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A BLISTER DIVERTOR FOR TOKAMAKS

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A BLISTER DIVERTOR FOR TOKAMAKS

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I. INTRODUCTION

The efficacy of the divertor as a means of isolating the interior of a toroidal plasma discharge from its surrounding boundaries and thereby effecting a limiter action along with effective impurity control and pumping has been demonstrated both in theory and experimentally [1-5]. Divertors, as previously conceived however, have added significantly to the complexity of the tokamak system, requiring large coil currents in many designs and occupying a large spatial volume. [6-8] This added complexity and concomitant expense has placed the eventual use of divertors on advanced tokamak experiments and power reactors in doubt in spite of their demonstrated value.

We propose here a new divertor concept that introduces minimal added complexity, (and hence cost), to the tokamak design. This concept is based on the creation of a localized region of enhanced toroidal field ripple by increasing the bore size of one or more of the toroidal field coils. Plasma particles diffusing outward from the main toroidal discharge to magnetic flux surfaces [9] that intersect the region of high field ripple, which we refer to as a blister, will experience a strong drift due to field gradient and inertial effects upon being trapped in the blister. This directed drift motion provides a means for the collection and evacuation of the plasma.

In the following, the results of model calculations that demonstrate the feasibility of producing the required blister region and a preliminary evaluation of the divertor collection efficiency are presented.

II. BLISTER GEOMETRY

Consider the following model problem designed to evaluate the magnitude of the toroidal field ripple produced on the equatorial plane of a tokamak by moving the outboard leg of a toroidal field coil to a larger radial distance from the symmetry axis of the machine: An infinitely long cylinder (see Figure 1), of radius R_i (cm) carries a positive current, I (amps), (the positive direction is taken as out of the plane of the figure), while a larger, concentric, infinitely long cylinder of radius R_o carries a negative current of the same magnitude. The effect of these currents is to produce a magnetic field in the annular region $R_i \leq R \leq R_o$,

$$B = \frac{I}{5R} \quad (\text{gauss}), \quad (1)$$

thereby modeling the toroidal field of the tokamak. An infinitely long wire is placed at the location $(R = R_o, \phi=0)$, and carries a positive current, $\frac{I}{N}$, where N is the number of toroidal field coils. An equal current of opposite sign is carried by an infinite wire at $(R = R_o + \Delta, \phi=0)$. The wires are used to model the field perturbation produced by moving the outboard leg of one of the toroidal field coils outward a distance Δ . (In the design of an actual device the ripple field will be produced by a more complicated change in coil geometry, see for example figure 2, and three dimensional field maps of the blister region will be required.)

The fields produced by the current fillaments at $(R_o, 0)$ and $R_o + \Delta, 0)$ are

$$B_1 = \frac{I}{5N\rho_1} \quad (2)$$

and

$$B_2 = \frac{I}{5N\rho_2} \quad (3)$$

respectively, (the notation is defined in the figure), and after some straightforward trigonometric considerations one finds that

$$\left(\frac{\delta B}{B}\right)^2 = \frac{R^2}{N^2} \left[\frac{\rho_1^2 + \rho_2^2}{(\rho_1 \rho_2)^2} - \frac{2}{\rho_1 \rho_2} \cos(\phi_1 - \phi_2) \right], \quad (4)$$

where δB is the perturbation field due to the two wires and B is the original "toroidal" field. Some further manipulations allow this to be written as

$$\left(\frac{\delta B}{B}\right)^2 = \frac{\left(\frac{k-1}{k}\right)^2 \xi^2 / N^2}{[1+\xi^2 - 2\xi \cos\phi] [1+ \left(\frac{\xi}{k}\right)^2 - \frac{2\xi}{k} \cos\phi]} \quad (5)$$

The displacement is measured by k , which is

$$k \equiv 1 + \frac{\Delta}{R_0}, \quad (6)$$

and ξ is a normalized length;

$$\xi \equiv \frac{R}{R_0} \quad (7)$$

Using equation 5 we have evaluated the percent field ripple as a function of ξ and ϕ for the cases $k = 1.05$ and $k = 1.10$ (see Figure 3). The maintenance of a region in which there is sufficiently small field ripple so as not to adversely effect confinement [10] is in question here. The criteria that we have adopted is to define the boundary of the confinement region by the occurrence of a 3% field ripple at any location on the bounding flux surface. Further exploration of the effects of the residual ripple in the confinement region will have to be considered.

In the blister region large ripple fields are present and the resulting magnetic well will trap a fraction of the particles that are on flux surfaces intersecting this region, effectively isolating them from the rotational transform and causing them to migrate due to the effect of the local ∇B and curvature drifts.

III. RIPPLE TRAPPING OF PARTICLES IN THE BLISTER DIVERTOR

Particles that experience scattering events while in the blister volume which result in pitch angles sufficiently close to $\pi/2$ (the pitch angle is taken here as 0 when the velocity vector is parallel to the magnetic field) will be trapped in the blister and removed from the system. The extent of the trapping region in velocity space will depend on the well depth of a particular design and will not be determined here; rather, a conservative estimate will be made by assuming that a 90° scattering is required.

A toroidal annulus is defined by the flux surface on which $\delta B/B$ is 3% and by the wall. This annular region contains a volume V_a , and we define δ to be that fraction of V_a that is in the blister, (field perturbation $\geq 3\%$). Now if the discharge is modeled as a circular toroid of minor radius, a , and the thickness of the annulus is Δr , the time that a particle will spend in the blister while diffusing across the annulus with characteristic particle containment time τ_p is

$$\tau_b = 2\delta \frac{\Delta r}{a} \tau_p . \quad (8)$$

The probability that in this time the particle will be trapped is

$$P = 1 - e^{-\tau_b/\tau_s} , \quad (9)$$

where τ_s is the 90° scattering time which we take as,

$$\tau_s = \frac{11.4 \sqrt{m/m_h} T^{3/2}}{n_e Z_{eff} \ln \Lambda} , \quad (10)$$

where T is in $^\circ K$.

P is a measure of the trapping efficiency of the blister divertor, and efficient operation requires $\tau_b \gg \tau_s$. If we assume that $\Delta r/a \sim .1$ and that $\delta = .05$,

$$n\tau_b = .01 n\tau_p , \quad (11)$$

and from Equation 10, (assuming scattering of a proton), we find then that

$$\frac{(n\tau_b)}{(n\tau_s)} = \frac{.01 (n\tau_p) Z_{eff}}{T^{3/2}} , \quad (12)$$

(where $\ln\Lambda$ is assumed equal to 11.4).

It is plausible that conditions of moderate confinement and high collisionality will occur in the scrape-off annulus and yield a high blister divertor trapping efficiency. For example, if the temperature in the annulus is 500 ev and $Z_{eff} = 2.5$, an $n\tau_p$ product of 5×10^{12} (in the annulus), will result in a divertor trapping efficiency of 1 to within 1 part in 10^4 . Conditions even more propitious for blister divertor operation (high scattering rates due to low temperature and high impurity concentration) are likely to occur, and even lower $n\tau_p$ values can be acceptable.

IV. PARTICLE EVACUATION WITH A BLISTER DIVERTOR

The purpose of any divertor is to provide a means of rapidly evacuating particles from a portion of the machine volume through an area that is not a large fraction of the plasma surface area by taking advantage of the rapid motion of the particles along the field lines, (near thermal speed), as opposed to the much slower diffusive motion transverse to the field. In the blister divertor the full sound speed motion cannot be taken advantage of as the mechanism of particle evacuation is the cross field drift of the trapped particle population. For this mechanism

to successfully evacuate the particles it must provide a current to the collection area,

$$\Gamma_{\text{coll.}} \sim n_t V_{\text{drift}} A_{\text{coll.}} \quad (13)$$

where n_t is the trapped particle density, V_{drift} is the drift velocity due to the local field gradient and curvature and $A_{\text{coll.}}$ is the collection area, that is equal to the diffusion current leaving the plasma,

$$\Gamma_{\text{diff.}} \sim n V_{\text{diff.}} A_{\text{plas.}} \quad (14)$$

Combining Equations (13) and (14) we find that this condition requires

$$\frac{A_{\text{coll.}}}{A_{\text{plas.}}} \frac{n_t}{n} = \frac{V_{\text{diff.}}}{V_{\text{drift}}} \quad (15)$$

Assuming particle containment times of the order of one second in a plasma approximately one meter in minor radius and estimating the drift velocity to be .1% of the thermal speed in the annulus. equation 16 gives

$$\frac{A_{\text{coll.}}}{A_{\text{plas.}}} \frac{n_t}{n} \approx .01$$

We conclude that if 10% of the plasma density is in the trapped particle population a collection area of 10% of the plasma area will be required.

V. CONCLUDING REMARKS

This letter has presented a new divertor concept for tokamaks, and demonstrated its feasibility based on simple model calculations. More refined calculations will need to be done in the context of a particular design to determine the depth and extent of the magnetic well of the blister configuration and to refine our estimates of the trapping efficiency and the ratio of the speed at which particles are evacuated from the blister to that at which they diffuse into the scrape-off annulus. Additionally, the effect of the residual field ripple that is introduced in the interior of the plasma must be considered in evaluating the confinement properties of this type of system. It would appear however that the blister divertor would perturb the discharge less than other divertor schemes that produce nulls in the toroidal or poloidal field in producing divertor action.

The principal advantages that we envision for the blister divertor over other divertor types is that it requires a considerably less complex design and does not necessitate a large increase of the vacuum chamber volume over that required for plasma confinement or large coil currents. Consequently, it provides a means of acquiring the benefits that accrue from the inclusion of a divertor in the design of a tokamak at a minimum of additional cost.

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Fig. 1. Model problem for determining the blister magnetic field perturbation on the equatorial plane of the torus.

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Fig. 2. The Blister Divertor, a conceptual model.

$K=1.05$ $N=24$

$K=1.10$ $N=24$

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Fig. 3. Mod B on the equatorial plane of the torus for $k = 1.05$ and for $k = 1.10$, $N = 24$.