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Coupled Monte Carlo neutral – fluid plasma simulation of Alcator C-Mod divertor plasma near detachment

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Abstract

Using the coupled fluid plasma and Monte Carlo neutral transport code, B2-EIRENE, we simulate and analyze a nearly detached Alcator C-Mod discharge exhibiting the divertor over-pressure or "death ray" phenomenon. Qualitative agreement is obtained between the measured and simulated density and temperature profiles at the outboard midplane and divertor target. In the simulation, the divertor over-pressure is caused by radial transport of parallel momentum. Momentum transport by the neutral species is negligible. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

As the core electron density is raised in Alcator C-Mod, four regimes of divertor operation are observed: low-recycling, high-recycling, "death ray", and detachment [1]. These terms are used to characterize individual flux tubes, and more than one regime may be present at a time. The accompanying divertor temperatures are <10 eV in each of the last three cases so that hydrogen atoms and ions are coupled via charge exchange, elastic scattering, and recombination. Thus, the transport of both plasma and neutral species, hydrogen as well as impurities, must be examined in order to understand the plasma behavior in these regimes.

Although plasma models incorporating fluid [2] descriptions of neutral transport have had success in simulating high-recycling and even detached divertor plasmas, the death ray phenomenon pleads for a kinetic treatment. Death rays are radially localized spikes in which the total divertor pressure (isotropic plus dynamic) exceeds the upstream value. Neighboring flux tubes are in either the high-recycling or detached regimes with downstream to upstream total pressure ratios less than or comparable to unity. LaBombard [1] has proposed that as the divertor temperature falls through the 5–10 eV range, neutral atoms acquire parallel momentum from ions in the detached flux tubes near the separatrix, transport it radially to the hotter death ray region, and deposit that momentum there when they are ionized.

Coupled Monte Carlo neutral and fluid plasma transport codes similar to those used successfully elsewhere [3] have been employed to address this issue [4]. Loarte [5] briefly discussed these simulations and suggested that radial viscosity, not neutral transport, is the cause of the divertor over-pressure or death ray. In this paper, the simulations are described and examined in detail.

2. Description of experimental conditions

The Alcator C-Mod discharge used here, shot 950308012, is attractive for modeling as it exhibits at

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different times high recycling, death ray, and detached divertor behavior on the outboard side. We will focus on a time slice 0.78 s into the discharge which shows a prominent divertor over-pressure. The radial temperature and density profiles to be used as a benchmark for the simulations are taken from a fast scanning probe in the main scrape-off layer and domed probes in the divertor targets. The radial coordinate used in both locations is the distance outside the separatrix, ρ, of the flux surface mapped back to the midplane. A comparison of chord-integrated H_α measurements will also be made against an absolutely calibrated and toroidally localized array of detectors viewing the divertor. Many other points of contact between the simulation and the experimental data can be made, but will be deferred to a later paper so that we can focus on the nature of the death ray phenomenon.

3. Description of simulation

The B2-EIRENE [6,7] code package consists of a coupled 2-D fluid plasma neutral transport code, B2 [8,9], and a 3-D Monte Carlo neutral transport code, EIRENE [10]. The coupled system treats hydrogen as well as multiple charge state impurities.

The SONNET grid generation code, an integrated part of the B2-EIRENE system, is used to create a non-orthogonal 2-D plasma mesh based on the experimental equilibrium poloidal flux data obtained from the EFIT code. Non-orthogonalities appear as SONNET deforms the transverse (with flux surfaces remaining fixed) surfaces to conform to the vacuum vessel shape which is specified using the actual Alcator C-Mod geometry.

High density Alcator C-Mod discharges are dominated by deuterium, but usually contain some carbon. Because the resulting impurity radiation can be significant in the electron power balance, we have included carbon in these simulations, although their number density and their contribution to the electron density is small. In particular, the carbon in these simulations does not appear to play any role in the death ray phenomenon.

Classical parallel transport is assumed in the B2 code. Cross-field transport, however, is taken to be anomalous and is described here with constant diffusion and viscosity coefficients. Our baseline simulation uses a particle diffusion coefficient $D_\perp = 0.2$ m^2/s, and equal ion and electron energy transport coefficients $\chi_i = \chi_e = 0.01$ m^2/s. The coefficient of the perpendicular viscosity is set to $\eta_{\perp,a}/m_a n_a = 0.2$ m^2/s, where m_a and n_a are the mass and density of ion species a, respectively. The core plasma boundary condition, set 3 cm inside the separatrix, for the ion and electron energy equations is set up to provide a flow of 0.4 MW into each channel. A separatrix density of 10^{20} m^{-3} is maintained by a feedback mechanism. An albedo of 90% for deuterium is assumed at the inner and outer divertor targets; all other surfaces have a recycling coefficient of unity.

Fig. 1 shows the comparison between the measured and simulated temperature and density profiles. Both the upstream, taken at the outboard midplane, and divertor, at the outboard target, data are shown. The simulated upstream density matches the measurements very well. However, this agreement is partly ensured by the use of the separatrix density feedback. Otherwise, the match may be described as qualitative rather than quantitative. Further adjustments in the transport coefficients, recycling coefficients, and boundary conditions may lead to better agreement [4]. However, this simulation does exhibit a divertor over-pressure, Fig. 2, and is thus well-suited for the purpose of studying that phenomenon. Note that Fig. 2 shows the total pressure (isotropic plus dynamic).

The simulated and measured chord-integrated D_α signals are compared in Fig. 3. The radial coordinate is the major radius at which the detector chords cross the midplane. The left-hand portion of the axis corresponds to the inner divertor; the outer target is at $R_{\text{mid}} \simeq 0.7$ m. This discrepancy in the D_α data is reminiscent of previous work [11] and may be indicative of insufficient recombination in the simulation, as might be expected

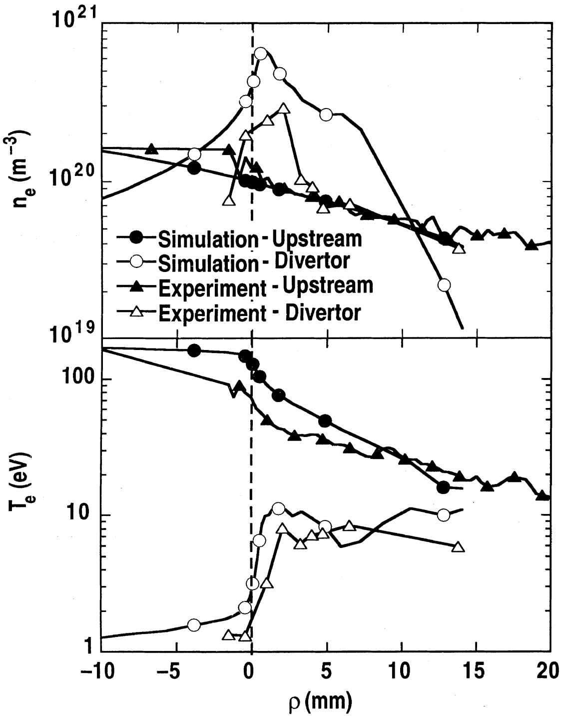

Fig. 1. Comparison of simulated and measured electron density and temperature at the outboard midplane ("upstream") and divertor.

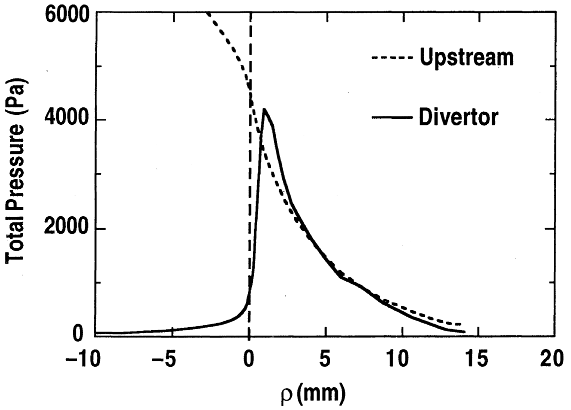

Fig. 2. Simulated total pressure (isotropic plus dynamic, summed over species) at the outboard midplane ("upstream") and divertor.

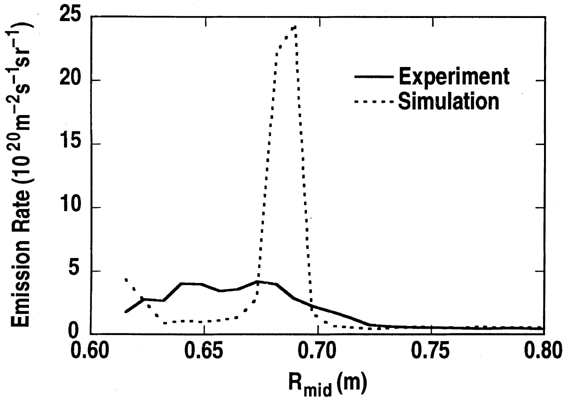

Fig. 3. Comparison of simulated and measured chord integrated D_α emission as seen by a divertor viewing detector array.

from the temperatures in Fig. 1. Because of the consequences for the neutral atom distribution, seeking conditions which better match or underestimate the divertor temperature should be a high priority for future parameter studies.

4. Investigation of the divertor over-pressure

The steady-state parallel momentum balance equation (e.g., see Ref. [9]) will be used as the basis for this investigation,

$$\begin{aligned}&\frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left(\frac{\sqrt{g}}{h_x}m_a n_a u_a u_{\|,a}-\frac{\sqrt{g}}{h_x^2}\eta_{\|,a}\frac{\partial u_{\|,a}}{\partial x}\right)\\&+\frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left(\frac{\sqrt{g}}{h_y}m_a n_a v_a u_{\|,a}-\frac{\sqrt{g}}{h_y^2}\eta_{\perp,a}\frac{\partial u_{\|,a}}{\partial y}\right)\\&=\frac{B_{\mathrm{pol}}}{B}\frac{1}{h_x}\left[-\frac{\partial p_a}{\partial x}-\frac{Z_a n_a}{n_e}\frac{\partial p_e}{\partial x}\right]+F_{\mathrm{th}}+F_{\mathrm{f}}+s_{mu_{\|},a},\end{aligned}\tag{1}$$

where a represents an ion species of mass m_a, density n_a, pressure $p_a\equiv n_aT_a$, parallel velocity $u_{\|,a}$, poloidal velocity $u_a=(B_{\mathrm{pol}}/B)u_{\|,a}$, diffusive radial velocity $v_a\equiv-\frac{D_\perp}{h_y}\frac{\partial}{\partial y}(\ln n_a)$, and charge Z_a. The equation is written for a general orthogonal mesh with radial coordinate y and poloidal coordinate x; the factors $\sqrt{g}$, h_x, and h_y are metric coefficients. The thermal force F_{th} and friction force F_{f} are negligible here, but will be retained for completeness. Furthermore, we will also ignore the carbon contributions to the pressure, and a will refer just to deuterium. The last term on the right-hand side is the momentum source due to neutrals.

We want to determine which terms in Eq. (1) are responsible for the divertor over-pressure. By integrating along the ith flux tube in the computational mesh from the outer midplane (upstream) $x=x_{\mathrm{up}}$ to the outer divertor target x_{div}, we can examine the transport of parallel momentum between flux tubes. In the absence of viscosity, neutral sources, radial gradients and poloidal variation of the metric coefficients, the result of this integration is that the total pressure is constant: $\Delta p_{\mathrm{tot}}=p_{\mathrm{tot}}(x_{\mathrm{div}})-p_{\mathrm{tot}}(x_{\mathrm{up}})=0$, where $p_{\mathrm{tot}}\equiv p_a+p_e+m_an_au_{\|,a}^2$. The divertor over-pressure corresponds to $\Delta p_{\mathrm{tot}}>0$.

The integral of Eq. (1) can be transformed into an expression for Δp_{tot}, but the result would contain terms involving the poloidal variation of the metric coefficients and the parallel viscosity which cannot be easily evaluated from the B2-EIRENE output data. Instead, we examine how the integrals of the perpendicular momentum flux,

$$S_\perp\equiv-\int_{x_{\mathrm{up}}}^{x_{\mathrm{div}}}\mathrm{d}x\,\Gamma_\perp\Bigg|_{y_i}^{y_{i+1}},\tag{2}$$

where

$$\Gamma_\perp\equiv\frac{\sqrt{g}}{h_y}m_an_av_au_{\|,a}-\frac{\sqrt{g}}{h_y^2}\eta_\perp\frac{\partial u_{\|,a}}{\partial y},\tag{3}$$

and the neutral source,

$$S_n\equiv-\int_{x_{\mathrm{up}}}^{x_{\mathrm{div}}}\mathrm{d}x\int_{y_i}^{y_{i+1}}\mathrm{d}y\,\sqrt{g}(F_{\mathrm{th}}+F_{\mathrm{f}}+s_{mu_{\|},a}),\tag{4}$$

for this simulation differ from those obtained from a run with $\Delta p_{\mathrm{tot}}\leqslant 0$. The overall signs used in Eqs. (2) and (4) have been chosen so that larger $S_\perp$ and S_n correspond to larger Δp_{tot}.

A simulation without the over-pressure can be obtained by reducing the recycling coefficient to 0.8. The resulting density and pressure profiles are shown in Fig. 4. The radial variation of Eqs. (2)–(4) for the baseline ("DR" for death ray) and low recycling ("No DR") runs are compared in Fig. 5 along with the values of Δp_{tot}.

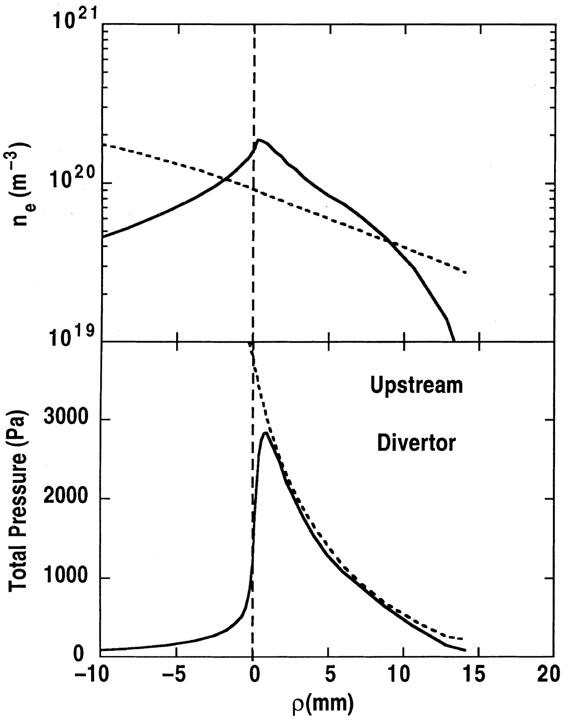

Fig. 4. Simulated total pressure and electron density at the outboard midplane ("upstream") and divertor in a run with a recycling coefficient of 0.8.

LaBombard [1] has suggested that the neutral momentum source S_n is responsible for the divertor over-pressure seen in the experimental data. However, Fig. 5(c) shows that S_n is smaller in the baseline simulation than in the low recycling run over most of the region where $\Delta p_{\mathrm{tot}} > 0$ and, thus, cannot be the cause of the over-pressure. A lower temperature solution, especially one with significant recombination, would provide a broader neutral distribution and might yield a neutral momentum source of the sort described in Ref. [1].

The perpendicular flux term $S_\perp$, however, is larger in the baseline simulation than in the low recycling case at those ρ for which $\Delta p_{\mathrm{tot}} > 0$, indicating that the divertor over-pressure arises from the radial transport of parallel momentum by the plasma. The values of $S_\perp$ and $\Gamma_\perp$ suggest that in the reduced recycling case parallel momentum is collected over the region $0 < \rho < 4$ mm (Fig. 5) and deposited in the private flux region ($\rho < 0$). The radial variation of $\Gamma_\perp$ is strikingly similar in the baseline case, except over $1 < \rho < 2$ mm where parallel momentum is deposited, roughly corresponding to the location of the divertor over-pressure. Note that S_n, the parallel viscosity, and the metric coefficients all contribute in detail to the values of Δp_{tot} obtained by B2-EIRENE and shown in Fig. 5. By itself, $S_\perp > 0$ is not a necessary or sufficient condition for $\Delta p_{\mathrm{tot}} > 0$.

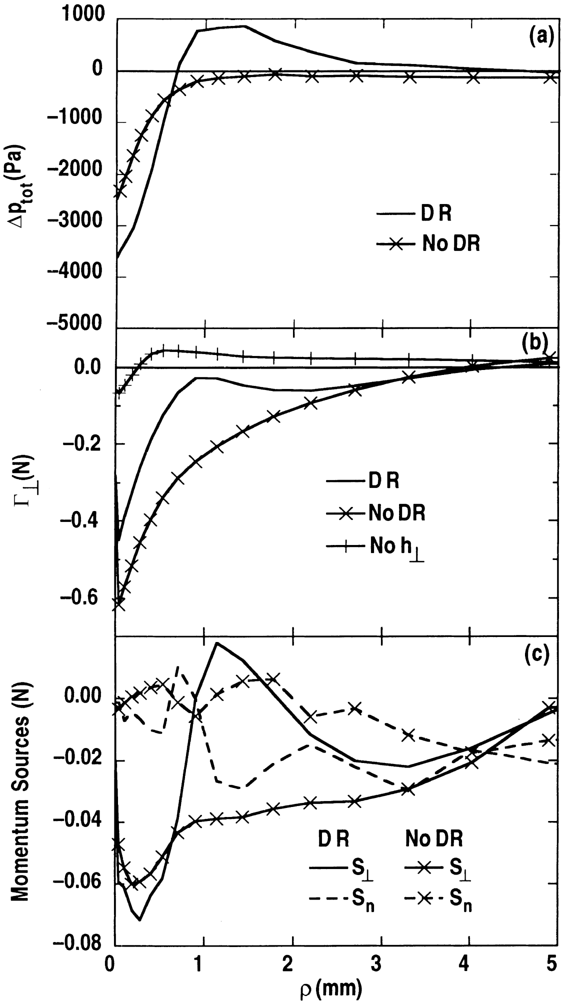

Fig. 5. Radial profiles of (a) divertor-midplane pressure difference, (b) perpendicular flux of parallel momentum, and (c) momentum sources due to perpendicular flux ($S_\perp$) and to neutrals (S_n). The values for the baseline (DR) and reduced recycling (No DR) runs are shown in each frame. The perpendicular flux from the zero viscosity run (No $\eta_\perp$) run is displayed in (b).

Loarte [5] suggested that the radial viscosity term in $\Gamma_\perp$ is responsible for the divertor over-pressure. To test this hypothesis, we reduce the perpendicular viscosity coefficient from $\eta_{\perp,a}/m_a n_a = 0.2$ m^2/s to zero. The steady-state simulation which results has a Δp_{tot} profile nearly identical to that of the baseline run. Rather than immediately concluding that the perpendicular convection of the parallel momentum (first term in Eq. (3)) is the cause of the over-pressure, we compare the value of $\Gamma_\perp$ with those obtained from the other two runs (Fig. 5(b)). Whereas the baseline and reduced recycling simulations indicate radially inward transport of parallel momentum, the zero viscosity case shows mostly *outward* transport since the radial and parallel velocities are both positive over most of the outboard divertor and scrape-off layer (SOL).

The qualitative differences in the $\Gamma_\perp$ profiles of the baseline and zero viscosity simulations, contrasted with the existence of some similarities in the baseline and reduced recycling $\Gamma_\perp$, suggests that the perpendicular viscosity is an important ingredient in the baseline and reduced recycling runs. To understand the death ray, then, we should attempt to explain the differences in the viscosity contributions to $\Gamma_\perp$ in these two simulations.

The radial density profiles in the outer SOL above the X-point are relatively broad (a scale length of $\sim$10 mm; total width of the computational SOL = 15 mm). As a result the parallel *particle* flux $n_a u_{\|,a}$ peaks toward the outer edge of the SOL in both simulations as the X-point is approached from above. The magnitude of the flux in the reduced recycling case, however, is larger by about a factor of 2 to balance (i.e., to maintain steady state) its greater particle loss rate at the target.

Continuing along the flux surfaces into the divertor region, a particle source (from ionization of neutrals) peaking along the separatrix gives rise via the continuity equation to a steady increase in $n_a u_{\|,a}$ with distance below the X-point. In the baseline case, these sources are significant, and the radial profile of $n_a u_{\|,a}$ develops a strong local peak near the separatrix as the target plate is approached. The smaller sources in the reduced recycling run do not substantially alter the $n_a u_{\|,a}$ profile, and it remains peaked well away from the separatrix.

The radial variation of $u_{\|,a}$ can then be understood by considering the density profiles (Figs. 1 and 4). In the reduced recycling run, $n_a u_{\|,a}$ peaks at a radius where the density is considerably smaller than its maximum value, so that the $u_{\|,a}$ profile increases strongly with radius. Consequently, the negative contribution made by the viscosity term to $\Gamma_\perp$ dominates the convection term. The net result is a predominantly inward transport of $u_{\|,a}$ into the private flux region.

The density profile in the baseline simulation peaks near the separatrix as does $n_a u_{\|,a}$. Thus, the $u_{\|,a}$ radial profile has a more complicated variation and is nonmonotonic for some values of the poloidal coordinate x. The $\Gamma_\perp$ shown in Fig. 5 is the balance between a smaller (still negative on the whole) viscosity contribution and the positive convection term (comparable to $\Gamma_\perp$ in the $\eta_\perp = 0$ case).

In summary, the higher recycling coefficient in the baseline simulation contributes to the formation of the over-pressure (1) by reducing the net ion current entering the divertor and (2) by increasing the ionization source along the separatrix. The magnitude of the latter is likely to be influenced by the geometry of the divertor.

5. Discussion

Recent observations and modeling [12] indicate that main chamber recycling is the dominant source of particles to the Alcator C-Mod core plasma. Although the details of this recycling are difficult to model because of nonaxisymmetric structures, our simulations do match the upstream density profiles well and do display significant recycling at a toroidally symmetric outer wall. In both the experiment and the simulations, however, the plasma velocities above the X-point are relatively small (Mach number <0.3) [1] so that the momentum exchange between the plasma and recycled neutrals in this region is negligible.

LaBombard [1] noted that the experimentally observed death ray is fixed in position and persists indefinitely as the plasma conditions are held constant. Since our simulations exhibiting the divertor over-pressure are steady-state, they are consistent with that characteristic.

A sweep of the strike point over a distance of 6 mm along the divertor surface demonstrated that the death ray held its position relative to the separatrix (i.e., 1–2 mm away from it) [1]. Our simulations do show a close relationship between the plasma – surface interactions near the separatrix and the divertor over-pressure, as would be consistent with this experimental observation.

Another experimental characteristic of the death ray is that it occurs on a flux surface with a target temperature which is >6 eV; this surface is always hotter than neighboring surfaces [1]. The first priority for future simulations would be to seek parameters which yield lower divertor temperatures and a death ray. Not only would such conditions better match the experimental data, they would also be conducive to increasing the role of the neutrals in the simulation and perhaps in the formation of the death ray. In the present work, the neutral species do not appear to be significant.

6. Conclusions

Using the coupled fluid plasma and Monte Carlo neutral transport code, B2-EIRENE, we have simulated and analyzed a nearly detached Alcator C-Mod discharge exhibiting the divertor over-pressure or death ray phenomenon. Qualitative agreement has been obtained between the measured and simulated outboard midplane and divertor density and temperature profiles. A low recycling (coefficient = 0.8) run does not display the over-pressure, but does have significant radially inward transport of parallel momentum. In the baseline simulation (recycling coefficient = 0.9), this momentum builds up at the radii corresponding to the over-pressure due to a combination of smaller (inward) transport by the viscosity and outward convection. The simulated electron temperatures are too high for the neutral species to carry out the momentum transport required to support the over-pressure [1]. Measurements of flow velocities in the divertor well above the target plate, would be useful in determining the experimental importance of radial transport of the parallel momentum by the plasma.

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