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Edge plasma modeling of limiter surfaces in a tokamak divertor configuration

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Abstract

We describe a 2-D model for edge plasmas with localized limiter surfaces penetrating the scrape-off layer. The model is used to simulate an idealized ITER startup configuration with variations in the limiter penetration depth and surface shape. The results show that the distribution of the total heat load between divertor plates and outer midplane limiter surfaces can be controlled by the penetration depth of the limiter. The limiter surface can be shaped to reduce the peak heat flux without significantly changing the total heat loads. The tentative conclusion is that ITER startup on an outer midplane limiter is reasonable because the total and peak heat loads can be controlled by the limiter positioning and shape.

Keywords: 2D fluid code; 2D modeling; Boundary plasma; Code simulation; Computer simulation; Divertor; Divertor modeling; Divertor plasma; Edge modeling; Edge plasma; Fluid model; Heat deposition; Heat flux; Heat load; ITER; Limiter; Magnetic surface; Non-orthogonal grid; Numerical simulation; Particle diffusivity; Particle flow; Particle flux; Particle recycling; Plasma edge; Plasma edge physics; Plasma modeling; Power deposition; Power flux; Pumping

1. Introduction

During the startup phase of a tokamak the plasma configuration may evolve from a limiter to a divertor configuration. Some of the particle and heat flux from the core will be deposited on material surfaces near the separatrix instead of the divertor plates. Examples of such surfaces include the center-post in most tokamaks, baffles near the X-point that create closed divertors, and outboard limiter surfaces. Two-dimensional edge plasma models for tokamak divertor configurations typically give detailed information about the particle and heat fluxes on the divertor plates, but yield little or no information about fluxes on these other localized surfaces near the core plasma. To realistically model the startup phase of a tokamak it is necessary to compute the plasma interaction with both limiter and divertor surfaces. The UEDGE code [1] has been modified to include these limiter surfaces. In this report we present simulation results for an idealized ITER [2] startup configuration with variations in the limiter penetration depth and surface shape.

2. Model

The UEDGE code is a fully implicit 2-D edge plasma transport code. It solves the classical Braginskii transport equations [3] for plasma density, parallel momentum and thermal ion and electron energy transport along the magnetic field, and assumes anomalous diffusive transport across the field. For the simulations in this report the anomalous particle diffusivity, $D_\perp$, is 0.33 m^2/sec and the thermal diffusivities, $\chi_\perp$, are 0.5 m^2/s for both ions and electrons. The code used a reduced Navier–Stokes model [4,5] for atomic neutrals with a single momentum equation for transport along field lines.

2.1. Mesh configuration

The 2-D simulation includes the scrape-off-layer region outside the separatrix and a narrow region of the

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core plasma just inside the separatrix. One set of mesh surfaces coincides with magnetic flux surfaces; the second set of mesh surfaces is nearly orthogonal to the magnetic flux surfaces, except in the vicinity of the divertor plates and limiter where the mesh is distorted to conform to the shape of the recycling surface. Along each magnetic flux surface there are 112 cells and radially across magnetic flux surfaces there are 16 cells. The mesh is nonuniform in both poloidal and radial directions. Near the limiter and divertor surfaces where the neutral mean free path for ionization and charge exchange is about 5 cm, the poloidal cell size is smaller (less than 1 cm) in order to resolve the strong plasma and neutral fluid gradients associated with strong recycling. Radially, the cell size is smallest (about 0.2 cm) near the separatrix where the abrupt change in parallel losses from closed to open magnetic field lines causes strong radial gradients. Since these gradients are stronger than those associated with the limiter, the radial mesh is not varied with the limiter–separatrix distance. The divertor plates in these simulations are orthogonal to magnetic flux surfaces. We use an idealized toroidally symmetric wedge-shaped limiter as shown in Figs. 1 and 2. The wedge angle and the penetration of the limiter tip relative to the separatrix are variable. When the wedge angle is zero, the limiter is a toroidally symmetric infinitely-thin plate (a horizontal line when viewed in the poloidal plane) inserted edge-wise into the plasma. While this wedge-shaped limiter is not realistic, the SOL plasma parameters (density and temperatures at the LCFS and radial decay lengths) are relatively insensitive to the wedge angle.

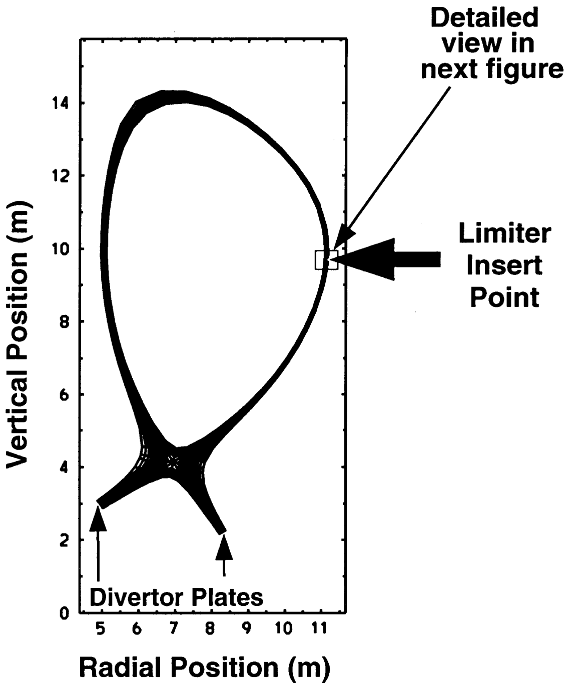

Fig. 1. Global view of the simulation region and limiter insertion point.

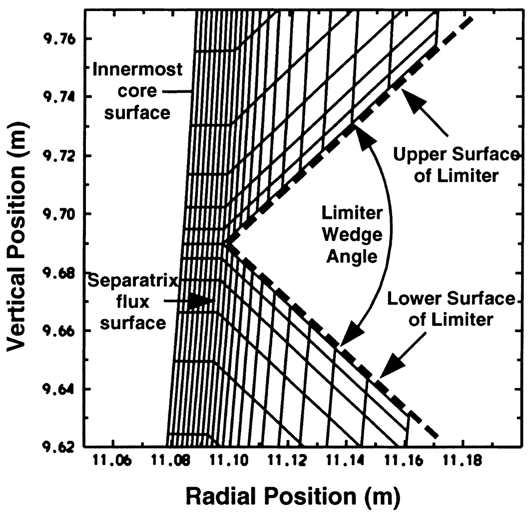

Fig. 2. Detailed view of the mesh and limiter configuration at the outboard midplane.

2.2. Boundary conditions

We assume standard recycling boundary conditions at the plasma-limiter interface, i.e., the neutral atom flux is $\Gamma_{\mathrm{neutral}} = -R_{\mathrm{p}} \cdot \Gamma_{\mathrm{ion}}$ where Γ_{ion} is the incident ion flux and R_{p} is the particle recycling coefficient; the ion parallel flow velocity at the surface is sonic; and the ion energy flux is $Q_{\mathrm{ion}} = \delta_{\mathrm{ion}} \cdot T_{\mathrm{ion}} \cdot \Gamma_{\mathrm{ion}}$ where δ_{ion} is the sheath energy transmission coefficient for ions. A similar condition is used for electrons. In general, these boundary conditions would change with the limiter shape if the self-consistent plasma potential and associated drifts were included in the simulation [6]. During plasma startup, a clean unsaturated limiter surface will initially absorb particles, so the particle recycling coefficient should be less than unity. The simulations in this report use a limiter particle recycling coefficient of 0.8 and ion (electron) energy transmission coefficients are 3.5 (5.0). The expected limiter recycling in ITER is unknown, so one should regard these as parameters to be varied in future simulations. The limiter surface could be saturated later in the startup phase, but we have not attempted to model such time dependent behaviour in this report. At the divertor plates we assume 100 percent recycling, a sonic flow condition for ions and sheath energy transmission coefficients 3.5 (5.0) for ions (electrons). This is appropriate for saturated divertor plates as expected in ITER. At the innermost core boundary, 1.4 cm inside the separatrix, the ion density

$n_{core} = 5 \times 10^{19}$ m^{-3} is fixed. The total radial power flow across the core boundary is $P_{core} = 150$ MW for modeling the ITER startup, equally divided between electrons and ions. The neutral particle flux across the core boundary is set to zero. At the outermost flux surface and innermost private flux surface we impose zero flux boundary conditions for both particles and energy.

3. Results

The results presented here are steady state plasma simulations. The mesh is based on the ITER equilibrium magnetic configuration in which the flux surfaces outside the separatrix all terminate at the divertor plates. To simulate a startup configuration, we introduce a shaped limiter surface near the outboard midplane that intersects the flux surfaces and absorbs heat and particles that would have gone to the divertor plates. We vary the limiter surface shape so as to approach a 'conformal' shape that is nearly tangent to flux surfaces in the poloidal plane, as in the ITER reference design.

The first set of simulations examines the redistribution of the power between divertor and limiter surfaces as a thin limiter plate is inserted at the outboard midplane. The results in Fig. 3 show that when the limiter tip is about 1 cm outside the separatrix flux surface the power is split equally between the limiter and divertor plates. This agrees with the simple estimate that the limiter power should be equal to the divertor plate power that would have been deposited beyond the 1 cm flux surface in the 'no limiter' case. If the limiter is inserted 0.5 cm beyond the separatrix, then essentially all of the power is deposited on the limiter.

Besides the power redistribution the limiter produces significant changes in the density profile of the SOL. In the absence of the limiter, there is no net particle removal and the SOL density is nearly uniform in the radial and poloidal directions except near the divertor plates. For these simulations the limiter particle recycling coefficient $R_p = 0.8$, so a large ion particle flux onto the limiter (as the tip approaches the separatrix) leads to a large net particle removal rate by the limiter. For example, with the limiter tip at the separatrix flux surface the total ion current to the limiter is 150 kA and the total particle removal rate is 30 kA. In our simulations these particles are supplied by a net current across the innermost core boundary. This current increases as the limiter tip approaches the separatrix because the exposed pumping surface and incident ion flux both increase. The radial ion particle flux from the core is the product of the anomalous particle diffusivity, $D_\perp$, and the radial gradient in the SOL density due to limiter pumping. Fig. 4 shows the steepening of the radial density profile in the SOL as the limiter is inserted to the separatrix.

A second set of simulations examines the effect of limiter shape on the heat flux profiles at the limiter surface. The results in Fig. 5 show the heat flux profiles for several wedge shapes with the limiter tip exactly at the separatrix. The total energy and particles deposited on the limiter are not significantly affected by the limiter surface shape. When the limiter surface is normal to flux

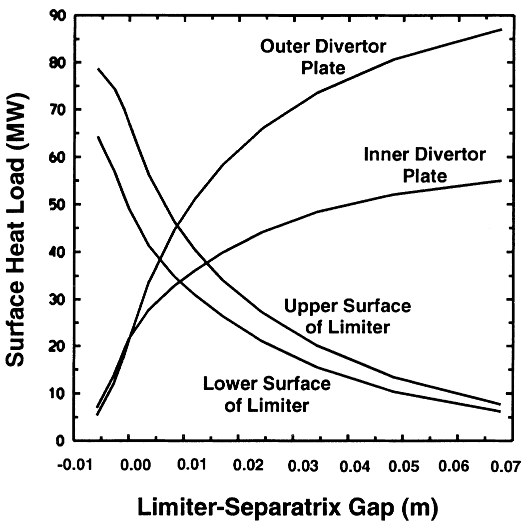

Fig. 3. Variation of the total heat load on limiter and divertor surfaces as a function of the radial distance between the limiter tip and the separatrix flux surface. The limiter wedge angle is zero.

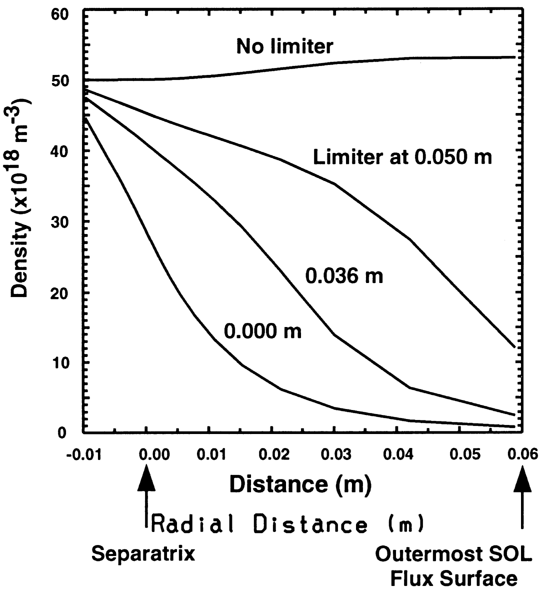

Fig. 4. Radial profile of the plasma density for varying limiter penetration. The profile is at a poloidal position half-way between the outboard midplane and the X-point.

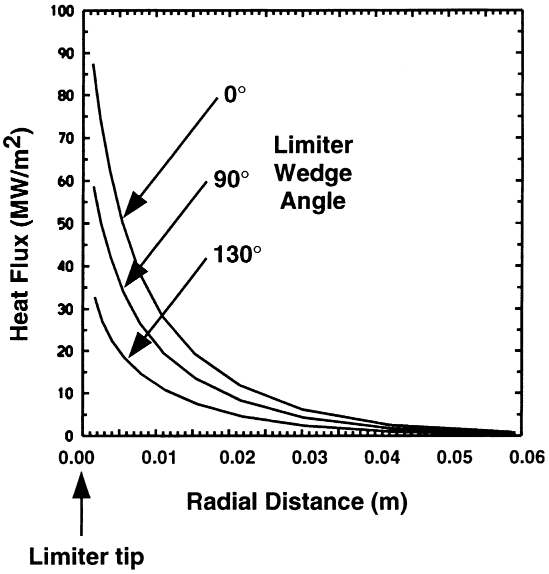

Fig. 5. Heat flux profile on the upper surface of the limiter as a function of radial distance from the separatrix for various wedge angles. The limiter tip is at the separatrix flux surface.

surfaces, the maximum heat flux on the limiter is about 90 MW/m^2. As expected, the maximum heat flux decreases to less than 30 MW/m^2 as the surface is tilted to be more nearly parallel to magnetic flux surfaces. The decrease in heat flux with increasing wedge angle is primarily due to the increase in the wetted area of the limiter. The integrated heat flux to the limiter is constant to within 5 percent as the wedge angle increases from 0° to 130°. Simulations with larger wedge angles present numerical difficulties because the mesh becomes very distorted near the limiter surface. In the limit where the wedge angle is 180° the limiter surface would represent a flat plate tangent to the magnetic flux surface, and we expect the heat flux at the tangent point to be very small; the heat flux would probably be a maximum at some point on the limiter that is further out in the SOL.

Changes also occur in the ion density profile along flux surfaces in the vicinity of the limiter. Recycling near the limiter tip produces a localized ionization source and a peak in the plasma density profile as shown in Fig. 6. The limiter tip is at the separatrix, so the ion density peak occurs inside the separatrix and radial diffusion produces a localized influx of ions into the core region. However, the integrated particle flux across the core boundary is radially outward due to the net pumping by the limiter surface. Our model assumes that neutral atoms from recycling at the limiter tip are reflected at the innermost core flux surface. The distribution of neutrals in the core will not be significantly affected by this boundary condition if the neutral mean free path is shorter than the distance from the limiter tip to the core

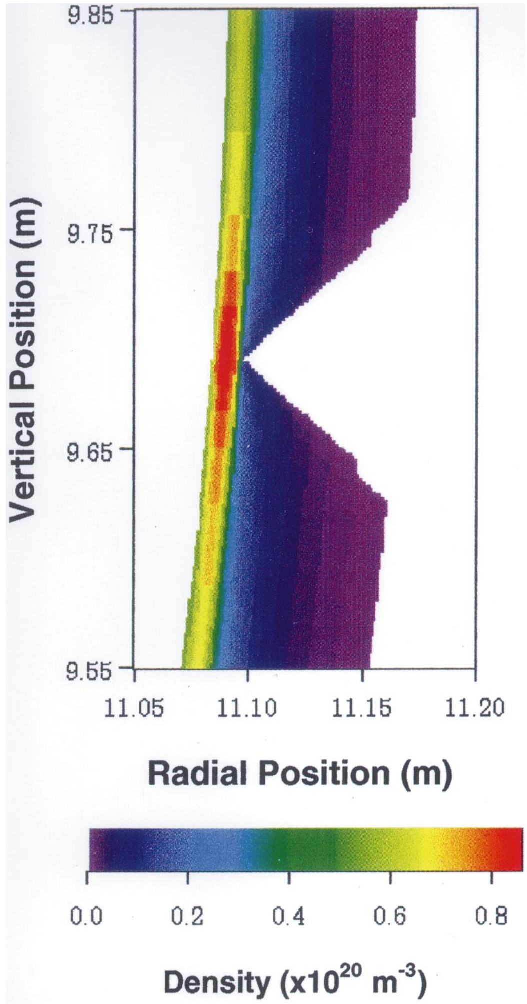

Fig. 6. Plasma density contours in the vicinity of the limiter. The limiter tip is at the separatrix flux surface and the limiter wedge angle is 90°.

flux surface. However, with the limiter tip at the separatrix as in Fig. 6, the neutral mean free path does extend beyond the innermost core flux surface and may produce a flux of high energy charge exchange neutrals on the outer wall. We are not able to estimate this flux within the limits of our present model. For flux surfaces which intersect the limiter, the density decreases along field lines approaching the limiter surface, although this is not apparent in Fig. 6. On these flux surfaces the ionization source is relatively weak because the low recycling at the limiter surface produces a relatively low neutral density in front of the limiter. As the ion flow accelerates to the sonic speed at the sheath near the limiter, the plasma density decreases to maintain parallel pressure balance. With the limiter tip at the separatrix, the peak plasma temperature at the limiter surface is 170 eV and the total ion particle flux on the limiter is about 150 kA, so impurity generation due to sputtering from the limiter could be a problem. The peak temperature could be reduced by starting up at lower power (less than 150 MW).

4. Summary

We have developed a capability for 2-D modeling of edge plasmas with localized limiter surfaces penetrating the SOL. The total power deposited on limiter and divertor surfaces is strongly dependent on the maximum penetration of the limiter, but is only weakly affected by changes in limiter shape. The peak heat flux on the limiter is reduced by tilting the limiter surface relative to the magnetic flux surfaces, but the total heat load on the limiter is nearly independent of the tilt for fixed limiter tip penetration. These results imply that ITER startup on an outer midplane limiter is reasonable because the total and peak heat loads can be controlled by the limiter positioning and shape. Particle pumping by the limiter induces strong radial gradients in the SOL plasma density and large ion currents from the core to the SOL. The limiter in these simulations was inserted at the outer midplane where most of the power enters the SOL from the core plasma; the relative distribution of this total power between limiter and divertor surfaces may be different if the limiter is inserted at the top or near the X-point because the magnetic connection lengths will be different.

Acknowledgements

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References

[1] T.D. Rognlien et al., Contr. Plasma Phys. 34 (1994) 362.
[2] R. Parker et al., J. Nucl. Mater. 241–243 (1997) 1.
[3] S.I. Braginskii, in: M.A. Leontovich (Ed.), Transport Processes in a Plasma, Reviews of Plasma Physics, Consultants Bureau, New York, 1965, p. 205.
[4] D. Knoll, Phys. Plasmas 3 (1996) 293.
[5] F. Wising et al., Contr. Plasma Phys. 36 (1996) 136.
[6] R.H. Cohen, D.D. Ryutov, Phys. Plasmas 2 (1995) 2011.