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Divertor target heat load reduction by electrical biasing, and application to COMPASS-D

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Abstract

A toroidally asymmetric potential structure in the scrape-off layer (SOL) plasma may be formed by toroidally distributed electrical biasing of the divertor target tiles. The resulting $E \times B$ convective motions should increase the plasma radial transport in the SOL and thereby reduce the heat load at the divertor [R.H. Cohen, D.D. Ryutov, Nucl. Fus. 37 (1997) 621]. In this paper, we develop theoretical modelling and describe the implementation of this concept to the COMPASS-D divertor. We show that a strong magnetic shear near the X-point should cause significant squeezing of the convective cells preventing convection from penetrating above the X-point. This should result in reduced heat load at the divertor target without increasing the radial transport in the portion of the SOL in direct contact with the core plasma, potentially avoiding any confinement degradation. Implementation of divertor biasing is in hand on COMPASS-D involving insulation of, and modifications to, the present divertor tiles. Calculations based on measured edge parameters suggest that modest currents ~8 A/tile are required, at up to 150 V, to drive the convection. A technical test is preceding full bias experiments. © 2001 UKAEA. Published by Elsevier Science B.V. All rights reserved.

Keywords: Biasing; SOL plasma; Transverse transport

1. Introduction

The avoidance of high heat loading on divertor target surfaces is one of the key issues in the design of next-step tokamak fusion devices. Operating scenarios have been devised to reduce the power incident at the divertor by controlled impurity radiation at the plasma edge and in the scrape-off layer (SOL), combined with momentum dissipation in neutral particle interactions. Whether these schemes can be integrated with the stringent core confinement requirements to achieve ignition is yet to be shown; however, the more power that the divertor target can safely accept, then the less prescriptive are the additional plasma power dissipation requirements. Heat loading at the divertor target is reduced by optimising the divertor geometry, orientating the tiles to spread the power over a larger area. Further reduction in heat loading on the target could be achieved if the SOL itself could be broadened, i.e., the radial extent of the power flow channel increased, by increasing the effective radial transport. One approach is by ergodisation of the edge field line structure, in limiter or divertor geometry, but it is yet to be demonstrated whether this is consistent with, for example, high confinement regimes based on an edge transport barrier. Another approach is to stimulate/enhance the production of convective cells in the SOL by the formation of a toroidally asymmetric potential structure. The resulting $E \times B$ convective motions, together with turbulent dissipation, should increase the SOL plasma radial transport and thereby reduce the heat load at the divertor [1]. Several scenarios for achieving the required potential variation have been discussed, one of which is to apply toroidally distributed electrical biasing to the divertor target tiles. In this paper, an analysis of this scenario suggests that strong magnetic shear near the X-point will cause significant squeezing of the convection cells in the radial direction and their rapid dissipation, localising the effect to below

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the X-point. This opens the possibility of reducing the heat load at the divertor target without increasing the radial transport in the portion of the SOL in direct contact with the core plasma, potentially avoiding any confinement degradation. It should be noted that application of electrical biasing is not advocated for power-producer scale devices, because of power consumption and other limitations, however, it provides a suitable means of testing the common concept of inducing convection by toroidal asymmetry of the boundary.

Electrostatic biasing has been employed in many tokamaks for modifying the edge plasma behaviour, but most of these experiments have concentrated on creating radial and poloidal, rather than toroidal, electric fields ([2] and references therein). JFT-2M have applied non-axisymmetric divertor biasing in an attempt to drive edge convection. However, only two out of 14 toroidal segments of the divertor were biased and only slight reductions in heat flux density were observed [3]; no detailed theoretical modelling was reported. On COMPASS-D, a compact tokamak ($R = 0.57$ m, $a_{\mathrm{sep}} \sim 0.17$ m) with powerful ECRH (60 GHz, $\leqslant 1.5$ MW), operating in ITER-like single-null divertor configuration, implementation of biasing to the full set of divertor tiles is now programmed for the end of this year (2000). We present below modelling estimates of the bias requirements and predicted effects, together with technical details of the modifications to the divertor.

2. Theoretical principles

The fundamental idea is to induce toroidally asymmetric variations of the electrostatic potential in the SOL and set the plasma into convective motion. If the SOL plasma is in good electrical contact with the divertor target then toroidal variations in biasing applied to the tiles can produce the required plasma potential distribution near the target. This toroidal potential distribution is then projected along the field lines into the bulk of the SOL, where it causes $E \times B$ drift motion of the ions, which broadens their deposition profile on the divertor target. In a diverted plasma such as that in COMPASS-D, the situation is complicated by the fact that the magnetic field is strongly sheared near the X-point. As a result, any magnetic flux tube passing through this region becomes very distorted: its cross-section is squeezed in one direction and elongated in the other direction [4]. This implies that the convection cells created by the biasing cannot penetrate much beyond (above) the X-point since they are squeezed to dimensions smaller than the ion Larmor radius. Induced $E \times B$ convection will therefore only take place in the region between the X-point and the divertor, and only this part of the SOL will be broadened. The parallel distance over which broadening is achieved is reduced and becomes of order the shear length, rather than the full connection length.

The magnetic field in the COMPASS-D divertor is well approximated by the expression for that of a straight field with an X-point in a low-beta plasma

$$B = \hat{z}B_z + \hat{z} \times \nabla\psi = \Big[(x\hat{x} - y\hat{y})/L + \hat{z}\Big]B_z,$$

where $\psi = -B_z xy/L$ is the poloidal flux and $L \sim 1.3$ m is the shear length (Fig. 1). Here (x, y, z) is a cartesian coordinate system with the origin at the X-point, the x-axis along the divertor leg, and the z-axis in the toroidal direction. The curvature associated with the toroidal

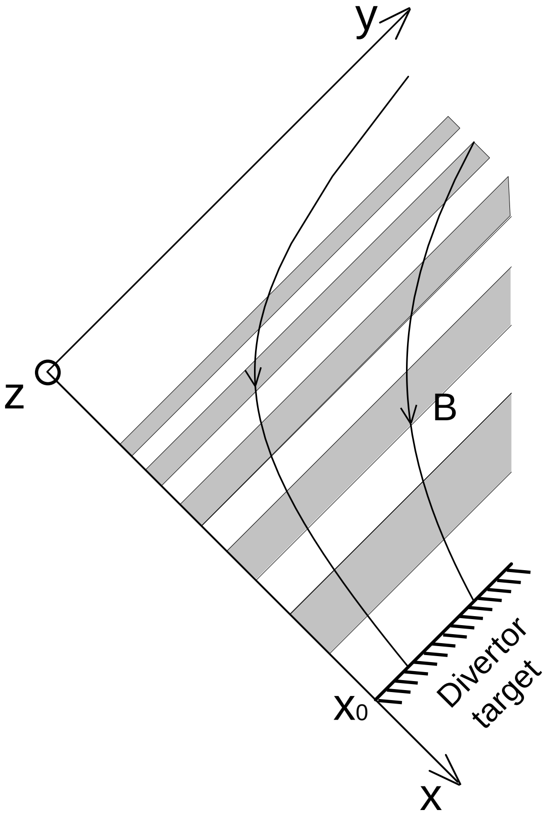

Fig. 1. Poloidal projection of the divertor region. The x-axis is along the divertor leg, from the X-point at the origin, to the target at $x = x_0$, the y-axis is along the separatrix between the core plasma and the SOL, and the z-axis is in the toroidal direction. The field lines are approximately equipotential in the divertor region. The shaded regions, and the unshaded regions between them, are projections of the divertor tiles along the magnetic field. Thus, if the tiles are biased alternately, these regions will be equipotentials, and $E \times B$ convection will occur, parallel to the y-axis, along the lines separating the shaded and unshaded regions. Close to the y-axis, these regions become very narrow.

field B_z has been ignored. The field lines are described by $x = x_0\,\mathrm{e}^{(z-z_0)/L}$, $y = y_0\,\mathrm{e}^{-[(z-z_0)/L]}$. Since, on COMPASS-D, the collisional mean-free path exceeds L, the field lines are nearly equipotentials and the electrostatic potential is determined by its value at the magnetic footprint

$$\phi_0(x, y, z) = \phi_0(z_0) = \phi_0\left(z - L\ln\frac{x}{x_0}\right).$$

The poloidal projection of the equipotential surfaces, along which $E \times B$ motion takes place is shown in Fig. 1. Note the strong squeezing of the 'convection cells' approaching the X-point. As already remarked, these cells are wider than the Larmor radius only in the divertor region below the X-point.

To estimate the effect of the induced $E \times B$ drift on ion orbits in the divertor, we note that in the guiding-centre approximation

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \frac{\mathbf{B} \times \nabla\phi_0}{B^2}\cdot\nabla\psi = \frac{\mathrm{d}\phi_0}{\mathrm{d}z_0}$$

and since z_0 does not change as a result of the drift, $\mathrm{d}\psi/\mathrm{d}t$ remains constant along the trajectory. The time an ion spends in the convection region as it travels towards the target is of the order $\Delta t = L/v_{T_\mathrm{i}}$, where $v_{T_\mathrm{i}} \leqslant (T_\mathrm{i}/m_\mathrm{i})^{1/2}$ is the ion thermal speed, and the total deflection of the orbit at the strike point is thus $\Delta\psi \sim \Delta t\,\mathrm{d}\psi/\mathrm{d}t = [(L/v_{T_\mathrm{i}})(\mathrm{d}\phi_0/\mathrm{d}z_0)]$ corresponding to

$$\Delta y = \frac{L\Delta\psi}{B_z x_0} \sim \frac{L^2}{v_{T_\mathrm{i}} B_z x_0}\frac{\mathrm{d}\phi_0}{\mathrm{d}z_0}.$$

Taking for COMPASS-D parameters $\phi_0 = \Phi_0\ (1 + \cos kz_0)$, $\Phi_0 = 40$ V, $k = N/2R = 16\ \mathrm{m}^{-1}$, $N = 16 =$ number of tiles, $v_{T_\mathrm{i}} \sim 5\times10^4$ m/s, and $B_z = 1$ T, this gives a mean-square displacement $\langle(\Delta y)^2\rangle \sim 7$ cm, which significantly exceeds the natural width of about 3 cm (at the divertor tiles), suggesting that a significant increase could be obtained with modest biasing voltage. (However, this also implies that the plasma electrons will perturb the induced electric field, so that strictly speaking a non-linear calculation is necessary.) Further calculations, which will be published separately, show that significant SOL broadening should occur even if there are turbulent fluctuations in the divertor plasma that are strong enough to destroy guiding-centre orbits.

In order to roughly estimate the power requirements for divertor biasing, suppose that half of the divertor tiles are biased at one voltage, ϕ_1, and the other half at another voltage, ϕ_2, while the plasma at the flux surface under consideration is at the potential ϕ_0. In a typical experiment alternate tiles would be biased, and the other half would be grounded, so that $\phi_1 \neq 0$, and $\phi_2 = 0$. The current density flowing to the tiles is $j_k = ne(u - v_{T_\mathrm{e}}\,\mathrm{e}^{\varphi_k - \varphi_0})$, where $\varphi_k = e\phi_k/T_\mathrm{e}$ are normalised potentials, n is the electron density, $u \sim v_{T_\mathrm{i}}$ is the velocity of the ion flow to the target, and $v_{T_\mathrm{e}} = (T_\mathrm{e}/2\pi m_\mathrm{e})^{1/2}$. If the two groups of tiles have the same total area, and if no current flows to other parts of the vessel wall, then $j_1 + j_2 = 0$ and by eliminating ϕ_0 from this equation we obtain the current density

$$-j_1 = j_2 = enu\frac{\mathrm{e}^{\varphi_1} - \mathrm{e}^{\varphi_2}}{\mathrm{e}^{\varphi_1} + \mathrm{e}^{\varphi_2}}$$

and the plasma potential

$$\varphi_0 = \ln\frac{v_{T_\mathrm{e}}}{2u} + \ln(\mathrm{e}^{\varphi_1} + \mathrm{e}^{\varphi_2}).$$

Thus, positive biasing of one group of divertor tiles can create significant variations of the electrostatic potential inside the plasma, as desired, while negative biasing does not produce a large effect. The current drawn from the tiles is of the order of the ion saturation current $j \sim neu$. Assuming again alternately biased tiles at one strikepoint, the baseline scenario, the total current driven by the biasing is $I \sim \pi R\Delta(B_\mathrm{P}/B_\mathrm{T})enu$. Using representative experimental values for COMPASS-D [5]: deuterium, $R \sim 0.7$ m, SOL width $\Delta \sim 3\times10^{-2}$ m, $B_\mathrm{P}/B_\mathrm{T} \sim 0.03$, $n \sim 5\times10^{18}\ \mathrm{m}^{-3}$, $T_\mathrm{i} \sim T_\mathrm{e} \sim 30$ eV, the total current becomes $I \sim 100$ A. Even a large biasing voltage, $\phi_1 \sim 5T_\mathrm{e}/e \sim 150$ V, gives a relatively low additional power deposited in the SOL, $P \sim 15$ kW.

3. Implementation on COMPASS-D

The COMPASS-D divertor target consists of inner, middle and outer tile sets (Fig. 2) each of 24 (16 broad and eight narrow) toroidally distributed graphite tiles, and hence is quite suitable in principle for these studies. The two strikepoints and power deposition zones in all configurations are confined to the inner two tile sets, and

Fig. 2. Photograph of the COMPASS-D divertor tiles near the position of the high resolution Langmuir probe array. All inner and middle graphite tiles will be insulated for the full implementation of divertor biasing.

only these are modified for the biasing. Up to this time, the graphite tiles have been bolted directly to stainless-steel plates mounted on the vacuum vessel, and hence clamped to torus potential. To insulate the tiles for biasing, 125 μm thickness polyetheretherketone (PEEK) sheets, moulded to fit the plate contour, are inserted beneath the graphite, and tile fixing bolts are isolated with Macor® (machinable glass–ceramic) 'top-hats', providing electrical isolation to 1000 V in air. Kapton® (polyimide) insulated wires are connected to each inner and middle tile and lead outwards through channels machined in the graphite to a circumferential cable duct, and then to multi-pin vacuum feedthroughs. All insulating surfaces are protected from direct plasma lines of sight by stainless steel or graphite shielding. In nearly all locations, the existing tiles are used, machining requirements for modifications being quite limited. All insulated tiles are capable of being individually biased or tied to torus potential, allowing many different configurations to be studied.

Because of machine access limitations, implementation of biasing to all divertor tiles involves removal and subsequent re-installation of the vacuum pumps, auxiliary heating and all major diagnostics, in addition to much demanding in-vessel work. This is resource intensive and estimated to take at least four months. In advance of commencing the full implementation, an experimental test of the technical design is being carried out, involving insulating six tiles, localised toroidally, of which four can be electrically biased. A potential problem is posed by halo currents, resulting from vertical displacement events (VDE). Detailed measurements of the intensity and distribution of halo currents in COMPASS-D [6] indicate that peak poloidal currents of up to $0.5I_P$, may be expected, suggesting that total currents of up to 100 kA could potentially be driven through divertor tiles. Fast acting trips protect the biasing power supply from such halo currents, by switching to an alternative external circuit when excessive currents are detected. However, if this alternative is an open circuit, then the changes in the poloidal flux at a VDE, together with the lack of a low resistance path could induce excessive voltages on the tiles, leading to insulation breakdown. If the alternative circuit is a low resistance path to the vessel, then high currents will flow through the wiring, leading to high $I \times B$ forces. Both of these options are available in the test segment, and measurements will be made of both open circuit induced voltage and short circuit induced currents, to decide on the preferred protection system for the full bias. The effect of $I \times B$ forces is minimised by close-coupling the halo return path with the bias wiring, and reacting the forces against each other. Halo current timescales on COMPASS-D are sufficiently short, $\leqslant 0.5$ ms, that resistive heating of the wires should not pose a serious problem.

4. Summary

By applying toroidally distributed electrical biasing to divertor target tiles, it should be possible to impose a toroidal variation in the near-target SOL plasma potential giving rise to convection cells and broadening of the power deposition zone on the targets. We show that strong magnetic shear near the X-point causes significant squeezing of the convection cells in the radial direction which should lead to their rapid dissipation by resistive and viscous effects. Under realistic conditions therefore, convection essentially does not penetrate above the X-point. Analysis of ion dynamics in a near-collisionless SOL, the case of the COMPASS-D tokamak, shows that significant broadening of the SOL below the X-point should be produced by the planned biasing voltages. This opens the possibility of reducing the heat load at the divertor target without increasing the radial transport in the portion of the SOL in direct contact with the core plasma, potentially avoiding any confinement degradation.

A test of the tile modifications and biasing system is underway on COMPASS-D, which should also determine the best approach to handling halo currents. Implementation of biasing to the full set of divertor tiles, with the flexibility to explore many tile configurations, is now programmed for the end of this year. COMPASS-D has a comprehensive set of edge diagnostics including a high resolution divertor Langmuir probe array, a reciprocating Langmuir probe and helium jet spectroscopy and in particular should be able to resolve different changes to the target and SOL plasmas.

Acknowledgements

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