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UCRL-52203

UPDATE OF PLASMA PARAMETERS FOR A MIRROR FERF

R. S. Devoto

January 6, 1977

Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

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Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$; Microfiche \$3.00

<u>Page Range</u>	<u>Domestic Price</u>	<u>Page Range</u>	<u>Domestic Price</u>
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249

Contents

Abstract	1
Introduction	1
Computation of Plasma Properties	2
Summary	6
Acknowledgments	7
References	3

UPDATE OF PLASMA PARAMETERS FOR A MIRROR FERF

Abstract

Based on our current understanding of plasma behavior in mirror reactors, we have recalculated plasma parameters for a fusion engineering research facility (FERF) which uses a magnetic mirror. The most significant changes from results previously reported are a higher

value of Q (0.51 vs 0.11) and a higher total neutron rate (2.82×10^{18} vs $1.2 \times 10^{18} \text{ s}^{-1}$) yielding a maximum neutron flux of $1.25 \times 10^{14} \text{ cm}^{-2}$ at the wall. The required beam current is approximately 550 A, slightly greater than the 500A previously estimated.

Introduction

In an earlier report,¹ the design of a mirror reactor for a fusion engineering research facility (FERF) was described. The main purpose of this reactor is to produce 1.14-MeV neutrons for materials testing. Since that report, 2X11B experiments have greatly improved our understanding of plasma behavior in mirror confinement devices. In particular, it has been found that the plasma can be stabilized against enhanced losses

due to the drift-cyclotron loss-cone mode (DCLC) by injection of warm plasma outside the mirrors. In addition, improved codes have been written which enable us to make more accurate predictions of plasma parameters. This report presents a set of revised parameters which should be attainable with the design presented in Ref. 1, i.e., the same vacuum magnetic field, injection energies, and physical layout.

Computation of Plasma Properties

The computation of the plasma properties we report here follows much the same lines as those discussed in Ref. 1. Our chief computational tools are a code for solving the multispecies Fokker-Planck equations for the ion and electron distribution functions² and a radial transport code³ which we use to compute the beam current necessary to sustain the plasma against volume and surface losses.

Physical parameters are taken in the same way as in the earlier FERF study. Beams are assumed injected at 65° with energies of 65 keV for D° and 97.5 keV for T°. In addition, we specify the ratio of end-wall electrostatic potential to that at the mirrors (ϕ_w/ϕ_m). This parameter, not considered in the earlier calculations,¹ arises because the electrons which escape the mirrors can still be electrostatically confined by the sheath potential where the magnetic field lines intersect the plasma collector plates. Ions which escape the mirrors, on the other hand, are almost immediately lost.

At present we are not able to theoretically compute the ratio ϕ_w/ϕ_m . Based on results from experiments and theory in gas discharges, we would expect the potential drop from the mirror to the collector

plates, $\phi_m - \phi_w$, to be a few times kT_e . As a conservative estimate, we have taken the multiplicative factor as about unity, with $\phi_w = 1.25 \phi_m$.

Results from the Fokker-Planck calculations as well as those given in Ref. 1 are listed in Table 1. Note that Ref. 1 allowed for a higher loss rate than that predicted by the Fokker-Planck code. Thus, the predicted $\langle nT \rangle$ was decreased by a factor of 3.1 to obtain the value listed in Table 1. This correction also affects the beam currents and the listed Q.

The beam currents listed in Table 1 are only those required to sustain the plasma against volume losses by scattering through the mirrors. Additional losses occur at the plasma boundary and are considered below.

The total fusion power is found from the expression⁴

$$P_F = \pi r_p^2 (2L) A^{(2)}(j) C^{(2)}(R) \times (R) n_0^2 \langle \sigma v \rangle E_F / 4 \quad (1)$$

where E_F is the DT fusion energy (17.6 MeV), r_p is the plasma radius (0.25 m), $2L$ is the length between mirrors (4.2 m), and $A^{(2)}(j)$ and $C^{(2)}(R)$ are factors depending on the radial and axial density profiles.

$C^{(2)}(R)$ is found from the expression

Table 1. FERF plasma parameters from Fokker-Planck computations.

	Reported in Ref. 1	This report
R_v	2	2
β_0	0.65	0.65
$E_{IN,D}$	65 keV	65 keV
$E_{IN,T}$	97.5 keV	97.5 keV
θ_{IN}	65°	65°
B_M	7.5 T	7.5 T
ϕ_w/ϕ_m	1.0	1.25
I_D	364 A ^a	150 A ^a
I_T	136 A ^a	61 A ^a
$\bar{E}_D$	73 keV	74.8 keV
$\bar{E}_T$	93 keV	93.4 keV
$\bar{E}_e$	7.2 keV	8.6 keV
n_0 ($\approx n_D + n_T$)	$2.95 \times 10^{14} \text{ cm}^{-3}$	$2.91 \times 10^{14} \text{ cm}^{-3}$
Q	0.11 ^b	0.512
$\langle nT \rangle$	$1.9 \times 10^{12} \text{ cm}^{-3} \cdot \text{s}^b$	$9.7 \times 10^{12} \text{ cm}^{-3} \cdot \text{s}$
$\beta_{\max}$	0.68	0.69
R	3.38	3.38
Radial profile	Cubic (j = 3)	j = 20
P_F	3.38 MW	7.95 MW
S (neutrons)	$1.2 \times 10^{18} \text{ s}^{-1}$	$2.82 \times 10^{18} \text{ s}^{-1}$

^a These currents only allow for collisional losses through the mirrors.

^b $\langle nT \rangle$ was reduced from the classical by a factor of 3.1 in Ref. 1.

$$C^{(2)} = \int_0^1 \frac{B_0}{B} f^2 \left(\frac{B_0}{B} \right) ds \quad (2)$$

where f is the axial variation of number density, normalized to unity at the center; for the present case $C^{(2)} = 0.21$. The radial factor assumes a radial density distribution of the form

$$n = n_0 [1 - (r/r)^j] \quad (3)$$

for which

$$A^{(2)}(j) = \frac{j^2}{(j+1)(j+2)}. \quad (4)$$

In the earlier studies, a cubic profile ($j = 3$) was assumed. The calculations of boundary effects described below indicate that a much flatter profile with $j \approx 20$ is appropriate. Inserting numbers into Eq. (1) we find

$$P_F = 7.95 \text{ MW}$$

and a neutron generation rate of

$$S = 2.82 \times 10^{18} \text{ s}^{-1}.$$

Both are a factor of 2.35 higher than was previously computed and represent much improved performance.

For a source uniformly spread throughout a sphere of radius r_p , the above value yields a flux of

$$\Gamma = 5.4 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$$

at the plasma surface. The peak flux at the wall should be $1.25 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$.

In the above calculations only the losses out through the mirrors were computed. Additional losses, mostly near the surface, arise due to two additional effects. One of these, only recently understood, involves enhanced velocity-space diffusion in regions of strong density gradients due to the drift-cyclotron loss-cone (DCLC) mode. Also, the plasma will be surrounded by cold gas arising from unabsorbed neutral beams, hot-plasma charge transfer off the beams, and streaming from the neutral-beam sources. Such cold gas can erode the plasma surface by charge-transfer replacement of a hot ion by a cold one.

A full treatment of the processes occurring at the boundary would include solution of the energy and diffusion equations, with finite Larmor-radius effects, for all species. We have not yet developed a code to include all these effects. However, with some approximations and a radial code for the density,³ we can estimate losses due to these effects.

Where the scale length for the density gradient $\ell_n \equiv (d \ln n / dr)^{-1}$ satisfies the criterion

$$\ell_n \lesssim 60 a_i,$$

injection of warm plasmas is necessary to stabilize the DCLC against turbulent fluctuations which cause excessive particle loss.⁵ In the central

region of the plasma, the density profile is quite flat, so $n > 60 a_i$. Near the plasma boundary, where $n < 60 a_i$, warm plasma density in the amount⁵

$$n_w \sim n \frac{3T_e}{2T_i} \quad (5)$$

is needed for stabilization. The electrons lose energy to the stream of warm plasma and are cooled, producing increased drag on the ions and a reduced particle lifetime. The appropriate expressions for the electron temperature and ion drag time with n_w given by Eq. (5) are

$$T_e \sim 1.14 \times 10^{-6} (L_p n)^{1/4} T_i^{1/2} \quad (6)$$

$$\langle n\tau \rangle \sim 5.10 \times 10^4 (L_p n)^{3/8} T_i^{3/4} \quad (7)$$

where cgs units are used for L_p and n , and T is in keV. In order to approximately account for the energy and density profiles in the surface region, we can base our estimates on $E_i = 25$ keV and $n = 1.4 \times 10^{14}$ to get

$$\langle n\tau \rangle \sim 1.1 \times 10^{12} \text{ cm}^{-3} \cdot \text{s}^{-1}.$$

Two different sets of calculations have been made with the radial transport code:

(1) Constant value of $\langle n\tau \rangle = 9.7 \times 10^{12} \text{ cm}^{-3} \cdot \text{s}^{-1}$, i.e., no enhanced losses due to turbulence near the edge.

(2) As in (1), but $\langle n\tau \rangle = 1.1 \times 10^{12} \text{ cm}^{-3} \cdot \text{s}$ in the outer region of

thickness approximately equal to $3a_i$, where the gyroradius is based on the vacuum field.

In accord with the design of Ref. 1, 33 A equivalent of molecules were assumed to stream in from the neutral-beam sources. The radial code was run for these two cases with the beam current and beam position adjusted to give a plasma radius approximately equal to 25 cm with a reasonably flat density profile. Virtually any profile is attainable, depending on the neutral-beam sources and their relative currents. A flat profile maximizes the total power output for a given magnetic field.

The total current required for the two cases is approximately

$$(1) \quad I \approx 270 \text{ A}$$

$$(2) \quad I \approx 550 \text{ A}.$$

These cases can be compared with a required current of 211 A (Table 1) if only losses due to scattering into the loss-cone are considered. The currents listed above are probably accurate to about 10%, as can be seen by reference to the plots of number density in Fig. 1. For case (1), the central number density is slightly less than can be held by the magnetic field ($\approx 2.9 \times 10^{14} \text{ cm}^{-3}$; see Table 1), indicating that slightly more current should be supplied. On the other hand, the central density for case (2) is somewhat higher than

allowed, indicating that less than 550 A is needed.

The radial density profiles for these two cases are compared with the model profile of Eq. (3) ($j = 20$) in Fig. 1. The deviation in the central region from a uniform density could be removed by minor adjustments in beam position; however, since this correction would affect the current requirements only

slightly, we did not attempt it. The profile for case (1) is seen to follow the model profile quite well near the boundary. The enhanced losses in this region for case (2) cause the gradient to be somewhat less with a resultant thicker boundary zone. It is remarkable that the required current for case (2) is quite close to the original design value of 500 A.

Fig. 1. Radial density profiles for FERF. Model profile: $n = n_0 [1 - (r/25)^{20}]$. Case (1): uniform $\langle n_T \rangle = 9.7 \times 10^{12} \text{ cm}^{-3} \cdot \text{s}^1$. Case (2): boundary $\langle n_T \rangle = 1.1 \times 10^{12} \text{ cm}^{-3} \cdot \text{s}^1$.

Summary

The most important result of this study is the much higher neutron flux available from the mirror FERF for approximately the same beam current. The chief reason for this difference is the much different radial density profile expected. Some difference in

axial profile also contributes to the increased power. The much higher Q value for the bulk of the plasma is offset by the enhanced losses expected in the boundary region due to energy losses to the plasma stream required for stabilization of the DCLC mode.

In the calculations of these losses, we considered only the particle transport; the mean ion energy was taken as given. Energy transport, by both ions and electrons, should be included to refine these estimates. There is also some recent evidence from the 2XIIB experiment⁶ that under certain conditions a halo forms around the mirror plasma and shields the surface against erosion by cold gas. Such a shield would reduce the amount of beam current required for FERF.

Acknowledgments

I thank Marv Rensink for the Fokker-Planck calculations and Barry

Stallard for much helpful advice on running his radial code.

References

1. T. H. Batzer et al., *Conceptual Design of a Mirror Reactor for a Fusion Engineering Research Facility (FERF)*, Lawrence Livermore Laboratory, Rept. UCRL-51617 (1974).
2. J. Killeen, A. A. Mirin, and M. E. Rensink, in *Methods in Computational Physics*, Vol. 16 (Academic Press, New York, 1976).
3. B. W. Stallard, *Radial Buildup Code for Neutral Beam Injection into a Mirror Machine*, Lawrence Livermore Laboratory, Rept. UCRL-51784 (1975).
4. R. W. Moir and C. E. Taylor, "Magnets for Open-Ended Fusion Reactors," in *Proc. Conf. on Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors*, Conf-721111, p. 853; also Lawrence Livermore Laboratory, Rept. UCRL-74326 (1972).
5. D. E. Baldwin, H. L. Berk, and L. D. Pearlstein, *Phys. Rev. Lett.* **36**, 1051 (1976).
6. B. W. Stallard, private communication.