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SHIELDING OF MIRROR FEF PLASMA BY ARC DISCHARGES

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SHIELDING OF MIRROR FERMION PLASMA BY ARC DISCHARGES

Abstract

We have investigated the feasibility of shielding a mirror-confined fusion plasma against erosion by incident neutrals with a plasma blanket generated by an array of hollow-cathode arc discharges. Such a plasma blanket could also be used for line-tying stabilization of a single mirror confined plasma as well as to provide a warm plasma stream for stabilization of microinstabilities. The require-

ments for the plasma blanket are dependent on the parameter γ , the ratio of the actual cross-field diffusion coefficient to the classical value. The power requirement compares favorably with power loss due to charge exchange without shielding. More importantly, the blanket permits a relaxation of vacuum requirements to prevent erosion of the hot plasma by background neutrals.

Introduction

It is well known that if a mirror-confined plasma is sustained at high density by energetic neutral injection, all the background neutrals will be attenuated at the plasma surface. Because of charge exchange, the attenuation of the background neutrals represents an additional loss of hot ions from the plasma. The condition required to sustain the plasma surface against erosion and hence to maintain the bulk plasma in steady state has been considered by Fowler.¹ Fowler has shown that a sufficient condition

requires that the rate of trapping the injected energetic neutrals at the plasma surface over a mixing length (on the order of an ion gyroradius) equal the charge exchange loss rate. The energetic particles trapped at the plasma surface are thus sacrificed to shield the bulk plasma. Charge exchange results in the emission of energetic neutrals by the plasma and is energetically costly as well as damaging to the first-wall material. It is therefore desirable to devise a suitable means to prevent

the hot plasma from interacting with the background neutrals. A possible approach is to surround the fusion plasma with a low-temperature high-density blanket plasma generated by arc discharge.² We con-

sider the feasibility of this approach as well as typical design parameters for incorporating this method into the mirror Fusion Engineering Research Facility (FERF).³

Plasma Blanket Concept

The configuration of the mirror FERG is shown in Fig. 1 and the relevant parameters are listed below.

- Center field $B_0 = 37.5$ kG.
- Vacuum mirror ratio $R = 2$.
- Vacuum radial well-shape is essentially flat.
- Field at end wall $= 0.4B_0$.
- Center plasma density $= 3 \times 10^{14} \text{ cm}^{-3}$.
- Density profile $n(r)$
 $= n_0 [1 - (r/25)^3]$.
- Injection energy $= 65$ keV.

We consider the arrangement of a series of reflex arcs around the fish tail of the fanning magnetic field lines located beyond the mirror throat on flux lines adjacent to the first wall. The arc discharge will tend to stream freely along the flux lines and to drift transversely to both the flux lines and the field-line curvature. Thus, it will form a blanket around the volume containing the hot plasma while diffusing slowly outward, toward the wall and inward, toward the bulk plasma. Given a suitable plasma

source, the basic requirement for establishing such a plasma blanket is that the collisional scattering time be short compared to the average lifetime of the ions in the plasma. This condition generally is well satisfied in high-density, low-temperature plasma typical of arc discharges. The critical questions, therefore, concern the source requirements, gas load, and power consumption. It is obvious that the discharge plasma must essentially be fully ionized. It is also desirable that both the power and gas efficiency for the system (which must operate in steady state) be high. The hollow-cathode discharge (HCD) has been applied previously to feed high-density plasma columns in steady state of several meters in length⁴; it appears to be well suited to this application. Therefore, our first concern is to establish the compatibility of HCD parameters from a single source with the requirements for effective shielding. We then consider a

Fig. 1. Characteristic dimensions of the Mirror Fusion Engineering Research Facility.

possible design of a system to provide an effective plasma blanket for

shielding against erosion by the background neutrals.

Hollow Cathode Discharge Source

For effective shielding, the plasma blanket must be opaque to the incident background neutrals of velocity v_0 , such that

$$\frac{\langle \sigma v \rangle}{v_0} \int n d\ell > 1, \quad (1)$$

where $\langle \sigma v \rangle$ is the reaction rate averaged over the distribution of the plasma and the integral is across the

thickness of the plasma blanket. For conditions typical of discharge plasmas ($T_e \approx 10$ to 100 eV, $T_i \leq 1$ eV), attenuation occurs primarily by electron ionization. The reaction rate parameter for a Maxwellian plasma is shown in Fig. 2.⁵ The rate of reaction peaks at 100 eV, representing an optimum electron temperature in the discharge for shielding.

Fig. 2. Ionization rate for Maxwellian electrons.

To determine the source requirements, we must consider the dynamics of the discharge in a strong axial magnetic field. For typical arc discharge conditions, the conductivity along the field lines is high and thus, the plasma generated in the hollow cathode will stream along the flux line. The like-particle scattering time is very short: $\tau_{ii} \lesssim 10^{-8}$ to 10^{-6} s. Consequently, the mirror field has virtually no effect on axial distribution of the plasma column. Ions returning to the cathode along the flux lines are recycled while those that are scattered across the field lines feed the external plasma to form the blanket. For HCDs arranged in the reflex mode, the external plasma column is generally found to be space-charge negative

because radial diffusion of the ions is the dominant loss mechanism. The spatial-density distribution in this case can then be described by the radial diffusion equation for the ions,

$$\frac{\partial n}{\partial t} + D \frac{\partial}{\partial r} \left(r \frac{\partial n}{\partial r} \right) = 0, \quad (2)$$

where D is the effective, cross-field diffusion coefficient that includes turbulence and ambipolar-end effects.

The steady-state solution for the boundary conditions where the density vanishes at a radius $r = a$ is

$$n = - \frac{Q}{2\pi D} \ln \frac{r}{a}, \quad (3)$$

where Q is the line-source condition per unit length of the external discharge. For effective shielding

by the plasma that is produced by a thin-line source of radius δ diffusing radially, the required conditions according to Eq. (1) are:

$$\begin{aligned} \lim_{\delta \rightarrow 0} \int_{\delta}^a n d\ell &= \int_{\delta}^a -\frac{Q}{2\pi D} \ln \frac{r}{a} dr, \\ &= -\frac{Qa}{2\pi D} \left[-\frac{\delta}{a} \ln \frac{\delta}{a} - 1 + \frac{\delta}{a} \right], \\ &\approx \frac{Qa}{2\pi D} \gtrsim \frac{v_0}{\langle v \rangle}. \end{aligned} \quad (4)$$

The effectiveness of the plasma blanket and the requirements of the source condition are inversely proportional to the effective transverse diffusion coefficient. Diffusion across the magnetic field in arc columns is strongly affected by the operating and boundary conditions. This is evident from the above discussion and is also considered extensively in Refs. (6-8). If the plasma is fully ionized, classical diffusion arises from electron-ion collisions. The transverse diffusion coefficient for a fluid plasma in a uniform magnetic field B and with internal energy kT is given by

$$D = \frac{nkT}{B^2} \eta, \quad (5)$$

where $\eta = (1.6 \times 10^{-9} Z) \ln \Lambda / T_e^{3/2} \Omega \cdot m$ is the Spitzer resistivity and T_e is expressed in keV. End effects and large scale oscillations tend to enhance the effective cross-field diffusion coefficient to values that

lie between the classical value and the empirical Bohm rate:

$$D_{Bohm} \approx \frac{1}{16} \frac{kT}{qB}. \quad (6)$$

It has been shown that, under suitable conditions, the transport in a fully ionized, long plasma column can be accounted for by classical processes.⁹ Typically, an arc column greater than 2 m in length has been sustained in magnetic fields of a few kilogauss and with a line density of $2 \int_0^a n dr \approx 10^{14} \text{ cm}^{-2}$ by a gas feed of $0.1 \text{ atm} \cdot \text{cm}^3/\text{s}$ ($3 \times 10^{18} \text{ atom/s}$). The plasma is generated within the hollow cathode where the gas feed maintains a localized condition that is suitable for the operation of a high-current discharge.¹⁰ The comparatively higher efficiency of the HCD arises from a trapping of positive ions and metastables inside the hollow cathode so that their energy is substantially recycled. The plasma formed in the cathode is then driven out by the pressure gradient and, in the presence of an axial magnetic field, this cathode plasma feeds the confined plasma column. The V-I characteristic of the discharge generally depends on the specific configurations of the electrodes. Typically, the gas is fully ionized with an energy requirement of a few hundred electron volts per particle. The electrons, when falling over the cathode sheath and upon thermalization, have temperature

T_e of several tens of electron volts while the ions lag with a $T_i < 1$ eV.

The classical cross-field diffusion coefficient for these typical operating conditions can be calculated from Eq. (5) to be about $10^{-3} \text{ m}^2/\text{s}$. Substituting this into Eq. (4) for a line density of 10^{14} cm^{-2} , the required source feed is approximately $10^{18} \text{ s}^{-1} \cdot \text{m}^{-1}$, a value which is consistent with the operating condition of the quiescent arc column. Typical ranges of HCD operating parameters are shown below.

- Cathode inside diameter = 0.2 to 1.2 cm.
- Gas feed = 0.05 to 2.0 $\text{atm} \cdot \text{cm}^3/\text{s}$.
- Magnetic field = 100 to 3000 G.
- Arc voltage = 10 to 100 V.
- Arc current = 10 to 200 A.
- Arc power = 1 to 3 kW.
- Center density = 10^{13} to 10^{14} cm^{-3} .
- Electron temperature = several to tens of electron volts.

To form a plasma blanket to shield the FERF plasma, the operating magnetic-field intensity is significantly higher than most previous HCD operations. Classical scaling implies a reduction of the source and hence, a decrease in arc-power requirements as B^2 , providing that the cathode configuration is scaled accordingly to meet the operating condition of the arc. Theoretically, we expect that transport in a fully ionized linear

plasma column will be classical. However, in addition to end effects which become more important at higher confinement fields, the field-line curvature of the minimum-B geometry could destroy both equilibrium and stability. As an upper bound on the source requirements, we might postulate Bohm diffusion which would enhance the loss rate by the factor

$$\frac{D_{\text{Bohm}}}{D_{\text{classical}}} = \frac{\frac{1}{16} \frac{kT}{qB}}{\frac{nkT}{B^2}} = \frac{1}{16} \frac{\omega_e}{\nu_{ei}}, \quad (7)$$

where ω_e is the electron cyclotron frequency and ν_{ei} is the electron-ion scattering frequency. For typical HCD parameters in an FERF field, $\omega_e \approx 2 \times 10^{11} \text{ s}^{-1}$ and $\nu_{ei} \approx 7 \times 10^6 \text{ s}^{-1}$. Hence, the loss-rate enhancement factor is about 3×10^3 . To estimate the source requirement, we define γ ,

$$\gamma = \frac{D_{\text{actual}}}{D_{\text{classical}}}, \quad (8)$$

as the ratio of the governing effective cross-field diffusion coefficient to the classical value, bearing in mind that Bohm-like diffusion corresponds to an enhancement of approximately 10^4 . The actual source requirement can then be scaled by the enhancement factor γ from the estimates based on classical diffusion.

Source Requirements

To shield the mirror FERF plasma against background neutrals that arise primarily from the neutralizer cell, we assume that the neutrals have a thermal velocity of 10^5 cm/s. Referring to Fig. 2, the reaction rate for ionization by electrons in the 10- to 100-eV range is several times 10^{-8} cm³/s. According to Eq. (4), the line-density requirements of the plasma blanket must be in the range of 10^{13} cm⁻². For the FERF design shown in Fig. 1, the fusion plasma is isolated at a distance of 10 cm from the vacuum wall. Therefore, the plasma blanket must be limited to a thickness of a few centimeters. Correspondingly, the average density in the central core of the plasma blanket should be approximately $n_0 \approx 10^{13}$ cm⁻³. Such a central density value is typical of HCD operations. The magnetic field in the FERF end-region is 15 kG, rising to 75 kG in the mirror throat in a distance of 3.5 m, and then dropping in 2 m to a center field of 37.5 kG. The scattering mean-free-path for the ions,

$$\lambda_i = \frac{v_i}{v_{ei}} = \frac{v_i}{v_{ei}} \left(\frac{m_i}{m_e} \right)^{1/2} \approx 0.1 \text{ m} \quad (9)$$

is much less than the characteristic distance of the system, assuring good communication between the end regions

and the mirror interior. The classical cross-field diffusion coefficient for these parameters (i.e., $n = 10^{13}$ cm⁻³, $T_e = 10$ eV, $B = 15$ kG) is found from Eq. (5) to be $D_{\text{classical}} = 1.14 \times 10^{-4}$ m²/s. Substituting into Eq. (4), the source requirement needed to maintain the desired line density of 10^{13} cm⁻² in a distance $a = 2$ cm is

$$Q = \frac{2\gamma D_i \int_0^a n di}{a},$$

$$= 3.55 \times 10^{15} \gamma \text{ s}^{-1} \cdot \text{m}^{-1}. \quad (10)$$

Assuming that each source feeds a column of 4 m, the gas feed per source is $1.4 \times 10^{16} \text{ s}^{-1}$, corresponding to $10^{-3} \gamma \text{ atm cm}^3/\text{s}$. To maintain the conditions required for operation of the arc, the inside diameter of the cathode can be appropriately scaled.

The total number of sources required to form the plasma blanket is determined by the loss rate. The total flux is,

$$F = 2A\Gamma_i = 2A\frac{Q}{2-a} = NQ, \quad (11)$$

where A is the surface area of the plasma blanket and Γ_i is the flux across the surface. The factor 2 accounts for the two surfaces of the plasma blanket. The total surface area is estimated to be approximately 40 m^2 . Hence,

$$N = \frac{A}{\pi a L} \approx 120. \quad (12)$$

The total gas feed into the system is approximately $0.1 \gamma \text{ atm} \cdot \text{cm}^3/\text{s}$ and, assuming that the energy requirement is 200 eV/atom, the power requirement is about 50 γ W. This power requirement should be compared with charge exchange losses without shielding. For a deuterium plasma of FERF parameters, the dominant interaction with background neutrals is still by charge exchange. The power loss associated with a background neutral density n_0 is

$$\frac{n_0 v_0}{4} A \frac{\langle \sigma v \rangle}{\langle \sigma v \rangle} \epsilon \approx 10^{-9} n_0 W \cdot \text{m}^3/\text{particle} \quad (13)$$

where E is the energy of the hot plasma ion (~ 65 keV in FERF). In the absence of shielding, the background neutral density must be kept below 10^{15} m^{-3} ($\sim 10^{-8}$ Torr) to prevent the erosion of the hot plasma. Even at this density, the power loss is approximately 1 MW, which makes the power requirement for the plasma blanket appear quite favorable.

Conceptual Design

Based on the above considerations, the shielding of a hot plasma by a low-temperature plasma blanket generated by arc discharge appears feasible. The possibility of feeding a plasma in a mirror region with external sources has been demonstrated in the 2XIIIB experiment¹¹ and Anderson and Hooper¹² have shown the tendency for the discharge plasma to follow the fanning minimum-B field lines. In both cases, the discharges are high-power pulses. The HCD is better suited for the steady state operations that are required for shielding and a conceptual design of the HCD source for the plasma blanket is shown in

Fig. 3. The electrodes are located in the end regions of the vacuum system. The cathode is an array of refractory metal tubes that have been scaled to provide the desired flow rate and are oriented along the fanning field lines. For the present application, the cathode does not need to be composed of discrete tubes and thus many variations are possible. The system is symmetrical about the center of the mirror system so that the discharges are operated in the double-ended reflex configuration. Electrons bouncing between the cathodes ionize the background neutrals that diffuse into the plasma blanket.

Fig. 3. Conceptual design of HCD source for a plasma blanket.

The discharge is terminated on the limiter which serves as the anode and also defines the width of the plasma blanket. To minimize the effect of the gas feed on the vacuum condition in the confinement region, an additional baffle is installed to permit differential pumping. The density profiles for the hot fusion plasma, the cold blanket plasma, and the background neutrals are qualitatively illustrated in Fig. 4. The interior edge of the limiter prevents inter-

mixing of the hot and cold plasmas while the plasma blanket effectively shields out the background neutrals.

A critical question for the feasibility of the system is whether the streaming gas load into the confinement region due to the arc is small compared to the background gas in the absence of the arc. The aperture that leads to the confinement region is approximately 10^3 cm^2 in area. If we require that the background influx of neutrals into the

Fig. 4. Density profile of a fusion plasma shielded by a plasma blanket.

Conclusion

The shielding of a FERF plasma against background neutrals by the use of a plasma blanket that has been generated by hollow cathode discharge appears feasible. The requirements are estimated to be a total gas feed $NQ = 3 \times 10^{18} \gamma \text{ s}^{-1}$ and a power requirement $P = 50 \gamma \text{ W}$, where γ is the ratio of the actual cross-field diffusion to classical diffusion in the fanned minimum-B configuration that forms the plasma blanket. The power requirement compares favorably with power loss due to charge exchange in the absence of shielding. More importantly, the blanket permits a relaxation of the severe vacuum

confinement region be small (less than 10^{-3}) compared to the energetic neutrals injected into the confinement region approximately 10^{22} s^{-1} , the maximum permissible density of neutrals in the baffle region is 10^{11} cm^{-3} . This corresponds to a base pressure of $3 \times 10^{-6} \text{ Torr}$. The pumping speed required for the appropriate gas feed into the arc discharge is $10^4 \gamma \text{ l/s}$. If γ is much greater than unity, it is highly desirable to incorporate an additional differential pumping stage. However, achieving the necessary vacuum condition does not appear to pose a serious problem.

requirements to prevent plasma erosion by charge exchange and reduces damage to the first wall. The major questions concern the behavior of the arc column in the fanned magnetic field configuration and can only be resolved experimentally.

It is interesting to note that the plasma blanket is also applicable to the poloidal divertors for toroidal systems. These divertors must serve the dual function of channelling the energetic flux out of the confinement region before it can diffuse to the first wall and, at the same time, ionize and dispose of the wall-emitted impurity neutrals prevent them from

reaching the hot plasma where they accumulate. The incorporation of a dense plasma blanket (separated from the fusion plasma by a highly conducting, magnetic divertor channel leading out of the toroidal reactor chambers) can provide this dual function. It can minimize the energetic-particle flux to the first wall which

is the cause of wall-emitted impurities. Also, the plasma blanket will ionize the wall-emitted impurities so that they too are channelled out along the diverted flux. In principle, such an arrangement can be an effective means of meeting the stringent impurity-control requirements of long-pulsed toroidal reactors.

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