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THERMONUCLEAR REACTOR TEST FACILITY

E. B. Hooper, Jr.

July 2, 1973

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THERMONUCLEAR REACTOR TEST FACILITY*

E. B. Hooper, Jr.

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ABSTRACT

A plasma, confined by minimum B magnetic mirrors, is considered as a facility for studying the entire environment of a thermonuclear plasma. A parameter study including neutron flux calculations is presented. Neutron fluxes greater than $10^{14}/\text{cm}^2\text{-sec}$ will be feasible in moderate size devices when neutral beam sustained thermonuclear plasmas are achieved.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

INTRODUCTION

It is clear that radiation damage may be a serious impediment to the achievement of a fusion reactor. Several proposals have been made to generate neutron fluxes high enough to study damage.¹⁻⁴ One possibility is a small, nonpower producing reactor. Such a device would have a significant advantage over other schemes as it would act not just as a neutron source but rather as a facility to study the entire reactor environment. Problems such as sputtering from surfaces, synchrotron radiation control, tritium production, neutron transport in the blanket, direct conversion and many others could be studied. When such a reactor neutron source is considered from this broad viewpoint it becomes attractive despite the complications inherent in plasmas; indeed, it is clearly a necessary step on the path to power producing reactors.

A mirror device is an obvious candidate for such a facility. It is important to emphasize that the results obtained from its operation would be important whether or not mirror machines were ultimately used as power producing reactors. Because of the possibility of constructing a small mirror machine, a mirror facility would be useful even if tori, for example, were used in actual reactors.

This paper considers the "conventional" case of a mirror confined plasma generated by neutral beam injection. The object is to consider a wide range of parameters in order to understand the options which may be available in such a device. The results do not apply to the two component, mirror confined plasma which was described in a recent publication⁵ and which offers an additional option for a neutron source.

THE PLASMA

It is important first to emphasize two important limitations of the results obtained below. First, for the device suggested here such quantities as the confinement time and average ion energy should be calculated using a spatially dependent Fokker-Planck code. Indeed, the entire calculation can be made at a higher level of sophistication. Second, and ultimately of more importance, the losses are assumed to scale classically, reduced by a factor of α . If this is valid and if $\alpha \gtrsim 0.1$ a facility of the sort proposed is quite feasible. If, however, the scaling is not classical, α may vary in such a way that the plasma of interest cannot be achieved. This problem is being considered, of course, by present day physics experiments.

For these calculations we take the plasma as approximately spherical with a peak density n_0 . The spatial distribution is taken as one of the possibilities analyzed by Moir and Taylor⁶

$$n = n_0 \left(1 - \frac{r^3}{r_p^3} \right) f(s)$$

with $f(s)$ indicating variation along field lines. Take the length to be $2\ell r_p$, so that ℓ parameterizes the effective length. We use the axial density variation corresponding to a mirror ratio of 5 as typical and adequate for the present analysis. The average density is then⁶

$$\bar{n} = 0.34 n_0$$

and the average of n^2 is

$$\overline{n^2} = 0.19 n_0^2 .$$

The plasma is assumed to be sustained by a neutral beam of energy E and current I , and the plasma ion energy is taken equal to E . Such a device is limited in beta; we will eliminate density in terms of β in our equations.

Fusion cross sections averaged over distribution functions can be found in References (7) and (8). The results (7), which extend to lower energies than (8), can be fit to better than 25% in the range 10-200 keV [and above by reference to (3)] by

$$\langle \sigma v \rangle = 10^{-18} E^2 / (1 + E^{2.5} \times 10^{-4}) \text{ cm}^3/\text{sec} \quad (1)$$

with E in keV.

We need the confinement time, τ , for the spatially inhomogeneous plasma. The ion loss from a mirror scales as⁹

$$\frac{dn}{dt} = -K(E) \frac{n^2}{\log R(r,z)}$$

with R the effective mirror ratio as a function of position. It follows that

$$n_0 \tau = K(E) \bar{f} / \left(\frac{f^2}{\log R(r,z)} \right)$$

where the bars indicate spatial averages. Rather than do the actual average including the mirror ratio term (which properly should be done in the Fokker-Planck Eq.), we note that previous calculations have indicated that the ratio of fusion to input power is effected only slightly by spatial dependence.¹⁰ This is equivalent to replacing the spatially dependent R by its maximum value; thus in terms of the square well confinement parameter $n_0 \tau = (n_0 \bar{n} / \bar{n}^2) (n_0 \tau)_{sw} = 1.8 (n_0 \tau)_{sw}$. Using published results⁸ for $(n_0 \tau)_{sw}$, we have

$$n_0 \tau = 4.9 \times 10^{10} E^{3/2} \alpha \log R \quad (2)$$

with α an anomaly factor; $\alpha = 1$ implies classical confinement.

The trapping of the beam is found from Ref. (10); to good approximation the length for $1/e$ attenuation by ionization is given by

$$\lambda = 1.05 \times 10^{14} E^{0.92} / n_0 \text{ cm} \quad (3)$$

where a factor of two has been introduced to approximate the spatial variation of the plasma and the finite beam diameter.

Also, note that

$$n_0 = 4.7 \times 10^{13} (B_0 \sqrt{\beta})^2 E \text{ cm}^{-3} \quad (4)$$

with B_0 the vacuum central field in kG. We use $T = E/1.8$ as did Moir, and a factor of 0.9 to account for electrons and alpha particles.⁶

We set up the following conditions:

- (a) The beam is highly ionized in the plasma, but penetrates it well. To approximate this requirement set $\lambda = r_p$; from Eq. (2)

$$E = \left[0.28 r_p (B_o \sqrt{\beta})^2 \right]^{0.52} \text{ keV.} \quad (5)$$

- (b) The beam sustains the plasma. In the limit of trapping corresponding to $\lambda = r_p$, (87%)

$$\begin{aligned} I &= 0.39 \frac{4\pi r_p^3}{3} \frac{n_o \ell}{\tau} \\ &= 1.2 \times 10^{-2} \frac{(B_o \sqrt{\beta})^4 r_p^3 \ell}{E^{7/2} \alpha \log R} \text{ Amp. equiv.} \end{aligned} \quad (6)$$

Conditions (a) and (b) together with the parameters presented in Eqs. (1-4) define our plasma. The beam power is, of course, $P_{in} = EI_b$ kW. The fusion power is given by (for $n_D = n_T$)

$$P_f = 0.19 \frac{n_o^2}{4} \langle \sigma v \rangle (E_f) \cdot \frac{4\pi r_p^3 \ell}{3}.$$

Let $E_f = 17.5$ MeV; then

$$P_f = 1.2 \times 10^{-6} \frac{(B_o \sqrt{\beta})^4 r_p^3 \ell}{1 + E^{5/2} \times 10^{-4}} \text{ kW.} \quad (7)$$

The ratio of fusion to input power is

$$\begin{aligned} Q &= P_f/P_{in} \\ &= 1.0 \times 10^{-4} \frac{E^{5/2}}{1 + E^{5/2} \times 10^{-4}} \propto \log R. \end{aligned} \quad (8)$$

Finally we are interested in the neutron flux. At the surface of the plasma this is

$$\begin{aligned} \Gamma_s &= 0.19 \frac{n_o^2}{4} \langle \sigma v \rangle \frac{r_p}{3} \\ &= 3.5 \times 10^7 \frac{(B_o \sqrt{\beta})^4 r_p}{1 + E^{5/2} \times 10^{-4}} \text{ neutrons/cm}^2\text{-sec.} \end{aligned} \quad (9)$$

The independent variables in these results are $B_o \sqrt{\beta}$ and r_p . The quantities $\propto \log R$ and ℓ can be scaled out, so in Figs. 1-7 we plot n_o , Γ_s , E , P_f/ℓ , $I \propto \log R/\ell$, $Q/\propto \log R$, and $P_{in} \propto \log R/\ell$. A rather surprising result is that (subject to our conditions) the neutron flux is almost independent of r_p ; energy variation balances much of it.

We note from the figures that small plasmas ($r_p = 10\text{-}30$ cm) are quite possible for the neutron source. This essentially follows from the lack of the usual reactor condition of net power production.

THE MAGNET COIL AND NEUTRON SHIELD

We are interested in making a small device. Because the neutron flux from the plasma will heat and damage the coil unless shields are present, it is by no means clear that a device much smaller than a power producing reactor is possible. We consider three specific options and conclude that a small device is feasible, although the coil will place definite constraints on the facility. It is emphasized that it is not the purpose here to design the best coil but rather to demonstrate feasibility and to identify problems.

The three coil designs which are considered are: (1) a cryogenic, high purity aluminum coil (nonsuperconducting) placed near the plasma; (2) a scaled down version of the Ying-Yang coil designed by Moir and Taylor⁶ for a reactor; (3) a scaled up version of the present Baseball coil. The Baseball coil yielded a successful match to the plasma.

We are attempting to build a plasma 10-30 cm radius so that the required neutral beam voltage and current will be low. The neutron flux at the plasma surface is to be of order of $10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$; a neutron shield of thickness $> 50 \text{ cm}$ is needed (as discussed later) to protect a superconducting coil. This places the coil far from the plasma. As an alternative (#1 above) a normal conductor coil was considered. By scaling from Baseball or from the Ying-Yang geometry, for a minimum field of 50 kgauss a magnet current of 7-12 MA (Ying-Yang and BB) is needed. A feasible winding cross-section is $\approx 400 \text{ cm}^2$ (plus cooling) and coil length $\approx 500 \text{ cm}$. For copper at room temperature the power requirements are $\approx 200 \text{ MWatts}$. No

manipulation of coil geometry can reduce this large power load to a reasonable level.

High purity aluminum can lower this to a manageable power if cooling is used. For example, a resistivity of 10^{-9} ohm-cm is possible at 20°K;¹¹ the power into the coil is then 0.2 MWatts. With a thermodynamic efficiency of 20/300 and a mechanical efficiency of 0.1 the total power required is 30 MWatts. However, radiation damage will destroy the purity extremely rapidly. With a transmutation cross section $\approx 10^{-24}$ cm², the probability of transmutation per atom at a flux of 10^{14} cm⁻² sec⁻¹ is 10^{-10} /sec. A purity ratio $< 10^{-5}$ is needed so the coil lifetime is 10^5 sec or one day. A minimum lifetime of 10^3 days is required; this needs a neutron shield to reduce neutron flux by 10^{-3} . Thus a normal conductor coil must be located as far from the plasma as a superconductor and is useful only if a direct comparison of the two demonstrates it.

The two minimum B coils which have received the most attention are the Ying-Yang and the Baseball. In both cases a neutron shield is necessary to protect the superconductors. The neutron power from the plasma will be 1-10 MWatts; if the net efficiency of the refrigerator is 10^{-3} , an attenuation of the neutron flux by 10^{-3} is required to keep the gross power at a reasonable level. This is also the attenuation needed to keep neutron damage acceptably low. The blanket will be designed to maximize neutron attenuation (no breeding is required); preliminary estimates indicate that a thickness of at least 50 cm will be required.¹²

Moir and Taylor designed a Ying-Yang coil (mirror ratio = 3) for a hypothetical reactor. Typical coil radii are 10 meters; a reduction

by a factor of 10 will permit a 20 cm plasma and 50 cm shield. If the field is kept the same, the current scaling is $I \propto r = I_{MI}/10$. However, if the geometry is unchanged, the coil cross section scales as $A \propto r^2$; thus the current density scales as $j \propto r^{-1}$ and is increased by 10. This is clearly unacceptably high. Furthermore, the radial well depth for the plasma is only 9%. It follows that a direct scaling of this set of coils is unsatisfactory. Any Ying-Yang geometry will need to be considered from "scratch".

The Baseball II coil¹³ (mirror ratio = 2) on the other hand is smaller than needed and can be scaled up. A factor of 2 in size and 5/2 above full design field (to 50 kG) is needed, yielding a current of $5I_{BB} = 12$ MA-turns. The coil cross section increases by 4 so current density increases only by 5/4 to 4.7 kA/cm^2 , a reasonable value for a first design. Reshaping of the cross section will undoubtedly be needed because of the high currents and fields, but there is no obvious barrier to success. A sketch of the BB II coil and fields is given as Fig. 8, relabeled for the present case and showing a possible neutron shield.

The plasma radius can be about 20 cm. It will clearly not be spherical, however, but will be extended along the axis by a factor of 2 or so.

The radial well depth is only 0.17, so hydromagnetic stability is a concern. If this depth must be $\geq \beta$, performance will be degraded from the high β otherwise desirable. Cordey and Watson¹⁴ calculate a well depth of only β/ℓ^2 is needed, and ℓ the length normalized to r_p ; in this case

adequate stability should be achieved. This result appears unduly optimistic,¹⁵ however, and thus detailed stability calculations will be required as part of the coil design.

Particle adiabaticity is no problem; Foote's¹⁶ estimates indicate that D^+ will be adiabatic to 240 keV, well above the energies anticipated in the device.

In conclusion, coil design appears feasible. The presence of a neutron shield, thick compared to the plasma, will impose a minimum size on the plasma. The resulting small radial well depth may permit MHD instabilities limiting the attainable β ; detailed calculations will be required to determine this limit.

AN EXAMPLE

We can now consider specific parameters for a thermonuclear reactor test facility. The magnet constraints require $r_p = 20$ cm, and $\ell = 2$; we also take $B_0 = 50$ kG and $R = 3$. Neutron damage measurements require $\Gamma_s = 10^{14}$ neutrons/cm²-sec.

Assume an anomaly factor $\alpha = 0.2$. By reference to Figs. 1-7 we see that

$$\beta = 0.49$$

$$n_0 = 5.6 \times 10^{14} \text{ cm}^{-3}$$

$$E = 98 \text{ keV}$$

$$I = 280 \text{ Amp.-equivalent}$$

$$P_{in} = 27 \text{ MWatts}$$

$$P_f = 2.4 \text{ MWatts}$$

$$Q = 0.089$$

These parameters appear to be achievable, subject to the caveats discussed previously. We conclude that a test facility based upon a "conventional" mirror machine has considerable promise.

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FIGURE CAPTIONS

Fig. 1: Peak Plasma Density

Fig. 2: Injection Energy

Fig. 3: Injection Current

Fig. 4: Injection Power

Fig. 5: Neutron Flux

Fig. 6: Fusion Power

Fig. 7: Reactor Q

Fig. 8: Magnetic Coil

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

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