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SURFACE CONDITIONS IN A CONCEPTUAL D-T MIRROR REACTOR
WITH DIRECT CONVERSION

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SURFACE CONDITIONS IN A CONCEPTUAL D-T MIRROR REACTOR WITH DIRECT CONVERSION^{*}

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Abstract

A conceptual D-T fusion reactor employing magnetic mirror confinement and periodic focusing electrostatic direct conversion is described with emphasis on surface conditions.

Introduction

Fusion reactors employing magnetic mirror plasma confinement must efficiently handle large currents of energetic ions and neutrals. The surfaces that intercept these currents must have useful life times and allow only minimal holdup of the circulating fuel, particularly tritium.

To give you an idea of what particle currents surfaces must handle in a mirror fusion reactor, I will use our conceptual 200-MW_e net prototype reactor as my model (1). This reactor is an outgrowth of an earlier mirror reactor parameter study (2). The reactor employs negative ion neutral injection, (3) Moir and Taylor's Yin Yang magnetic mirror coil design, (4) and Post's electrostatic periodic focusing type of direct conversion (5,6).

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Reactor Description

Figure 1 shows an artist's sketch of this conceptual prototype reactor system. Starting at the injector (pictured as a tube), deuterium and tritium fuel is injected into the plasma (a 3-m-radius sphere) as 550 keV neutral atoms. Nearly all of these atoms are ionized by the plasma and trapped in the magnetic well produced by the Yin Yang magnetic coils. Only 7.5% of the trapped fuel ions undergo fusion reactions before they scatter into the loss cone. Once in the loss cone, nearly all the unreacted ions, as well as the reaction products, leak through a local minimum in the mirror field and into the expander-collector, housed in the 100-m-radius fan-shaped vacuum structure.

As the leaking plasma ions and electrons leave the mirror and enter the expander nearly all their energy is rotational. One purpose of the expander is to convert the rotational energy of the ions and electrons to translational energy necessary for the electrostatic collector. This conversion is accomplished by expanding the 150 kG magnetic field at the mirror down to 1.5 kG at the entrance to the collector. This expansion converts 99% of the plasma's rotational energy to translational energy. Another purpose of the expander is to reduce the leakage plasma density and beam height to a level the periodic focus electrostatic collector can handle. Just before entering the collector, electrons are removed from the plasma stream by abruptly folding back the magnetic field. The light, low-energy electrons follow the folded field while the heavy, high-energy ions cross the folded field and enter the collector.

The collector consists of 20 collection and focusing electrode cells. These electrode cells increase in potential with distance from the mirror. Multiple electrode cells are needed to efficiently collect the energy carried by the plasma leakage ions since they range in energy from about 300 keV to about 2 MeV. Plasma energy not converted directly to electrical energy ends up as heat, which, along with fusion neutron induced blanket heat, is converted in a conventional thermal converter.

The power flow diagram for this reactor system is shown in Fig. 2. Starting at the injector, 490 MW of injected, 550 keV deuterium and tritium atoms (890 A) are trapped in the plasma. This trapped neutral current maintains the plasma at an average density of 1.2×10^{14} atoms/cm³ and an energy of 610 keV. The fusion rate in this plasma is 590 MW. Approximately 80% of this fusion power, or 470 MW, is in the form of 14 MeV deuterium-tritium fusion neutrons that interact with the blanket to produce 520 to 940 MW of heat as the blanket energy multiplier is varied from 1.1 to 2.0. The 1.1 multiplier is achieved in a simple lithium-stainless steel blanket while the 2.0 multiplier is believed to be an upper limit for nonfission blankets.

Approximately 20% of the fusion power, or 120 MW, is released as 3.5 MeV alphas. Adding this alpha power to the trapped injected power results in a mirror leakage power of 610 MW. The direct conversion efficiency is 70%; therefore, 430 MW of the mirror leakage power is converted directly to electric power and 180 MW end up as heat. This heat, plus the blanket heat, is used to produce 320 MW_e in a 45% efficient thermal converter. Adding this to the direct converter output results in a total electric power of 750 MW. Of this, 20 MW are needed to power auxiliary systems such as the refrigerator system for the cryogenic magnets, and 560 MW are needed for the 88% efficient injector system. Net electric power is therefore 170 MW for the simple blanket case and 350 MW for the exotic blanket case. Overall system efficiencies for the two cases are 27% and 33%.

A summary of system dimensions and characteristics is given in Table 1.

Surface Loadings in the Injector System

Starting with the conceptual injector system (7) shown schematically in Fig. 3, recall that the trapped injected current of 550 keV deuterium and tritium atoms is 490 A (equivalent). To get 490 A trapped requires the ion source output to be 6650 A of D⁺ and T⁺ ions. This ion current is accelerated to about 1.5 keV, then passed through the alkali-metal-vapor cell that converts 20% (1330 A) of the H⁺ ions to the H⁻ ions

TABLE 1

System Dimension and Characteristics of a 200 MW_e
D-T Mirror Reactor With Direct ConversionMagnet coil

Radius = 10 m
 Width = 6.6 m
 Mirror separation = 4.2 m
 Central field = 50 kG
 Mirror field = 150 kG

Expander

Expansion ratio = 100
 Expander angle, $\theta = 240^\circ$
 Avg. ion energy = 620 keV
 Beam height = 0.87 m
 Radius = 76 m

Blanket

Thickness = 1. m (avg.)
 Individual tube diameter = 0.06 m
 Shape = conform to field lines
 Composition = Li-C-Fe-Ni
 Energy multiplication = 1.1 - 1.2
 Tritium breeding ratio = 1.4 - 1.0

First wall

14 MeV neutron energy flux = 1.6 MW/m^2
 Synchrotron radiation = 2.5 W/cm^2
 Bremsstrahlung = 2.6 W/cm^2
 Max. temp. = 925 K
 Material = S, S

Injector

Injected power = 915 MW
 Injection energy = 550 keV
 Total trapped current = 890 A
 Max. current density = 100 mA/cm^2
 Injection area required = 1 m^2
 Type = neutral beam
 Injectors = 2
 Accelerating stages = Unknown

Plasma

Shape = ellipsoid (minimum B volume)
 Z-axis intercept = 3.5 m
 Volume = 130 m^3
 Beam height at mirror exit = 0.74 m
 Beam area at mirror = 1.5 m^2
 Density $n = 1.2 \times 10^{14}$
 $\beta = 0.85$

Collector

Depth = 22 m
 Elements = 20
 Focusing = electrostatic

Power Distribution

$P_{\text{Fusion}} = 590 \text{ MW}$
 $P_{\text{Injection}} = 490 \text{ MW}$
 $P_{\text{Neutron}} = 470 \text{ MW}$
 $P_{\text{Trn}} = 610 \text{ MW}$
 $P_{\text{Elec}} = 170 \text{ MW}$

desired. The 80% (5320 A) not converted to H^+ ions is a mixture of H^+ and H^0 which is directed into beam dumps. Total power into these beam dumps or thermal converters as they are called in the figure is 8 MW and the impact energy is 1.5 keV. The 1330 A of H^+ produced by the alkali-metal-vapor cell is then accelerated to 550 keV, the desired injection energy. After acceleration, the H^+ beam passes through the neutralizer cell

needed to strip the extra electron from the H^- ions, thus producing the H^0 energetic neutral atoms that can cross the magnetic field and be ionized by the plasma. The neutralizer cell is 68% efficient; therefore, its output is 905 A of H^0 atoms. The remaining 32% (426 A of H^+) is turned out of the neutral beam by a turning magnet and directed into a high-voltage dc direct convertor. This Faraday cup type of direct convertor is assumed to be 90% efficient. Therefore, of the 234 MW entering the direct convertor, 211 MW are converted directly into electrical power, while the remaining 23 MW end up as thermal power. Average implantation energy of the D and T ions and charge exchange neutrals striking the collector surface of this direct convertor is about 10% of 550 keV, or 55 keV.

Out of the 905 A (equivalent) of 550 keV atoms produced by the injector system, 890 A are trapped in the plasma, 11 A penetrate the plasma, and 4 A charge exchange with plasma ions resulting in their loss to the plasma chamber first wall.

The energy and fuel carried by the 11 A that penetrate the plasma are recovered by passage through a stripping cell and into a second, single-stage high-voltage direct convertor. The efficiency of this second direct converter is 70%. Therefore 4.2 MW of the 6.0 MW penetrating the plasma are recovered directly as high-voltage direct current while the remaining 30%, or 1.8 MW, heats the collector surface. Average energy of the H ions and neutrals striking this collector's surface is 30% of 550 keV or 165 keV.

No attempt has been made to determine the current densities of H ions or atoms striking the various collector surfaces in this injector system because these will be determined, in large part, by what surfaces can tolerate. The current density of the neutral beam produced by the injector system is assumed to be approximately 0.1 A/cm^2 ($6 \times 10^{17} \text{ atoms/cm}^2 \text{ sec}$). But, the fluxes striking the various collector surfaces in the injector system can be reduced by expanding the beams to any level the surfaces can tolerate.

Plasma Chamber First-Wall Loadings

The first wall surrounding the plasma is exposed to currents of both neutral and charged particles.

Energetic Neutral Atoms

Neutralization of plasma ions by charge exchange with the energetic atoms of the neutral beam and with cold leakage gas will result in energetic deuterium and tritium atoms striking the first wall. The doubly charged Helium ions in the plasma are not expected to charge exchange twice and reach the wall.

Plasma ion neutralization by the beam results in a hydrogen atom first wall current of 3.6 A (2.2×10^{19} atoms/sec) (8). Average energy of these neutrals is 560 keV; therefore, power to the wall is 2.1 MW. Average flux of these neutrals on the 4.8-m-radius first wall is 7.0×10^{12} atoms/cm²-sec (0.71 W/cm²). This neutral flux is strongly peaked in and around the injected neutral beam that produces it. The peak-to-average flux is about 25 to 1, resulting in a peak atom flux of 2.0×10^{14} atoms/cm²-sec and a peak energy flux of 18 W/cm².

A potential second source of neutral hydrogen atoms that hit the first wall is the plasma ions neutralized by background gas. Assuming that the major source of background gas is leakage from the injection system neutralizer, the leak rate is 1% of the neutral beam, that the ratio of charge exchange to ionization is 1 to 10, and that all energetic neutrals created hit the wall, results in a charge exchange current of approximately 0.8 A (5.6×10^{18} atoms/sec). This current gives an average first-wall flux of about 2×10^{12} atoms/cm²-sec. I must emphasize that this estimate of background-gas-caused first-wall load is very crude and is included only to identify a potential source of energetic neutrals to the first wall.

Energetic Ions and Electrons

Most of the plasma chamber first wall is protected from the energetic plasma ions and electrons by the magnetic field confining the plasma. Plasma ions and electrons escaping confinement do so along field lines. Nearly all do so on about 5% of the field lines that thread a local minimum in one mirror and become the expander field.

It is estimated that 5% of the escaping plasma does not find this local minimum in the field and escapes on the other mirror field lines (8). This escaping plasma must be interceptable by a surface. Currents, energies, and fluxes are given in Table 2.

TABLE 2
Nonselective Leakage Currents to the First Wall in Mirror Region,
(~5% of plasma current to a 30 m² area)

Species	Current, A	Energy, keV	Power, MW	Current, particle/ cm ² sec	Power, W/cm ²
D ⁺	25.7	550	14.13	5.37×10^{14}	47.1
T ⁺	15.4	580	8.93	3.20×10^{14}	29.8
He ⁺⁺	3.3	1200	3.96	3.48×10^{13}	13.2
e ⁻	44.5	58	2.58	0.27×10^{14}	8.6
Totals	0	-	29.6	1.82×10^{15}	98.7

The 30 m² interception area used to calculate the tabulated fluxes is a minimum. If these particle or energy fluxes prove to be too high the interception area can be increased by backing out of the mirror into a lower field region.

Synchrotron Radiation

Calculated synchrotron radiation, (10) assuming a wall hole fraction of 1% and an electron temperature of 56 keV, is a flux, of 225 W/cm² at the 4.8-m-radius first wall. Flux absorbed by the first wall is 2.5 W/cm². Radiation is in the far infrared energy range.

Bremsstrahlung Radiation

Calculated bremsstrahlung radiation (11) is 0.058 W/cm^3 , resulting in a first-wall flux of 2.6 W/cm^2 , which is all absorbed. This radiation is in the x-ray energy range.

Neutrons

The fusion rate of 590 MW produced in the plasma results in a 14-MeV neutron wall loading of 1.6 MW/M^2 on the 4.8-m-radius first wall. First-wall current of 14 MeV neutrons is $7.2 \times 10^{13} / \text{cm}^2\text{-sec}$ and 14 MeV neutron flux is $8 \times 10^{13} / \text{cm}^2\text{-sec}$. Total neutron flux in the first wall is about $6 \times 10^{14} / \text{cm}^2\text{-sec}$.

Surface Loads in Direct Converter Expander

Column Interception

The fan shaped vacuum vessel that houses the expander and collector of the leakage plasma direct energy converter uses columns to support the vacuum load (Fig. 4). The innermost columns are at a radius of 23 m. With a beam height of approximately 1 m, the total area occupied by the expanding leakage plasma at 23 meters is about 96 m^2 . The energy flux existing at this radial position is approximately 600 W/cm^2 . Particle fluxes and average energies existing at this radial position are given in Table 3.

TABLE 3
Column Shield Particle Fluxes and Energies

Species	Flux, $\text{ions/cm}^2\text{-sec}$	Energy, keV
D^+	3.2×10^{15}	~610
T^+	1.9×10^{15}	~640
He^{++}	2.1×10^{14}	~1300

Particle fluxes on column shields can be reduced as needed by using a wedge shaped shield.

Charge Exchange Neutrals to Expander Walls

Background gas in the expander will cause some of the expanding plasma ions to charge exchange and strike the wall. Assuming background gas pressure and temperature to be 10^{-5} Torr and 900°C , the charge exchange current is about 3.9 A (2.4×10^{19} atoms/sec). The average H atom energy is 320 keV. Total expander wall area is about $2.4 \times 10^8 \text{ cm}^2$; therefore, the average expander wall flux is 1×10^{11} H atoms/ cm^2 -sec. Average expander-wall thermal flux is 0.005 W/cm^2 .

Surface Loading in Direct Converter Collector

The collector structure is attached to the periphery of the expander and is made up of 20 electrostatic periodic focusing and collection cells. Figure 5 shows a few such cells. Total radial depth of the collector structure is 20 m.

Primary currents, average ion fluxes, and average implantation energies experienced by the collection surfaces are given in Table 4. Only the primary mirror leakage ions are included here. Ion (and neutral) current produced in the collector by charge exchange and ionization is expected to be a few percent of the primary current,

TABLE 4
Collector Surface Particle Fluxes and Energies

Specie	Current, A	Flux, ions/ cm^2 -sec	Energy, keV
D ⁺	400	4.3×10^{13}	100
T ⁺	290	2.5×10^{13}	100
He ⁺⁺	63	2.7×10^{12}	200

The high transparency grids that the ions must pass through before being collected will be exposed to the same ion fluxes as the collection surfaces, but the grids are about 200 V lower in potential than collection surfaces, therefore, average ion impact energy on the grids will be about 300 keV for the hydrogen ions and about 600 keV for the helium ions. The average thermal flux heating the grids is about 3 W/cm^2 and about 1 W/cm^2 for the collection surfaces. Since it is desirable to convert some of this thermal energy to electrical energy these surfaces must run hot. Collection surfaces run in the 600 to 900°C range. The radiantly cooled grids will run considerably higher. The average fluxes are based on a collector plan view area of $7.2 \times 10^7 \text{ cm}^2$.

A much more detailed treatment of this type of collector is given in a companion paper by Moir, Barr, and Miley. (12)

Summary

The major components that make up our conceptual mirror reactor system, namely the injector system, the plasma confinement chamber, and the direct converter must have surfaces capable of intercepting large current of energetic ions, neutral atoms, neutrons, and photons. The magnitude of these currents are summarized in Tables 5, 6, and 7. The fluxes these surface are exposed to will depend to a great degree on what surfaces can handle while having useful lifetimes and low tritium holdup. For this conceptual prototype reactor desired lifetimes are in the 1 to 10 year range and tritium holdup should be limited to a few hundred grams. Any surface flux that proves to be too high can be reduced by increasing interception area.

Surface sputtering, spalling, tritium holdup, and voltage breakdown problems must be examined for the particle types, energies, fluxes, surface materials, conditions, temperatures, and electric field gradients contemplated in mirror reactors. Only when we have such information in hand can interception surfaces be designed. I must emphasize that the surface conditions presented are in most cases crude incomplete estimates based on one conceptual mirror reactor system. While crude the

estimates presented should indicate the magnitude of the surface problems faced in this type of mirror reactor systems. As our understanding of such systems improve so will our estimates of surface conditions.

TABLE 5

Summary of Surface Currents in the Injection System of a Conceptual
200 MW_e D-T Mirror Reactor With Direct Conversion

Surface	Current source	Species	Current, A	Average impact energy, keV	Thermal power, MW
Ion source beam dumps	Ion source	D&T	5300	1.5	8
1st HVCD ($\eta_{DC} \sim 0.9$)	Neutralizer losses	D&T	430	55	23
2nd HVCD ($\eta_{DC} \sim 0.7$)	Untrapped neutral beam	D&T	11	165	1.8

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TABLE 6

Summary of Surface Currents in the Plasma Chamber of a Conceptual 200 MW_e D-T Mirror Reactor With Direct Conversion

Surface	Source	Specie	Current A	Avg. impact energy, keV	Thermal power, MW	Avg. flux, particles/cm ² -sec	Avg. thermal flux, W/cm ²	Peak flux Avg. flux
Mirror region	Non-selective plasma leakage	D ⁺	25.7	550	14.1	5.4×10^{14}	99	~1
		T ⁺	15.4	580	8.9	3.2×10^{14}		1
		He ⁺⁺	3.3	1200	4.0	3.5×10^{13}		~1
		e ⁻	44.5	58	2.6	9.3×10^{14}		~1
First wall	Plasma ions neutralized by beam		3.6	550	2.1	7.9×10^{12}	0.71	25
	Plasma ions neutralized by background gas		~1	~300	~0.3	$\sim 2. \times 10^{12}$	~0.1	?
	Plasma synch- rotron radiation	photon	-	infrared	7.1 absorbed	225 (W/cm ²)	2.5 absorbed	~1
	Plasma brems- strahlung radiation	photon	-	x-ray	7.5	2.6 (W/cm ²)	2.6 absorbed	~1
	Fusion	neutron	-	14 MeV	-	7.2×10^{13}		~1

TABLE 7

Summary of Surface Currents in the Direct Converter of a Conceptual 200 MW_e D-T Mirror Reactor With Direct Conversion

Surface	Source	Specie	Current A	Avg. impact energy, keV	Thermal power, MW	Avg. flux, particles/cm ² -sec	Avg. thermal flux W/cm ²	Peak flux Avg. flux
Expander column shield (inner- most col)	Plasma transmitting expander	D ⁺	-	~610	-	3.2×10^{15}	635 W/cm ²	~1
		T ⁺	-	~640	-	1.9×10^{15}		
		He ⁺⁺	-	~1300	-	2.1×10^{14}		
Expander walls	Charge exchange	D ⁰ + T ⁰	3.9	~300	~1.6	1×10^{11}	0.01	~100
Electro- static collec- tion elec- trodes	Primary collector current	D ⁺	490	~100	~100	4.3×10^{13}	~1	?
		T ⁺	290	~100		2.5×10^{13}		
		He ⁺⁺	63	~200		2.7×10^{12}		
Collector grids	Primary collector current	D ⁺	-	~300	-	4.3×10^{13}	~3	?
		T ⁺	-	~300	-	2.5×10^{13}		
		He ⁺⁺	-	~600	-	2.7×10^{12}		

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FIG. 1.
Conceptual Mirror Reactor with Direct Conversion.

FIG. 2.
Power Flow Diagram. (All powers are in megawatts; parenthetical entries are for a blanket energy multiplier, $m = 2.0$.)

FIG. 3.
Schematic of a Neutral Beam Injection System.

FIG. 4.
Cross Sectional View Through the Mirror Reactor With Direct Converter.

FIG. 5.
Collector Electrode Configuration.