picture of a small, medium-field reactor cell lends itself to modularized construction. Moreover, since each relatively small cell is self-contained as far as its plasma confinement properties are concerned, development costs should be greatly reduced. However, again we stress the speculative nature of the entire concept at this time.

Fig. D-1. Reversed-field mirror reactor: side view.

Fig. D-2. Reversed-field mirror reactor: end view.

Table D-1. Machine parameters for reference case
reversed-field mirror reactor

$$B_0 = 2.5 \text{ T}$$

$$I_{\text{deuteron}} = 5.32 \text{ A}^c$$

$$n_{e0} = 2.6 * 10^{14} \text{ e}^-/\text{cm}^3$$

$$I_{\text{Triton}} = 2.00 \text{ A}^c$$

$$R_p = 28.32 \text{ cm}$$

$$I(\text{Ioffe}) = 5 \text{ (copper) MA}^d$$

$$a = 14 \text{ cm}$$

$$I(\text{Ioffe}) = 45 \text{ (superconductor) MA}^e$$

$$T_e = 30 \text{ keV}$$

$$\text{Wall } R_w = 64 \text{ cm}$$

$$\ln \Lambda = 19$$

$$\text{Main coil length} = 600 \text{ cm}$$

$$\tau_D^{\text{(scattering)}} = 0.0213 \text{ s}$$

$$\text{Ioffe bar length} = 460 \text{ cm}$$

$$\tau_{\text{classical}} = 0.88 \text{ s}^a$$

$$\text{Cell power} = 9.3 \text{ MWT}$$

$$L_{\text{eff}} = 84 \text{ cm}^b$$

$$\text{Neutron load} = 1.7 \text{ MW/M}^2$$

$$n\tau = 2.3 * 10^{14} \text{ s/cm}^3$$

$$^a \tau_{\text{classical}} = \tau_{DD} * a^2 / 2.4 \rho_D^2$$

$$^b L = 3R_p$$

$$^c \text{ Split per Ref. 20 } (I_T = 0.034 I_D)$$

$$^d \text{ Centered at 85-cm radius}$$

$$^e \text{ Centered at 250-cm radius}$$

Table D-2. Machine parameters for improved-case,
reversed-field mirror reactor

$B_0 = 4.5 \text{ T}$	$L_{\text{eff}} = 174 \text{ cm}^b$
$n_{e0} = 2.6 * 10^{14} \text{ e}^-/\text{cm}^3$	$n\tau = 1.3 * 10^{15} \text{ s/cm}^3$
$R_p = 34.8 \text{ cm}$	$I_{\text{deuteron}} = 2.79 \text{ A}^c$
$a = 17.4 \text{ cm}$	$I_{\text{Triton}} = 1.04 \text{ A}^c$
$T_e = 100 \text{ keV}$	Wall $R_w = 64 \text{ cm}$
$\ln\Lambda = 20$	Cell power = 33 MWT
$\tau_{\text{DD}}^{(\text{scattering})} = 0.124 \text{ s}$	Neutron load = 3.0 MW/m^2
$\tau_{\text{classical}} = 5.18 \text{ s}^a$	Triton radius = 1.74 cm

$$^a \tau_{\text{classical}} = \tau_{\text{DD}} * a^2 / 2.4 \rho_D^2$$

$$^b L = 5R_p$$

$$^c \text{Split per Ref. 20 } (I_T = 0.3745 I_D)$$

Appendix E: Conditions to Achieve Field Reversal by Neutral Injection

J. A. Byers

Our best working tool for analyzing the reversed-field mirror configuration is the SUPERLAYER code developed for the Astron program. Revised to simulate neutral injection, it is now being used to study buildup to field reversal in a mirror machine and to determine properties of the steady state. The code now includes electron drag and charge exchange on the neutral beam, but as yet no angular scattering. The main function of the code is to calculate the self-field generated by the ions and the ion orbits in this field as a function of time. In the past, the code predicted reasonably well both the failure to achieve field reversal by multiple injection of electrons in the LLL Astron experiment and the success achieved at Cornell by injecting a single, high-current pulse.

For the present purposes, the main defect of the code is the assumption of axisymmetry (no quadrupole component). We believe this to be of limited importance in determining the equilibrium configuration in the interior region where the closed-field pattern forms. However, imposing symmetry suppresses possible modes of instability that must then be examined

either analytically or numerically with other, more complex codes (see below). Also, as of this writing all runs have concentrated on the present 2XIIIB parameters ($a/\rho_1 \approx 2$), but modifications to treat a/ρ_1 up to 10 are in progress.

The code is limited in scope, allowing no electron currents or space-charge effects. Within these limitations, the code should be able to examine the r, z equilibrium, including all effects of the mirror-tearing mode and also the effects of another related electromagnetic mode with $k_\perp = 0$,²¹ and including the full generality of five-phase space dimensions. One rather severe approximation is made: the relevant time scales, τ , such as the drag time or filling time, are shortened considerably, typically by factors of order of 100. The product $\tau\Gamma$ is kept consistent with the experiment, and an attempt is made to keep τ long compared to an axial bounce period.

The initial work indicated that field reversal was easily obtainable and persisted in steady state after initial transients if the beams were arranged to form a coherent ring current. This injection prescription

is actually unrealistic, and this past year we have concentrated on simulating 2X with realistic injection. Currently, the code predicts that reversal is possible in the 2XIIB experiment provided the beams are focused off axis; high β ,

$$\beta = \frac{8\pi p}{B_{\text{vac}}^2} > 1,$$

is obtainable regardless of the focusing. This condition, however, is accompanied by a slow but steady axial loss of particles (this did not occur with ring-like injection). This loss is persistent but it is not yet known if it is caused by the physics (nonadiabatic containment?) or by numerical effects. Even if real, the loss rate is sufficiently slow that it may not prevent buildup in a system with realistic time constants. That is, the loss rate is of the same order as the actual real time loss rate of hot particles due to electron drag ($T_e \approx 100$ eV).

For 2X-like parameters, we have obtained a strong reversal

$$\left(\xi = \frac{\Delta B}{B_{\text{vac}}} \approx 2 \right)$$

steady state for $I \approx 600$ A. This case used uniform injection over a length, L_{inj} , of 20 cm centered at the midplane, and over a radius $r_0 = 5$ cm, a drag coefficient appropriate to $T_e = 100$ eV, and

included charge exchange on the beam. Allowing higher T_e will lead to higher ξ and β for the same current or to marginal ξ for lower currents.

A typical result is shown in Fig. E-1. The mirror ratio R_{vac} over the occupied region is only 1.05; that is, the self-field alone confines the axial pressure.

Shown in Fig. E-1 are typical field lines in an r - z cross section indicating a central core of closed field lines. The figure shows that the high-density region, defined as the region enclosed by the contour of half-peak density, is contained nearly entirely within the closed lines. This still leaves a sizable fraction of the total number of particles - perhaps half - outside the closed-line region, since for equal densities the amount of net mass is greater at a layer radius in the open-line region. The plasma has expanded radially to a radius $r = a$, somewhat beyond the injection radius r_0 . Much of this contact with the open region is due to the large orbits,

$$\frac{\rho_i}{r_0} \sim 1$$

in this example. Smaller orbit systems may improve on this.

The plasma has also pinched in axially to a mean length (full-width half-maximum) of:

$$\text{FWHM} \approx \frac{L_{\text{inj}}}{4} \approx r_0.$$

This is a typical result. Longer axial systems can occur if the injection region is extended. In one example, a steady state occurred for a FWHM $\approx 8r_0$. Longer systems are subject to breakup due to tearing modes. In essence, the system adjusts itself to a finite-length equilibrium with conditions necessary for prevention of any instability of the mirror-tearing mode type and of other related modes. The questions remaining are the modes lacking azimuthal symmetry ($e^{im\theta}$, $m \neq 0$).

In progress are the following:

- Inclusion of classical Coulomb scattering.
- Inclusion of rf-induced velocity-space diffusion.
- Control of equilibrium state via choice of injection length and vacuum magnetic field shape.

- Examination of small ρ_i/a systems. Some reversed-field results have been obtained for $\rho_i/a = 1/4$. In principle, there appears no obstacle to reversal for yet smaller ρ_i/a .

- Examination of instability mode involving θ perturbations. We are actively developing three-dimensional particle codes that will start from a given steady state and examine the stability to $e^{im\theta}$ modes, specifically the sausage and kink modes, considered to be the greatest danger, as discussed in Appendix C. These codes will enable us to examine stability without any restrictions on ρ_i/a .

We have experience with similar three-dimensional linear codes for the relativistic negative mass instability in Astron.

Fig. E-1. Field lines and half-peak density contour (dashed closed line) for a field-reversal example in an r - z cross section. The density of field lines does not indicate field strength due to the geometry. The closed field lines are shown as dotted curves.

Appendix F: Intense Ion Beams*

J. W. Shearer and D. S. Prono

INTRODUCTION

Start-up plasmas for future mirror machines are likely to require several Coulombs of ions in the 100-keV energy range. In addition, the achievement of a reversed-field configuration by injection of energetic neutrals (or ions) will likely require a prompt injection of similar numbers of energetic particles. Although present ion-beam technology as developed at LLL/LBL provides sufficient beam current and energy to sustain mirror plasmas and/or a field-reversing ion ring, the ability to initiate these conditions in appropriately short time scales is beyond present technology. The research we propose is designed to explore a new and unique means of generating intense, short-duration ion beams.

The method of intense ion-beam generation has evolved along the following lines. In 1973, experiments at Cornell University²³ using pulsed electron-beam diodes demonstrated that electrons leaving the cathode and undergoing reflex-like trajectories through a transparent anode

create an overabundance of electron charge density within the diode. If the anode becomes a source of ions, then space-charge neutrality within the diode is established by a modest ion flow from the anode. In 1974-75, experiments performed by Physics International²⁴, Sandia Laboratories²⁵, and LLL²⁶ demonstrated that if the overabundant electron charge density within the diode was not made uniform but rather peaked near the anode, then significant enhancement of ion flow intensity resulted.

It is important to understand the fundamental differences between these intense ion sources and conventional ion sources. Both the conventional ion source and the pulsed, high intensity ion source have the basic property of a potential difference between parallel planes, one plane at ground and the other plane (the ion source plasma) at high potential. This gives rise to the usual Childs-law ion current emission. The new additional feature of the high intensity ion source is that electron emission from the grounded plane is allowed. Net electron current flow in the external circuit is inhibited by causing the electrons

* Abstracted from Ref. 22.

to reflex through the ion source plane, and having these electron trajectories collapse into the ion emission plane. The spatial distribution of electrons peaks near the ion emitter and increases the gradient of the potential there, resulting in increased ion flow. That is, the electron cloud essentially neutralizes the ion charge density throughout the gap, except for a narrow sheath near the ion emission plane. The conceptual difference between the conventional ion source and the intense ion source is schematically shown in Fig. F-1.

For completeness, we need to clarify that the conventional ion sources are meant for dc operation; thus, electron emission from the ground plane is to be prevented since this leads to breakdown. In the intense ion source, the pulse duration is limited to the time scale for the plasma flow from the two emitters (one of electrons and the other of ions) to drift across the gap at a thermal speed and short out the accelerating potential.

In this new approach to ion-beam generation, the intensity and time scale of the ion beam are dependent upon the nature of the electron emission. Very intense but short duration ion beams (several kA/cm^2 for 100 ns) require the very high electron emission of a relativistic

electron beam generator. Thus far, intense ion beams have been experimentally produced only in this manner. However, the basic concept should be applicable to somewhat longer durations (microseconds) and lower currents (hundreds of A/cm^2) by appropriate modifications of the techniques for producing the ion and electron emission. This would match into a technology of fast capacitors rather than high voltage Marx-charged Blumleins, greatly increasing the practicality of the concept for CTR applications.

CORRELATION WITH OTHER PROJECTS

This work is closely related to the large neutral beam research and development effort in progress at LLL and LBL. It can be viewed as an extension of that effort into the regime of much higher current density for a short burst. The 100-keV ion energy range is still sufficiently low for efficient conversion into a neutral beam by charge exchange.

TECHNICAL PROGRESS IN FISCAL YEAR 1976

Exploratory experiments were carried out using 2 weeks of rented time on the OWL-2 relativistic electron beam machine at Physics International. Preparations for

the experiments involved prior development and fabrication at Livermore of deuterium-loaded anode foils and cathode plates, as well as the construction of mechanical hardware to attach the experiment to the OWL-2 generator, the fabrication of Faraday cups, and the calibration of silver-foil-activation neutron detectors. In addition, extensive use was made of previously calibrated voltage and current diagnostics on the OWL-2 machine.

Direct detection of ion currents was accomplished in these experiments, despite the negative polarity of the OWL-2 voltage. Faraday collectors were mounted inside the cathode, and their signals were brought out to the scopes through a specially installed transit-time isolator. The Faraday collector signals correspond to peak ion current densities in excess of 1 kA/cm^2 . In a few experiments, both the anode foil and the cathode foil were loaded with deuterium ions. In these cases, the calibrated neutron detectors recorded 10^7 to 10^8 neutrons per shot. When these data are combined with diode voltage measurements, thick-target yield calculations also correspond to average ion current densities of the order of 1 kA/cm^2 or greater. Thus, the initial exploratory experiments established the existence of large pulsed ion currents in the 100-keV energy range

and verified the concept of intense ion beam generation.

PROJECT GOALS FOR FISCAL YEAR 1977

Our goal is the design and fabrication of an intense ion beam system based on fast capacitor banks. Such a system will replace the high-voltage Marx-charged Blumleins used for experiments in FY1976 and will be more practical for CTR application. With this system, we aim to achieve a 100-keV ion beam of current density 1 kA/cm^2 and 1 ms pulse duration. The 100-keV energy limitation is dictated by the most advantageous injection scheme of neutralizing the beam before penetration into the mirror (for energies exceeding 100 keV, the neutralization efficiency falls rapidly). Our second major goal is to optimize beam emittance.

PROPOSED RESEARCH FOR FISCAL YEAR 1977

Considerable research effort must be devoted to the creation of the two emitting plasmas required by the intense ion source concept. Once this hurdle is passed, research will be directed toward extraction of ion beams and optimization of beam intensity and emittance. Paralleling this effort, we will initiate computational effort. The primary charter of computation will be to furnish

guidance in source optimization, to model the transient behaviour of the plasma emitting surfaces as they close on one another, and to address the beam emittance question.

PROJECT GOALS FOR FISCAL YEAR 1978

The project goal of this year will be the demonstration that this new concept of intense ion sources can supply the necessary Coulombs at the 100 keV required for mirror start-up and possibly field reversal.

PROPOSED RESEARCH FOR FISCAL YEAR 1978

Assuming reasonable success in previous research, we foresee that half of this year's effort will be directed toward optimizing the intense ion beam divergence. Embodied in this research will be studies on field shaping and contouring the emitting plasma surfaces. For the second half year, we will couple by way of a beam transport system a charge-exchange neutralizer and the grounded-plasma emitter of the ion source. Experiments on this total system will furnish size-scaling laws needed to establish our goal.

Fig. F-1. Conventional ion source vs intense ion source.

Appendix G: 2XC Magnet Set*

F. H. Coensgen

INTRODUCTION

Beyond demonstration in 2XIIB of basic scaling laws for plasma in open magnetic geometry is the question of optimum magnet design for either reactors or FERF's utilizing open magnetic geometry. Thus, following the 2XIIB program we propose that optimization experiments be carried out in the 2X area. To avoid unnecessary delays in acquisition of information, we plan to fabricate in FY1977 a new magnet set (2XC, Fig. G-1) and high-vacuum chamber for the first such experiment. 2XC will be installed during the first part of FY1978. Operation of 2XC will begin later in FY1978. Major elements of the 2XIIB system such as the intense neutral beams, the diagnostics, the data acquisition systems, the machine controls, and a large part of the 2XIIB vacuum system will be utilized in the 2XC experiment.

Among the magnetic field variations considered in reactor and FERF designs those most frequently discussed are use of $\int \frac{dl}{B}$ stability

rather than absolute min-B stability, multiple mirrors, and large mirror ratios ($R > 3$). Preliminary design of a magnet set which provides for a continuum of magnetic field geometries from those which are minimum-B stable through progressively weaker $\int \frac{dl}{B}$ stable fields to an unstable simple-mirror configuration. Only modest modification of the existing capacitor bank is required for operation of the $\int \frac{dl}{B}$ system near the 0.9 T central field and $R \approx 2$ of the present 2XIIB experiments.

With the proposed increased energy storage included herein, mirror ratios of 3 could be achieved in an $\int \frac{dl}{B}$ stable field. Large mirror ratios are common to all reactor designs, and investigation of the predicted advantages is of prime importance.

These advantages are the following:

- Reduced collisional loss through reduction of the loss cone angle and the effect of the ambipolar potential.
- Increased beta threshold for the "mirror instability". The reaction rate per unit volume and hence the power density increases with β .

* Abstracted from Ref. 27.

- Reduced departure of the ion velocity function from Maxwellian; thus, reduced saturation level, and hence lower loss rates for residual instabilities.

High β is predicted to increase the effective mirror ratio and hence further reduce collisional loss, bringing the ion velocity function closer to Maxwellian. Numerical Fokker-Planck computations indicate that higher betas can be sustained if the neutral beams are injected close to the loss cone rather than perpendicular to the magnetic field lines. Thus, the new magnet will provide the oblique injection of neutral beams.

Although the energy limit for adiabatic particle containment in the vacuum magnetic field seems assured, adiabaticity at high- β values is uncertain. Test of the theoretically predicted limit in the presence of dense energetic plasmas is an important goal of the 2XC experiment.

The option of simple-mirror geometry in 2XC will provide the opportunity to experimentally re-examine MHD stabilization by line tying. Use of the extensive, sophisticated, 2XIIB diagnostic capability will for the first time allow a quantitative determination of the minimum heat drain associated with line tying.

CORRELATION WITH OTHER PROJECTS

This project, as the 2XIIB project, is dependent upon the development of reliable, high-current, high-energy, neutral beams being developed in the LLL/LBL Neutral Beam Program.

Plasma target and transition to a neutral beam sustained plasma will follow the methods currently under development in 2XIIB.

PROGRESS IN THE PRIOR FISCAL YEAR (FY 1976)

Alternative magnet designs including dc magnet sets and power supplies, combined Yin-Yang and circular magnets, and high-mirror-ratio, pulsed Yin-Yang systems have been considered. At present, these designs have been rejected in favor of a pulsed Yin-Yang set combined with pulsed "cee"-shaped magnets beyond the Yin-Yang mirrors. The four-coil set provides for minimum-B or $\int \frac{dl}{B}$ stable systems and for a rather modest investment in energy storage a high (R of at least 3) mirror ratio experiment.

Analysis has shown that the theoretical threshold for the "mirror instability" is a function of mirror ratio, R. Detailed numerical analysis indicates that the β limit is a function of angle of injection as well as the mirror ratio. Experimental

confirmation of the predicted increase of β with mirror ratio and oblique injection is needed.

PROJECTED GOALS FOR THE CURRENT FISCAL YEAR (FY 1977)

The following goals are projected for FY 1977.

- Preparation for winding and vacuum impregnation will proceed concurrently with detailed engineering design during the first quarter of FY 1977. Actual magnet construction will begin about December 1976. Lay up of the glass-reinforced magnet support structure will begin in April 1977. By October 1977, the new magnet should be ready for installation.

- The 2XC magnet set may be as much as a metre longer than the 2XIIB set. This may increase the overall weight beyond the 435 crane capacity and may necessitate changes in the construction procedure. These changes (which would require considerable in-site construction) would prolong the

"down time" between 2XIIB and 2XC.

Fabrication and construction techniques will be the same as those used for 2XIIB, thus no engineering or materials test programs will be needed. The construction uncertainty is the cost and availability of petroleum based resins and glass-fiber reinforcement.

PROPOSAL FOR RESEARCH IN THE BUDGET YEAR (FY 1978)

Approximately 6 months will be required to replace 2XIIB with 2XC. Following installation, approximately 3 months will be required to re-establish vacuum conditions, neutral beam operation, and diagnostic capability. Thus, comparison of plasma containment of line-tied $\int \frac{dl}{B}$ and minimum-B stable configurations should begin in the last quarter of FY 1978 and continue through FY 1979. The capacitor bank will also be upgraded during the first half of FY 1978.

Fig. G-1. The 2XII magnet set.

Appendix H: Operating Modes and Trade-Offs for Mirror-Torus Reactors

W. C. Condit

INTRODUCTION

The combination of a toroidal return link and a mirror reactor cell (or cells) has been proposed as a possible steady-state high-beta fusion reactor.^{11,28,29} Broadly speaking, such reactors can run in one of two modes: two component or conventional. The first is usually thought of as having the tritium density much higher than the deuterium density, whereas $n_T = n_D$ for the second. It is the purpose of this appendix to show that the need to minimize the required $n\tau$ in the toroidal link drives one to choose approximately equal tritium and deuterium densities. Thus it appears that there is no two-component toroidally linked system which is optimal for a reactor: the 2-component mode merges into the conventional 1-component mode. The only feature of the two-component idea that is clearly retained is the idea of having the tritium temperature well below the deuterium temperature. The possibility of this is implicit in the toroidally-linked mirror proposal of Watson and Cordey,^{11,28} which has a peak in the particle-containment time at energies well

below the injection energy. Thus, any mirror-torus hybrid is apt to be similar to that of Watson and Cordey. We will examine a series of reactor designs leading to their design as the optimum. We will assume (arbitrarily) a central field of $B_0 = 2.0$ T, realizing that this can be scaled up.

ENERGY BALANCE FOR 2-COMPONENT SINGLE-CELL MODEL

The two-component model is taken to be one in which deuterium ions are injected with $E_0 \geq 10 T_e$ into a background tritium plasma with density $n_T \gg n_D$. They acquire an average energy, E_{av} , before being lost. The deuterium scattering losses from the mirror and energy loss to the tritons are neglected relative to D-e drag (τ_{dem}) in the first approximation. The plasma in the torus is assumed to be a pure tritium plasma — deuterons are taken as lost immediately after leaving the mirror. Tritons and electrons leave the torus at a rate n_T/τ_{TT} per unit volume. Let the tritium temperature T_T equal the electron temperature T_e . Let V_T , V_m be the toroidal and mirror plasma

volumes, and assume the tritium density is the same in the torus and the mirror. Then the condition that the power injected into the mirror be able to sustain the toroidal losses is

$$3 n_T T_e V_T \tau_{TT}^{-1} = n_D E_{av} V_m \tau_{dem}^{-1} \quad (H1)$$

We will now make an estimate of the volume ratio, and solve Eq. (H1) for $n_T \tau_{TT}$. It is hard to make a toroidal return with radius less than the distance between field maxima in the mirror, which is typically about four times the effective length of the mirror plasma.²⁰ Since the cross-sectional areas of the plasma in the torus is assumed to be down by the mirror ratio, R, from that in the mirror, the volumes are related (for a single mirror cell) by

$$V_T/V_M = 8\pi/R \quad (H2)$$

To reduce the $n\tau$ requirements as much as possible, we assume a total mirror ratio of 6, coming, for instance, from $R_{vac} = 2.68$, $\beta = 0.8$. Combining Eqs. (H1) and (H2) and solving for $n_T \tau_T$, we get a minimum reasonable toroidal ($n\tau$):

$$n_T \tau_{TT} = \left[\frac{4\pi T_e}{E_{av}} \right] \frac{n_T^2 (n_e \tau_{dem})}{n_D (n_D + n_T)} \quad (H3)$$

Thus, we see that any restriction of the form of Eq. (H2), ultimately imposed by engineering considerations, results in a minimum toroidal $n\tau$ which is a product of a density dependent factor, an energy-dependent factor given within narrow limits by Q considerations (see below), and the basic $n\tau$ for deuterons slowing down on electrons. It is obvious that one wants to drop n_T and raise n_D to ease the $n\tau$ requirements; this leads one out of the 2-component regime. As an example of the stringent requirements placed on the torus by the conditions of Eqs. (H1) and (H2), consider the case $n_D = 0.33 n_T$, $T_e = 16$ keV, $E_0 = 200$ keV, $E_{av} = 120$ keV. The toroidal component using Eq. (H3), must have an $n\tau$ of 2.7×10^{14} s/cm³. If a torus of this quality could be built, it would be better to run it as a thermal reactor with $n_D \approx n_T$: using the bare Lawson criterion at 16 keV ($n\tau \approx 2.5 \times 10^{13}$ at $Q = 1$), a thermal reactor would have $Q \geq 10$ while the 2-component reactor would only have $Q = 3$ at the same temperature with $n_T \gg n_D$. At 8 keV, the $n\tau$ requirements are somewhat reduced, as shown for the one-cell case in Table H-1. However, Q is also reduced (to about 2), and the reactor parameters are not attractive. For this reason, we examine multiple-cell designs to investigate

improvements in the torus/mirror volume ratio given by Eq. (H2).

MULTIPLE-CELL 2-COMPONENT DESIGNS

A possible two-component, six-cell mirror layout is shown in Fig. H-1. The floor-plan shape of an individual mirror cell has been found in previous studies to be the projection of a cone plus a hemisphere of radius L , where L is the distance between mirrors.^{20, 30} Since blanket and magnet-shielding requirements set a lower limit of about $L = 10$ m, the overall layout is rather large and is fixed by the individual cell shape and the number of cells. So far, I have not provided a location for the direct converters. If we assume that these can be worked in at diverters placed near the corners, we note that $V_{\text{cell}} = 0.25 \pi R_p^2 L$ and find

$$\begin{aligned} V_{\text{torus}} &= V_{\text{cell}} (72/R) \\ &= V_M (12/R). \end{aligned} \quad (\text{H4})$$

An alternative eight-cell layout due to Watson and Cordey is shown in Fig. H-2. Here we find

$$\begin{aligned} V_{\text{torus}} &= V_{\text{cell}} (77.25/R) \\ &= V_M (9.65/R) \end{aligned} \quad (\text{H5})$$

A similar relationship will hold for any number of cells, with the limiting value of $V_{\text{torus}} = (8/R) V_M$ for a large number of cells, since the effective plasma length is 1/8 of the reactor cell diameter. The case in Eq. (H5) is already quite close to this limit, and is well worked out,¹¹ so we choose it as our reference design. Parameters for $Q = 2$ are given in Tables H-1 and H-2 with the assumption that $n_T = 3n_D$. The n_T requirement for the multiple-cell reactor is reduced over a factor of 2 from the single-cell case.

ESTIMATES FOR TWO-TEMPERATURE WATSON-CORDEY REACTOR

If we set $n_D \equiv n_T$, but allow the deuterium and tritium temperatures to be different, we can estimate the performance of an eight-cell reactor by neglecting the reactions of the thermal component, assuming all reactions occur between trapped deuterons and cool tritons, and again neglecting mirror scattering losses. We will use the same value of $\overline{\sigma v}$ for a 200-keV injection as used above for $n_T \gg n_D$, realizing that a more complete reactor design would require a Fokker-Planck calculation modified to take into account the energy dependence of the cold-component loss rate from the torus.²⁹ The results are shown in

Tables H-3 and H-4: one can see that $n_T \tau_{TT} = 4 \times 10^{12}$ may lead to a viable reactor, and $n_T \tau_{TT} = 2 \times 10^{13}$ looks very interesting. According to Ref. 29, the actual reactor Q's may be enhanced considerably over those shown. (For instance, thermal reactions in the toroidal section will help.) Thus the apparent drop in "Estimated Q" from the first two tables should not be considered as significant.

CONCLUSIONS

Two-component toroidal return links, with $n_T \gg n_D$, appear to require such high values of n_T for the toroidal component as to be practically in the regime for a purely toroidal reactor. A two-temperature version of the scheme

proposed by Watson and Cordey¹¹ appears, however, to allow interesting reactors to be built with significantly reduced values of n_T . This would seem to be the logical direction for research on mirror-torus hybrids to proceed. The key remaining question is whether the required n_T 's can be achieved in a nonaxisymmetric system in the face of possible microinstabilities. A related question is whether the hot ions can be contained in the torus to any appreciable extent — we have not assumed this, in computing fusion yield, but it may allow us some increased output, perhaps by increasing L_{eff} .

The power outputs shown in Tables H-1 through H-4 are disappointingly small, and a subsequent report will discuss higher outputs at larger magnetic field values.

Fig. H-1. Plan view of six-cell, linked-mirror reactor. Distance between throats is L .

Fig. H-2. Plan view of eight-cell linked-mirror reactor. Distance between throats is L .

Table H-1. Two-Component Reactor for $Q = 2$.

$E_{D0} = 200 \text{ kV}$	$\tau_{\text{dem}} = 0.1195 \text{ s}$
$B_0 = 2.0 \text{ (vacuum.) T}$	Plasma radius ^a = 47 cm
$B_{\text{throat}} = 5.36 \text{ (vacuum.) T}$	Wall radius ^b = 112 cm
Mirror Ratio = 6 (total)	Major radius = 703 cm
$\beta = 0.8$	Fusion density = 28 W/cm ³
$T_D = 73 \text{ kV}$	Input density = 7.74 (deuterons) W/cm ³
$T_e = 8 \text{ (} T_e = T_T \text{) kV}$	Estimated $Q = 3.64$
$n_D = 0.52 \times 10^{14} \text{ D/cm}^3$	Limiting $Q^c = 2.1$
$n_T = 1.57 \times 10^{14} \text{ T/cm}^3$	Torus $n\tau$ (one-cell) ^d = $5.16 \times 10^{13} \text{ T-s/cm}^3$
$\overline{\sigma v} = 12 \times 10^{-16} \text{ cm}^3/\text{s}$	
$2n\Lambda = 18$	Fusion power = 35 MW [at 17.7 MeV/fusion]

^a Injection requires $nR_p = 10^{16}$.

^b Wall flux = $10^{14} \text{ n/cm}^2 \text{ s}$.

^c From Ref. 30. Discrepancies are due to $\overline{\sigma v}$ variation in estimate and to neglect of energy transfer to tritium.

^d From Eq. (H3) — for comparison only.

Table H-2. Two-component reactor: $Q = 2$ (8 cells).

$$E_{D0} = 200 \text{ kV}$$

$$B_0 = 2.0 \text{ T}$$

$$T_e = 8 \text{ kV}$$

$$n_D = 0.52 \times 10^{14} \text{ D/cm}^3$$

$$n_T = 1.57 \times 10^{14} \text{ T/cm}^3$$

(Other plasma parameters per Table H-1.)

$$\text{Wall radius} = 112 \text{ cm}$$

$$P_F' = 20 \text{ MW (fusion)/m}$$

$$L_{\text{cell}} = 7.03 \text{ m}$$

$$L_{\text{eff}} = 1.76 \text{ m}$$

$$P_F = 281 \text{ MW (at 17.7 MeV/fusion)}$$

$$\text{Torus } n\tau = 1.98 \times 10^{13} \text{ T-s/cm}^3$$

Table H-3. One-component reactor for $Q = 2$ (eight cells)

$E_{DO} = 200 \text{ kV}$	$\tau_{dem} = 0.188 \text{ s}$
$B_0 = 2.0 \text{ (vacuum) T}$	Plasma radius ^a = 74.9 cm
$B_{throat} = 5.36 \text{ (vacuum) T}$	Wall radius ^b = 150 cm
Mirror ratio = 6 (total)	Major radius = 937 cm
$\beta = 0.8$	Fusion density = 15 W/cm^3
$E_{DAV} = 110 \text{ kV}$	Input density = 6.22 W/cm^3
$T_e = 8 \text{ (} T_e = T_T \text{) kV}$	Estimated $Q = 2.42$
$n_D = 6.6 \times 10^{13} \text{ D/cm}^3$	Limiting $Q^c = 2.1$
$n_T = 6.6 \times 10^{13} \text{ T/cm}^3$	Torus $n\tau = 4.40 \times 10^{12} \text{ T-s/cm}^3$
$\overline{\sigma v} = 12 \times 10^{-16} \text{ cm}^3/\text{s}$	Fusion power = 500 MW [at 17.7 MeV/ fusion]
$\ln \Lambda = 18$	

^a Injection requires $nR_p = 10^{16}$.

^b Wall flux = $10^{14} \text{ n/cm}^2 \text{ s}$.

^c From Ref. 30. Discrepancies are due to $\overline{\sigma v}$ variation in estimate.
Neglects burn of cool component.

Table H-4. One-component reactor for $Q = 3$ (eight cells).

$E_{DO} = 200 \text{ kV}$	$\tau_{dem} = 0.67 \text{ s}$
$B_0 = 2.0 \text{ (vacuum) T}$	Plasma radius ^a = 95 cm
$B_{throat} = 5.36 \text{ (vacuum) T}$	Wall radius ^b = 150 cm
Mirror ratio = 6 (total)	Major radius = 937 cm
$\beta = 0.8$	Fusion density = 9.3 W/cm^3
$E_{DAV} = 120 \text{ kV}$	Input density = $1.48 \text{ (deuterons) W/cm}^3$
$T_e = 16 \text{ (} T_T = T_e \text{) kV}$	Estimated $Q = 6.29$
$n_D = 5.2 \times 10^{13} \text{ D/cm}^3$	Limiting $Q^c = 3.0$
$n_T = 5.2 \times 10^{13} \text{ T/cm}^3$	Torus $n\tau = 2.28^* 10^{13} \text{ T-s/cm}^3$
$\overline{\sigma v} = 12^* 10^{-16} \text{ cm}^3/\text{s}$	Fusion power = 500 MW [at 17.7 MeV/ fusion]
$\ln \Lambda = 18$	

^a Injection requires $nR_p = 10^{16}$.

^b Wall flux = $10^{14} \text{ n/cm}^2 \text{ s}$.

^c From Ref. 30. Discrepancies are due to $\overline{\sigma v}$ variation in estimate.
Neglects burn of cool component.

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