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SURFACE BOMBARDMENT RATES FOR MIRROR FUSION REACTOR DESIGNS*

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ABSTRACT

Arrival rates of D^0 , T^0 , D^+ , T^+ , He^{++} , neutrons, and photons are given for FERF (Fusion Engineering Research Facility, a mirror confinement reactor dedicated to materials research and to component testing), a hybrid fusion-fission reactor designed primarily to produce fissile fuel, and a D-T power reactor design. For comparison a next-generation confinement-mirror experiment called MX is included. The surfaces of interest are the first wall, the end wall, the direct converter and the injector.

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INTRODUCTION

The purpose of this paper is to collect in one place the data concerning the bombarding fluxes of particles on surfaces as envisioned in the several mirror reactor conceptual designs. The nature of the surface problem and the conceptual designs will be described only incidentally. The numbers reported should be regarded as mere examples, each conceptual design is in one phase or another of redesign incorporating new ideas and better understanding of the problems.

REACTOR DESCRIPTION

Several distinctive features of the mirror confinement concept are worth pointing out. Mirror reactors are envisioned to operate in a steady state, except for a brief (a few seconds or less) start-up period. Impurities are expected to play a minor role. Due to the open-ended nature of the confining fields and the positive plasma electrical potential impurities entering the plasma are quickly ejected through the ends. For a power reactor the ion energies are of the order of 200 keV and the electron energies of the order of 10 keV. A general description of the physics of mirror reactors is given in Ref. [1] and references cited therein.

We will now briefly describe the several conceptual mirror reactor designs in order of increasing size, with a next-generation experimental device for comparison. Table 1 lists the characteristics.

MX

The mirror experiment (MX) is designed to explore the physics of mirror confinement at higher energies, larger sizes, and longer confinement times than the present mirror experiments 2X-IIB [2] and BBII-T [3]. The design is described in Ref. [4] and shown in Fig. 1.

FERF

The Fusion Engineering Research Facility was designed to produce a large flux of 14-MeV neutrons to study radiation damage and to get system experience in operating a large fusion reactor. The first design [5] emphasized irradiation of many samples. The FERG was redesigned with remote handling and maintenance in mind. [6] Another redesign from the user's point of view added a significant blanket module resting capability. [7] Figures 2 and 3 show the first FERG design and a later vertically oriented design. The numbers in Table 1 are labeled low field and high field. The low field design uses NbTi superconductor whereas the high field design takes advantage of the higher field capability of Nb₃Sn superconductor.

Hybrid Fusion-Fission Reactor

This conceptual design emphasizes production of fissile fuel by (η, γ) reactions in either ²³⁸U or ²³²Th. The fusion power balance is not such an important design criterion by comparison to the mirror power reactor for two reasons. First, the 14-MeV neutrons release up to ten times their own energy in the subcritical blanket by the fast fission process and second, the product to be sold and thus amortize capitalization of the reactor is both fissile fuel and electricity rather than just electricity. Figure 4 shows the first hybrid reactor design.

The hybrid design is described in detail in Ref. [8]. A recent redesign [9] considerably reduced the peak to average power by employing a spherical shell blanket shown in Fig. 5. The numbers reported on here will be for the redesigned hybrid.

Reference Mirror Power Reactor

This conceptual design now underway and described in a preliminary way in Ref. [10], has as its objective the production of electrical power from the

D-T fusion process. The reactor is characterized by, among other things, highly efficient neutral beam injectors, efficient direct energy conversion of the plasma leaking out the ends, and a fusion power of the order of the injection power (i.e. $Q \sim 1$). This design is very similar in appearance to the fusion-fission reactor design of Fig. 5.

SURFACES OF INTEREST

Four distinctly different surface regions will be considered: the first wall, the end wall, the direct converter and the neutral beam.

The first wall is located between the plasma and the blanket in a direction transverse to the confining magnetic field lines. This wall will receive large fluxes of neutrons, moderate fluxes of neutral atoms resulting from the charge-exchange process, small amounts of radiation in the microwave, optical and x-ray range, and almost no charged particles.

The end wall is any material wall located just beyond the mirror field along field lines leading from the plasma region. All of the reactors discussed here are designed without end walls. However, end walls for these machines are under consideration and so deserve to be discussed.

The concept of selective leakage (the plasma leaks out regions where the mirror field is somewhat weakened) allows magnetic shielding of plasma from structural members immersed in the otherwise open end region. Speculation indicates the selective leakage process can be over 90% effective, i.e. 10% or less of the leaking plasma would impinge on the end wall surfaces by large-angle scattering and other processes. Therefore the end wall will receive large fluxes of charged particles, D^+ , T^+ , He^{++} . If selective leakage does not work well then there can be no material near the mirrors because of the high power loading. The field lines must finally end in a wall but this can be far away in the direct converter discussed next.

The direct converter is distantly located along field lines leading back into the confined plasma region. The neutron and radiation fluxes will be low. The charged particle fluxes will be reduced to a tolerable value by a magnetic expansion that increases the cross section area of the leaking plasma.

The neutral beam will be located moderately far from the plasma and will see moderate bombarding fluxes originating from the confined plasma. The important problem of electrode bombardment (discussed in Ref. [11] and elsewhere) due to beam interception and secondary processes will not be discussed here. The significance of treating the neutral beams from the point of view of the radiation emitted from the plasma is that the insulators in the ion source and the beam direct converter will be essentially unshielded from the neutrons. If necessary limited amounts of shielding could be provided.

BOMBARDMENT RATES

Neutron Flux

The neutrons emitted in the D-T fusion reaction are spread in energy due to the finite energy of the reacting deuterium and tritium. This energy spread has been calculated by Lessor [12] and is shown in Fig. 6. Although the energy spread is fairly large no resulting major effects have yet been predicted.

From the data given in Table 1 we can compute the uncollided current of 14-MeV neutrons at the surfaces of interest. These are compiled in Table 2. Detailed neutron flux data on FERF is given in Appendix D of Ref. [5].

Neutral Atom Fluxes D^0 , T^0 , He^0

The plasma is sustained by continuous injection of neutral D^0 and T^0 . There are two principal sources of neutrals striking the walls, the injected neutral atoms that pass unchanged through the plasma and the plasma ions that

become neutral by charge exchange with neutral gas or with the neutral beam atoms. Except during start-up the plasma is designed to be quite thick in the reactors; much less than 1% of the beam will pass on through the plasma without undergoing atomic collisions. In MX the plasma is less dense and considerable wall bombardment opposite the injectors is expected. In addition this beam is spread over a considerable area due to the 20°-30° spread in injection angles as can be seen in Figs. 2 and 3.

The larger source of neutrals is charge-exchange of ions on the neutral beam. Calculations in Appendix C of Ref. [5] and in Ref. [13] account for one charge-exchange event and one subsequent ionization event. These calculations for the FERF are summarized in Table 3 (Table C-2 from Ref. [5]).

The energy distribution of the neutrals striking the first wall of FERF and an indication for the other cases is shown in Fig. 7 (Fig. 11 of Ref. [14]).

In the fusion-fission hybrid reactor the peak power density on the first wall due to neutral particles is 20 W/cm^2 ($10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$) composed of D^0 and T^0 at energies of about 100 keV. This is only 17% of its neutron power loading. The peak power density of neutrals on the first wall for the power reactor on the other hand, is estimated to be 2 W/cm^2 and is composed of D^0 and T^0 at energies of about 200 keV, only 0.7% of the neutron power loading on this reactor.

A Monte Carlo method that follows multiple generations of events and treats the full three-dimensional nature of the beams and plasma has been developed [14]. Use of this method will soon routinely give detailed spatially resolved fluxes and energy distributions of neutrals bombarding the first wall of mirror reactor designs.

No estimates of helium bombardment rates to the first wall have been made. The rates should be very low, however, because the helium would come from two

charge-exchange events in series, and because the gas available for causing charge exchange will be a small fraction of the plasma density averaged over the helium orbit.

Ionic Fluxes D^+ , T^+ , He^{++}

The charged particle flux to the first wall should be very small compared to the neutral flux because there will be provided a vacuum space greater than one helium Larmor diameter between the plasma and the first wall. The end wall will however have a large power flux. At the mirror point the power density escaping along a flux tube is

$$\frac{P}{A} = \frac{g \overline{n^2 L} \bar{W}}{n \tau} R f \quad (1)$$

where n is the density, τ the confinement time, $\bar{W}$ the mean escaping energy, L the length, R the mirror ratio and f is the fraction of leaking ions that leak out along that field line.

For the power reactor parameters (taking $\overline{n^2 L} = \frac{1}{3} n_0^2 L$) the power density is $\frac{P}{A} = f \times 1260 \text{ MW/m}^2$. If selective leakage as discussed in Ref. [15] were not employed, the f would be 0.5 (i.e. leakage out both ends) and the power density would be 630 MW/m^2 . It is clear that no material end wall could stand such high power loadings. Selective leakage might be so effective that $f = 0.05$. Then the end wall flux would be 63 MW/m^2 , which is still too high for material end walls. Electrostatic plugging of certain regions, however, could possibly reduce this power loading even further.

The flux of He^{++} on the end walls can be estimated as follows. One half of the He^{++} born in the loss cone will be lost immediately. This fraction of He^{++} born is $1/(4 R)$ and the energy is about 3.5 MeV. The value of f here is 0.5. The rest of the He^{++} particles slow down and scatter out along with the

D^+ and T^+ . These He^{++} have on the average twice the energy of the D^+ and T^+ when they leave. The number of He^{++} born is smaller than the D^+ and T^+ loss rate by the burn fraction ($BF = 2 W_{inj} Q/E_F = (nT)(\overline{\sigma v}_{DT})/2$). The power density of 3.5 MeV He^{++} is

$$\frac{P}{A} = \frac{q n^2 L}{16} (\overline{\sigma v})_{DT} \quad 3.5 \text{ MeV} \quad (2)$$

Alternately this can be written as

$$\left(\frac{P}{A}\right)_{He^{++}} = \left(\frac{P}{A}\right)_{D^+, T^+} \frac{1}{8R} \frac{3.5 \text{ meV}}{W} Q \frac{2 W_{inj}}{E_F} \quad (3)$$

For the power-reactor parameters the full-energy He^{++} is 13 MW/m^2 .

The He^{++} bombarding the end wall at an average energy of $2\bar{W}$ is

$$\frac{P}{A} = q n^2 L \bar{W} R (\overline{\sigma v})_{DT} f \quad (4)$$

alternately this can be written

$$\left(\frac{P}{A}\right)_{He^{++}} = \left(\frac{P}{A}\right)_{D^+, T^+} Q \frac{4 W_{inj}}{E_F} \quad (5)$$

For the power reactor parameters this is $f \times 58 \text{ MW/m}^2$. The above arguments for f apply here as well so that selective leakage might give $f = 0.05$ and an He^{++} power density from this source of 3 MW/m^2 . This added to the full-energy He^{++} gives a combined He^{++} power density of 16 MW/m^2 . If the power density at the mirrors is too high for material walls then the mirror region must be kept open.

The direct converter (or end wall in the case of MX and FERF) is located where the magnetic field is small and the magnetic flux bundle is greatly expanded thus reducing the power density.

The direct converter employed in the fusion-fission and power reactors is of the venetian blind type. The power flux in this type of direct converter is limited to about 500 kW/m^2 . To achieve 500 kW/m^2 the field lines must be expanded by a large factor. For $f = 1.8$ we see from Eq. (1) that R becomes 0.002. The surface conditions therein have been discussed in Ref. [16]. The fluxes of D^+ , T^+ and He^{++} are 4×10^{13} , 2×10^{13} and $6 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$ respectively. The grid wires could be made of tungsten or rhenium and the collector-plate ribbons could possibly be made of graphite, all operating above 1500°C . Experimental studies on these grid wires with He^+ -induced blistering show no significant loss of voltage-holding ability [17,18].

Electromagnetic Radiation Fluxes:

The plasma will emit radiation by Bremsstrahlung, by synchrotron radiation, and by optical processes. The first wall will receive the most intense flux. The Bremsstrahlung power density is $4.8 \times 10^{-31} n_{Te}^{1/2} \text{ W/cm}^3$ (Te in keV and n in cm^{-3}). For the power reactor this is 0.1 W/cm^3 or 0.3% of the fusion power density. The Bremsstrahlung wall power density is 8 kW/m^2 or 0.3% of the neutron wall loading.

The synchrotron wall loading for the power reactor parameters has been calculated by Carlson [19] to be 4.8 kW/m^2 absorbed. The reflectivity of the niobium wall is 96%. So the power density streaming up the injector ports or out the open ends is 1.2 MW/m^2 . The fundamental frequency of this radiation is 520 GHz with the bulk of the power in the eighth harmonic.

The density of gas between the plasma and the wall is low so that optical radiation power should be low. Calculations should be done to support this assertion as it is one of the strong points of the mirror concept.

The first wall will see an intense back shine of γ radiation from the (n, γ) reactions in the blanket.

CONCLUSION

The first wall of the power reactor will have neutron fluxes of 3 MW/m^2 . By comparison, all other radiation on the first wall deposits energy in the surface and totals to 0.03 MW/m^2 or 1% of the neutron loading for the power reactor and similarly for the FERF and the hybrid. End walls at the mirror are tolerable only if selective leakage works very well (i.e. enough to reduce the D and T flux to about 31 MW/m^2 and the He flux to about 16 MW/m^2). The fluxes in the direct converter are 0.5 MW/m^2 at 100-200 keV of D^+ and T^+ . Surface bombardment during start-up, restart or abnormal operating conditions are topics for future work.

Table 1. Parameters for mirror reactors.

	Plasma length (m)	B_M (T)	R_{VAC}	Plasma radius (m)	D^0 injection energy (keV)	β	$\left(\frac{P}{W}\right)$ 17.58 MeV center (w/cm ³)	Injection current (A)		Neutron flux (10 ¹⁸ n/s)	n_0 (10 ¹⁴ cm ³)
								D^0	T^0		
MX	3.4	4	2.0	~0.3	80	0.5	~3 ^a	750		0.1	~1
FERF low field	4.2	7.5	2.0	0.25	65	0.65	60	360	140	1.2	2.95
FERF high field	4.2	10	2.0	0.25	65	0.65	~180	1080	420	3.6	5.1
Hybrid fusion-fission	18	6.8	2.25	3.0	100	0.73	10.9	5200	2600	210	1.3
Reference power reactor	16	12.8	2.5	3.2	200	0.74	32	6000	2700	720	2.4

^aAssuming D-T operation.

Table 2. Neutron power flux (14 MeV)^a and distance from the center.

	First wall		End wall		Direct converter		Neutral beam	
	Distance (m)	Power (MW/m ²)	Distance (m)	Power (MW/m ²)	Distance (m)	Power (MW/m ²)	Distance (m)	Power (MW/m ²)
FERF low field	0.3	1.8	2.1	0.1	6.5	0.01	4.5	0.01
FERF high field	0.3	5.4	2.1	0.3	6.5	0.03	4.5	0.03
Hybrid fusion fission	5.6	1.2	10	0.4	40	0.02	~13	0.1
Power reactor	6.5	3.1	10	1.5	~60	0.03	~13	0.3

^a A power flux of 1 MW/m² corresponds to a 14-MeV neutron current of 0.444×10^{14} n/cm² · s.

Table 3. Summary of FERF first-wall bombardment.

Amps injected = 145 A per injector

(106 A of 65 keV % D⁰)

(39 A of 97.5 keV % T⁰)

Power injected = 10.7 MW per injector

Area of first wall illuminated by each injector = 0.81 m²

With no plasma

Amps to the wall = 145 A for each injector

Power to the wall = 10.7 MW for each injector

Average particle flux density to wall

= 1.1×10^{17} particles/cm²·sec

Peak particle flux density to wall

= 2.8×10^{17} particles/cm²·sec

Average power density to wall = 1.3 kW/cm²

Peak power density to wall = 3.3 kW/cm²

With plasma

Amps to the wall = 23 A for each injector

Power to the wall = 1.7 MW for each injector

Average particle flux density to wall

< 1.8×10^{16} particles/cm²·sec

Peak particle flux density to wall

< 6.8×10^{16} particles/cm²·sec

Average power density to wall < 210 W/cm²

Peak power density to wall < 790 W/cm²

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Figure Captions

- Fig. 1. MX — mirror experiment.
- Fig. 2. FERF in the horizontal orientation.
- Fig. 3. FERF in the vertical orientation.
- Fig. 4. Hybrid fusion-fission reactor.
- Fig. 5. Hybrid redesigned with a spherical shell blanket.
- Fig. 6. Energy distribution of neutrons and alpha particles emitted from the plasma of the fusion-fission reactor.
- Fig. 7. Comparison of the aggregate neutral atom wall-bombardment spectrum with the mirror-confined-ion energy spectrum.

Moir - Fig. 1

Moir - Fig. 2

Moir - Fig. 3

Moir - Fig. 4

Mirror fusion-fission hybrid reactor

Moir - Fig. 5

Moir - Fig. 6

Moir - Fig. 7