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ABSTRACT

The parametric analysis and preliminary conceptual design for a multicell field reversed mirror reactor (FRM) are described.

INTRODUCTION

The field reversed mirror (FRM) is a plasma confinement concept that uses the diamagnetic current of the deuterium-tritium fuel plasma to convert the open magnetic field pattern of a standard mirror machine into a closed field pattern that has considerably improved confinement. Preliminary calculations for a fusion reactor based on FRM confinement were reported in 1976.¹ This report discusses our updated analytic model of the FRM, the results of some optimization calculations, and some of the characteristics of our present reactor design concept. Work is still continuing on the conceptual design of an FRM reactor; so the results given here must be considered preliminary.

PHYSICS MODEL

Calculations of properties of a reactor plasma are necessarily dependent on extrapolations of observed plasma behavior. Somewhat more uncertainty is involved in the present case, since only a very limited range of parameters has been explored in field-reversed devices. Based on information from the known experiments we have formed a model with certain assumptions about the plasma behavior.

Basic to our model is the assumption that a stable, field-reversed plasma can be created by beam injection. We assume a long, fat toroidal plasma with minor radius of a few gyroradii. We further assume that this plasma, once created, can be maintained by injection of a beam current sufficient to balance the particle loss rate and we solve only for the steady state conditions. Particle and energy transport

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scaling laws for this configuration are as yet unknown; we allow for various possible choices for particle and electron and ion heat conduction loss times.

The basic equations governing the plasma behavior are those for the density, the mean ion and electron energies (or temperatures), the beam absorption and the relation between magnetic field and plasma pressure. To allow a rapid survey of possible combinations of parameters, we employ zero-dimensional equations with a number of parameters which can be adjusted to duplicate more detailed calculations or experiments. We treat only one "average" ion species and assume constant electron and ion energies throughout the plasma.

The equations of the zero-dimensional plasma model along with their method of solution and sample results are given in Ref. 2.

REFERENCE CASE PHYSICS PARAMETERS

The physics parameters for the reference case discussed in this paper are given in Table 1 and the plasma cell cross section is shown in Fig. 1. Note that the parameters are divided into assumptions, optimized input (the injection energy, to be discussed later), and calculated output. Note that we have assumed a plasma minor radius equal to 5 ion gyroradii. Tangential injection means injection perpendicular to the plasma cross section shown in Fig. 1. We have also assumed a hot plasma boundary (which results in a negligible energy loss by ion heat conduction) and a 10% deposition of alpha particle energy (2/3 into the electrons, 1/3 into the ions). (These last two assumptions differ from those made for the reference case of Ref. 2.) Note that our reference case plasma produces about 20 MW of fusion power and has a Q of 5. The required vacuum central magnetic field is 4.1 T.

DESIGN OF A MULTICELL REACTOR

Because the fusion power of the FRM plasma cell is only 20 MW, it is unlikely that a single cell reactor would be economically viable for central station power production. One way to increase the power output while maximizing the efficiency

of magnetic field usage is to arrange a number of plasma cells on a common axis. For this arrangement the primary magnetic field can be provided by a long solenoid, the neutron loading on the cylindrical first wall can be fairly uniform, and all of the plasma end leakage can be handled by two direct converters.

One of the complications of a multicell FRM is that the attractive force between two adjacent plasma toroids (due to their field reversal currents) must be resisted by an axial magnetic well in each cell. We propose to produce these axial wells by placing a circular mirror coil between every two cells at the first wall radius (see Fig. 1). The mirror coils are resistive coils made of copper.

It is anticipated that stability of the FRM plasma may require a radial magnetic well in each cell. We propose to produce these radial wells with a set of 4 Ioffe bars passing axially through the reactor (see Fig. 1). These coils are also made of copper and placed at the first wall.

The scaling relationships for the geometries and currents of the mirror coils and Ioffe bars are developed in Ref. 3. Several optimizations are involved; they are discussed in a later section of this paper. For our reference case we have assumed that axial and radial mirror ratios of 1.0001 will be sufficient. (The axial and radial mirror ratios are specified as "vacuum" conditions for an individual cell, i.e., without the effect of the plasma for that cell. The axial ratio is the on-axis ratio from slightly beyond the end point of the plasma to the center; the radial ratio is the midplane ratio from the outer radius of the plasma to the center.)

The cell geometry for our reference case 11 cell FRM reactor is shown in Fig. 1 and the characteristics of the magnets are given in Table 2. The net electric power of the reactor is 74 MW_e.

We have chosen to arrange the reactor with the common centerline of the eleven cells horizontal. Each cell is 9 meters in diameter and 7 meters long and can be

extracted from the chain of cells by retraction of two bellows (to separate flanges) and a direct vertical lift. A traveling gantry crane of about 500 tonne capacity will lift and translate modules to a portal leading to a servicing bay. Figures 2 and 3 illustrate this machine arrangement.

Each blanket module has four beam access ports in the half above the horizontal center and six coolant gas inlet and six coolant gas exit ports all approaching the module vertically from below. The neutral beam sources must be rolled back from the reactor to provide clearance for the vertical lift.

Each blanket module will contain two coils (one on either side of the beam ports). The coils will be Niobium-Titanium superconductor enclosed in super-insulation except where magnet forces must be transmitted to the containers. Glassrock[®] pads carrying 5000 lbs/in² or a similar insulating material developed by Lockheed may be used in those areas. Cell-to-cell magnetic forces will be absorbed by massive hinged spacer struts attached to the outer vacuum wall of each cell. These struts must be disengaged, after shutting off the magnets, each time a module is to be removed for service or replacement. Magnetic forces are extremely large on the end magnets of the solenoid, so a means of restraining them by adjacent building structure is planned.

For our reference case reactor the peak first wall neutron loading is 2.7 MW/m^2 and the axial average is 1.6 MW/m^2 . With an estimated blanket energy multiplication of 1.2 the blanket thermal power is 17 MW per cell. The blanket and shield structural material is Inconel 718. The thermal energy is extracted by flowing helium gas at 50 atmospheres pressure. An inlet temperature of 350°C will allow a first wall temperature somewhat under 400°C and the gas exit temperature will be about 550°C . The blanket consists of a dense cluster of lithium canisters arranged so coolant flows radially outward around and through the metal envelopes encapsulating the lithium. The lithium canisters are each furnished with a small evacuated tube into

which bred tritium diffuses; continuous removal keeps the tritium blanket inventory at a low level. The whole blanket/shield structure is tire-shaped with a 1.4 meter diameter center hole (first wall), a 4.6 meter outside diameter (shield O.D.) and a 2 meter axial length. It may be tested as a critical pressure vessel and thoroughly leak-hunted prior to installation.

We are studying several methods of mounting the small mirror coils and Ioffe bars near the plasma zone, at or near the first wall. It is not possible to use continuous fixed Ioffe bars running the full length of the reactor, because they would prevent removal of individual cells during blanket change operations. We are investigating a system which permits an electrical break at each module separation plane. Cooling circuits will be self contained in each module but Ioffe bar current will enter one end of the chain of cells and leave at the other end with no intermediate electrical current leads. Also, we hope to protect the bars by having them slightly behind the first wall - built solidly into the blanket structure. They may be helium or water cooled.

Similarly, the mirrors (of slightly smaller cross section) also should be built into the blanket for support and protection from direct plasma exposure. If a symmetrical module is designed each mirror will have to be split so half is in one module and the other half is in its neighbor. An assymetric module design allows both a one-piece mirror design and one larger solenoid coil replacing two. This has cost advantages and (for the superconducting solenoid coil) a reduced heat loss since there is less surface area per unit volume of conductor.

The neutral beam injector for each cell of the FRM reactor must provide 19 A of 200 keV D and T atoms. Four of the present LBL source designs would furnish sufficient current so that one could be held in reserve as a spare for each cell. We propose negative ion acceleration and neutralization due to the higher efficiency obtainable. The sources would be arranged in two banks, one on either side of the

upper half of the reactor. Each bank of 22 beam sources will be mounted in a single wheeled enclosure which can be rolled back for service on the sources and to permit blanket changes. Cryopump panels will occupy a large percentage of the space within the enclosure.

The direct converters of the FRM reactor each receive 43 MW of charged particle power. We assume an acceptable average power density into the direct converter to be 100 watts per cm^2 . Detailed studies of the field lines escaping the end cell show that we must locate the plans of the direct converter elements 60 meters from the center of the reactor so as to not exceed that power density. The rate of expansion of the end flux is so great that the lost ions will be non-adiabatic. We are now engaged in ion trajectory studies which will help us design the direct converter in detail. The vacuum tank will be about 12 meters in diameter surrounding the direct converter and its associated cryopumping panels. The technique of using prestressed concrete building structure to carry the vacuum loads is favored in our current design work. A stainless steel membrane anchored to the inside of the concrete shell will provide the clean vacuum environment. Each of the two direct converter tanks will be about 25 meters long.

SYSTEM STUDY AND PARAMETER OPTIMIZATION

It was mentioned previously that several optimizations were involved in specifying the parameters of our reference case FRM reactor. The first optimization involves the cross sectional size of the copper mirror coils and Ioffe bars. The current density may be set at any desired value below that which is practical to cool, about 2000 A/cm². As we lower the current density, the resistive power loss decreases, but the increased conductor size causes an increase in fusion neutron attenuation. We have chosen to minimize the sum of the resistive power and the lost electrical power which could have been produced (via the blanket and thermal conversion system) without the neutron attenuation in the copper. This optimization

is shown in Fig. 4. Note that the minimum in the total copper coil power loss is quite shallow. We have chosen a copper coil current density of 1500 A/cm^2 for our reference case.

The next optimization involves the length of the individual FRM cell, defined as the distance between adjacent mirror coils, and the cell radius, defined as the radius of the mirror coil. The radius is selected to be the greater of: (a) the outer plasma radius plus two alpha particle radii and (b) that radius which results in a specified fusion neutron flux on the cell midplane. (For the cases discussed here the specified neutron flux was 4 MW/m^2 .) There is a lower limit on cell length below which it is impossible to establish an axial magnetic well; and for all lengths near this minimum, the copper coil currents are very large, resulting in large copper coil power losses. There is no absolute limit for maximum cell length, but there is an economic optimum because longer lengths reduce the overall fusion power density of the reactor. Using the engineering/economics portion of our analytic model for the FRM, we have calculated the results shown in Fig. 5. There is a fairly sharp cost minimum at our reference case value for cell length, 2 m.

The final optimization we will discuss here concerns the neutral beam injection energy, which is 200 keV for our reference case. The scaling laws for the dependence of the FRM plasma parameters on injection energy are given in Ref. 2. The variation with injection energy of Q , fusion power, required magnetic field strength, and copper coil power loss is shown in the top half of Fig. 6. (Each of the cases in Fig. 6 has an optimized cell length.) As we increase the injection energy, Q first increases, then levels off, and decreases slightly above 250 keV. The fusion power, magnetic field strength, and copper coil power increase monotonically with injection energy. Our engineering/economics code predicts that there is cost minimum near 200 keV. At lower energies both Q and the fusion power are too low; at higher energies Q has leveled off, the magnet becomes expensive, and the copper coil power is too high.

CONCLUSIONS

The FRM confinement concept has the potential for high Q operation in very small sizes. The technology requirements of an 11 cell FRM reactor producing 74 MW net electric appear to be quite modest. The parametric analysis and conceptual design work done to date encourage further work on the FRM.

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- ¹ W. C. Condit, G. A. Carlson, R. S. Devoto, J. N. Doggett, W. S. Neef, J. D. Hanson, "Preliminary Design Calculations for a Field-Reversed Mirror Reactor." Lawrence Livermore Laboratory Report No. UCRL 52170, November 5, 1976.
- ² R. S. Devoto and J. D. Hanson, "Computation of Properties of a FRM Reactor." Lawrence Livermore Laboratory Report, No. UCRL 80220, prepared for submission to Nuclear Fusion, September 26, 1977.
- ³ R. S. Devoto, J. D. Hanson, G. A. Carlson, "Engineering Parameters for the Plasma Cell of a Field-Reversed Mirror Reactor." Lawrence Livermore Laboratory report in preparation.

TABLE 1

FRM PHYSICS PARAMETERS

ASSUMPTIONS

$$\frac{a}{\rho_I} = 5 \quad \frac{R}{a} = 2 \quad \frac{L_p/2}{a} = 6$$

Tangential Injection

Beam Attenuation, e-Folds to Plasma Center = 1.75

Cubic Density Profile

$\beta = 1.5$

Hot Plasma Boundary

10% Alpha Heating

Particle Confinement $\propto$ Ion-Ion Scattering Time

OPTIMIZED INPUT

Injection Energy = 200 keV

CALCULATED OUTPUT

$$\begin{aligned} a &= .071 \text{ m} & R &= .142 \text{ m} & L_p &= .848 \text{ m} \\ n_o &= 6.5 \times 10^{20} \text{ m}^{-3} \\ E_{ion} &= 95 \text{ keV} & E_e &= 48 \text{ keV} \\ P_{inj} &= 3.7 \text{ MW/Cell} & P_{Fus} &= 19.9 \text{ MW/Cell} \\ Q &= 5.35 \end{aligned}$$

TABLE 2

11 CELL FRM - COIL PARAMETERS

SUPERCONDUCTING SOLENOID

Niobium - Titanium

$B = 4.1 \text{ T}$

Outer Coil Radius = 3.4 m

Length = 22 M (Axial Coverage = 25%)

COPPER MIRROR COILS (12)

$j = 1500 \text{ A/cm}^2$

$I = 5.1 \times 10^4 \text{ A (each)}$

Coil Radius = 0.57 m

COPPER IOFFE BARS (4)

$j = 1500 \text{ A/cm}^2$

$I = 1.8 \times 10^5 \text{ A (each)}$

Length = 22 m

TOTAL RESISTIVE POWER OF COPPER COILS = 6.9 MW

FRM REPORT - FIGURE CAPTIONS

<i>Fig. 1</i>	<i>Plasma Cell Cross Section</i>
<i>Fig. 2</i>	<i>FRM Reactor, side view</i>
<i>Fig. 3</i>	<i>FRM Reactor, end view</i>
<i>Fig. 4</i>	<i>Copper Coil Power Loss</i>
<i>Fig. 5</i>	<i>Cell Length Optimization</i>
<i>Fig. 6</i>	<i>Injection Energy Optimization</i>

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FIG. 1 FRM PLASMA CELL CROSS SECTION

FIG.2 FRM REACTOR, SIDE VIEW

FIG 3 FRM REACTOR, END VIEW

SCALE
0 5 10 15 20
METERS

FIG. 4

FIG. 5

FIG. 6