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FEBRUARY 1981

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SYMMETRIZING THE EDGE PLASMA

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Active Tokamak Limiters; Symmetrizing the Edge Plasma

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ABSTRACT

The surface layers of tokamak plasmas are strongly unstable to low frequency oscillations. The limiter, by imposing a non-axisymmetric state in the plasma scrape-off layer, may be the source of the free energy driving the instabilities. An active, two-faced sandwich limiter is proposed to symmetrize the scrape-off layer, thereby minimizing the mismatch between the inner and outer tokamak states.

DISCLAIMER

I. Introduction

There exists a substantial body of evidence to show that the surface layers of tokamak plasmas are collisional, that they are strongly unstable to low frequency ($\omega/2\pi \leq 1$ MHz) oscillations, and that the plasma in this region diffuses across the magnetic field at ~100 times the classical rates.¹⁻⁴ Similar problems have long been evident in stellarator plasmas.⁵⁻⁶

It is possible that the limiter itself may be the source of much of the electrostatic activity in the surface layers. In a symmetric circular tokamak torus the charge accumulation is removed by current flow along the helical field lines,

$$j_{\parallel} = nev(r_L/\Lambda)q \cos \theta = \alpha \cos \theta, \quad (1)$$

where θ is the poloidal angle, $v^2 = 2 kT/m_e$, $r_L = nvc/eB$, $T = T_e + T_i$, $\Lambda = n kT/d(n kT)/dr$ and q is the tokamak safety factor. (The plasma current I and the toroidal field B are parallel.) We neglect the loop current.

In the collisional Pfirsch-Schlüter regime⁷ just inside the limiter an electric field $E_{\parallel}$ must exist to drive the equilibrium currents, giving rise to a variation of the poloidal plasma potential

$$\begin{aligned} \frac{eV}{kT_e} &= 2q^2 (R_0/\Lambda) (T/T_e) (v/\omega_c) \sin \theta + eV_0/kT_e \\ &= \beta \sin \theta + eV_0/kT_e, \end{aligned} \quad (2)$$

where R_0 is the major radius of the torus, ν is the electron-ion collision frequency, and V_0 is the plasma potential in the midplane.

Outside the limiter radius at $r = a$ the plasma is in electrical contact with the limiter. In this region the relation between the equilibrium current and the potential is determined by the Langmuir relation⁸ as well as by the condition that no net charge accumulate. Just outside the limiter sheaths the current j_1 is related to the plasma potential V_1 by^{8,9}

$$j_1 = nev(m_e/2m_i)^{1/2} [1 - C \exp\{-e(V_1 - V_L)/kT_e\}] \quad (3)$$

where $C = (m_i T_e / m_e T)^{1/2}$ and V_L is the limiter potential.

If the limiter is an equipotential surface, this additional restraint means that the plasma potential outside $r = a$ cannot be matched to the interior potential. Poloidal and toroidal discontinuities of order $\sim \beta kT_e/e$ (at high density) or $\sim \gamma kT_e/e$ (at low density) arise at the boundary interface and may lead to Kelvin-Helmholtz instabilities in the surface layers.¹⁰ Also, the disruption of axisymmetry by the limiter forces a current distribution with helical characteristics in the scrape-off region. This shift in the current pattern from the $\cos \theta$ dependence in the interior may contribute to the still poorly understood MHD activity near the surface of tokamak plasmas.¹¹

II. Active Limiters

Both of these perturbing influences can, in principle, be eliminated by replacing the equipotential limiter by a two-faced, driven limiter with a variable poloidal potential. We insulate the two faces (Fig. 1) and require that the plasma potential in the scrape-off layer ($r \geq a$) be identical to Eq. (2), that the current be the same as Eq. (1), and at the same time Eq. (3) be satisfied. In other words, the limiter should be matched to the plasma load.

These requirements can be met on each side of the limiter provided one applies different poloidal potentials on each face. On the side facing the loop current the limiter potential must be

$$\frac{eV_{L1}}{kT_e} = \beta \sin \theta + \ln[1 - \gamma \cos \theta]$$

$$\approx \beta \sin \theta - \gamma \cos \theta \quad (4)$$

if $\gamma = q(r_L/\Lambda)(2m_i/m_e)^{1/2} \ll 1$. On the opposing face

$$\frac{eV_{L2}}{kT_e} \approx \beta \sin \theta + \gamma \cos \theta. \quad (5)$$

[The front and back faces must be mirror images of each other; the general symmetry operation is $V_{L1}(\theta) = -V_{L2}(-\theta)$.] One can readily check that Eq. (4), inserted into Eq. (1)-(3), yields a potential V_1 and a current j_1 identical to those of the interior equilibrium at the limiter. Then by integrating the potential drop $-\int E_{\parallel} dL$ from the back to the front of the limiter along a helical flux tube one can demonstrate that the

current flow, the potential surfaces, and the ambipolar flow patterns are identical inside and outside the limiter shadow. With this operation, therefore, we have transformed the exterior state into an axisymmetric one. There is a corresponding reduction of the free energy to drive instabilities.

Further adjustments to Eq. (4) and (5) may be imposed by plasma rotation¹²⁻¹⁴ and by the sheath drop due to the loop voltage. Instead of relying on Eq. (4) and (5) it would be preferable to place several special limiters around the torus. Potentials picked up by the passive limiter(s) could then be amplified and fed back to the others. The limiters themselves can be either voltage-driven (multi-segmented) or current-driven carbon loops —note (Fig. 1).

The magnitude of the applied potentials need be only a few volts in present-generation tokamaks, unless $\gamma \sim 1$. If the surface ions are strongly heated, then $\gamma > 1$. Stabilization by the special limiters will be impossible. The current through the limiter sheath must be reduced by (1) increasing the toroidal and poloidal fields, (2) adding more limiters ($V_1 \sim j_1 \sim N^{-1}$, where N = number of limiters), or (3) choosing a limiter material with a large secondary emission coefficient.

The driven poloidal limiters of Fig. 1 will not be practical in a reactor-like environment, because they require insulators close to the hot plasma. For these applications we require an alternative solution to the problem of edge stability. The form of Eq. (2) suggests that toroidal rail limiters may be a more practical alternative. Such limiters (in which $\theta = \text{constant}$) can readily be biased to match the

potential requirements of the interior equilibrium. Current flow across the sheath still creates a potential asymmetry. Fortunately, with a toroidal limiter the sheath potentials are reduced by a factor of a/R_0 because of the larger area of interception. Further reduction by $1/R_0 N$ can be obtained by adding more limiters.

We suggest a configuration like that shown in Fig. 2(a). Here the plasma is confined by four toroidal rail limiters at $\theta = \pm \pi/4, \pm 3\pi/4$. This positioning yields the following: (1) the limiters do not restrict the normal diagnostic lines-of-sight; (2) the equilibrium currents are intercepted efficiently (no currents flow at $\theta = \pm \pi/2$). In order to allow for biasing, two of the rails must be supported away from the vacuum vessel by bars inserted from the outside.

Should the necessity for biasing two of the limiters prove technically troublesome, then the stability requirements might be further compromised by a split two-rail limiter, as in Fig. 2(b). In this design the tokamak plasma has been elongated in the vertical direction. Limiters at ground potential can then be placed well above and below the midplane, since there is no charge accumulation in this region and therefore no change in plasma potential.

III. Discussion

Our analysis applies only to a tokamak plasma with a circular limiter that does not emit secondary electrons.

Extension of the analysis to include secondary emission¹⁵ or thermionic emission is readily carried out. Tokamak plasmas confined by horizontal or vertical bars, or diverted tokamaks, will require more complicated interfacing formulae. Our limiters can also be adapted to stellarators, with appropriate modification to take into account the non-circular flux surfaces.

The magnetic field gradients and the vertical stabilizing field of tokamaks are now carefully tailored to center the discharge within the limiting aperture. In this article we point out that limiters introduce an additional source of free energy to drive surface instabilities. To ensure electrostatic stability in the plasma-limiter interface, the tokamak discharge should also be matched electrically into the limiting aperture. The introduction of stabilizing limiters such as those described here should reduce the surface noise level. If this reduction is substantial, it should have the following beneficial effects: (1) in small, weak-field tori it might improve the overall plasma confinement; (2) in large tori it may help reduce arcing from the buildup of large electric fields near the limiter and thereby reduce the outgassing and inflow of impurities; (3) it may possibly allow the tokamak to operate more reliably as q is reduced below 3; and (4) boundary stabilization will facilitate the generation and propagation of lower hybrid waves to heat the interior.

To realize the full benefits of the driven limiters, it will also be necessary to redesign the tokamak refuelling operations. As a general rule, to satisfy the ambipolar flow relations, gas should be injected on the inside rather than on the outside of the torus.

R. L. Hickock¹⁶ has suggested one further application of the two-faced limiters — as sensors and control elements to reduce the MHD activity at the torus edge. These limiters should improve on previous efforts^{17,18} in this area, since the poloidal fields will not be shorted out by the plasma connecting the front and back faces of the limiter.

The author thanks S. Cohen, H. Hsuan, T. K. Chu, and R. L. Hickock for stimulating discussions.

This work was supported by the U.S. Department of Energy Contract NO. DE-AC02-76-CHO3073.

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Fig. 1. Two types of poloidal sandwich limiters: (a) dual current-drive carbon rings and (b) a 16-element, segmented voltage-drive limiter. The five taps on each carbon ring provide a linear approximation to Eq. (4) and (5). More taps may be added for closer matching.

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Fig. 2. Toroidal rail limiters: (a) a 4-rail limiter for a circular plasma, with two biased rails and (b) a split 2-rail limiter for an elongated tokamak.