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Recycling impurity compression in Alcator C-mod divertor

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Abstract

Impurity retention is a key role of a divertor in a tokamak. One of the measurements of retention performance is the impurity compression ratio c_z, defined as the ratio of the impurity neutral density in the divertor to the impurity ion density in the core plasma. DIVIMP Monte-Carlo modeling of argon recycling impurity compression in C-Mod has been performed to explore the physics behind impurity compression. It is found that the frictional force is dominant over the temperature gradient forces in determining the impurity compression in C-Mod divertor.

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Keywords: Alcator C-Mod; Recycling impurity; Impurity compression

1. Introduction

Impurities will inevitably be present in a fusion reactor and will affect the operating conditions. High impurity concentrations deteriorate energy confinement in the core, while they can reduce the power flux on targets via radiated power. Impurity control is accordingly required to retain impurities in the divertor region (away from the core plasma).

One of the measures of retention performance of divertor is the impurity compression ratio c_z. We define c_z as the ratio of impurity neutral density in the divertor, n_0^{div}, to the impurity ion density in the core plasma, n_z^{core} as

$$c_z = \frac{n_0^{\mathrm{div}}}{n_z^{\mathrm{core}}}. \tag{1}$$

In a simple picture, there are two competing factors in determining c_z: impurity penetration into the core plasma and impurity neutral accumulation in the divertor plenum. The ionization mean-free path of the impurity neutral recycling on targets and walls and the impurity ion radial transport in SOL affect closely the core penetration. The background plasma force parallel to the field and the divertor structure are related mainly to the neutral concentration in the plenum.

The DIVIMP [1] Monte-Carlo code developed at the University of Toronto is used to explore the physics of impurity compression in the Alcator C-Mod divertor. The modeling has been performed on C-Mod divertor bypass discharges in Ohmic L-modes [2].

2. Experimental measurements

A cross-section of the Alcator C-Mod vacuum chamber with the unique divertor bypass [3] structure is given in Fig. 1. Impurity ion density in core is estimated with combined methods of HIREX measurements and MIST code calculation [4]. The RGA system connected to the divertor plenum measures the impurity neutral density [5]. The gas leakage from the plenum into the main chamber is controlled by divertor bypass. In

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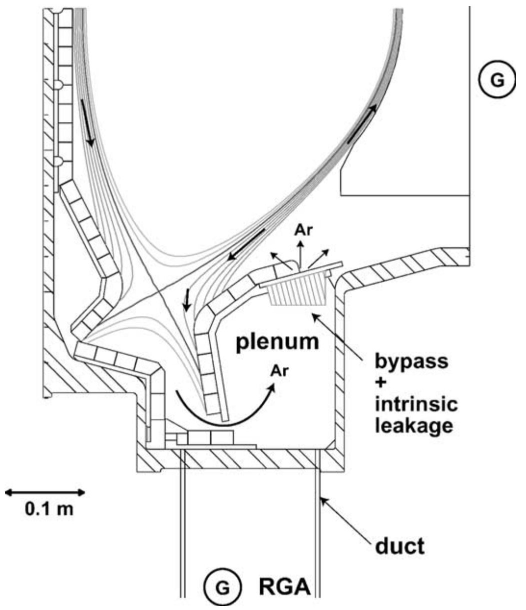

Fig. 1. Cross-section of the Alcator C-Mod divertor with bypass structure. Conceptual illustration of Ar impurity transport is made.

addition, there is intrinsic gas leakage through the gap between the divertor structure and the wall. With the measured impurity ion density in core plasma ($n_z^{\rm core}$) and the impurity neutral density in divertor plenum ($n_0^{\rm div}$), the impurity compression ratio is estimated in Eq. (1). This figure is used as the measurement of impurity retention performance of divertor.

3. DIVIMP code

DIVIMP follows individual impurity particles launched in a given background plasma and calculates steady state 2D distributions of impurity density and temperature in a Monte-Carlo way (Ch. 6 in Ref. [6]). The background plasma used in this work is calculated independantly by a solver based on 2P-OSM method (Ch. 11 in Ref. [6]) and is specified as input. The plasma solution in the solver is constrained by a number of experimental measurements (e.g. probe measurements at midplane and targets, D_α, D_γ signals in the divertor, and Stark broadening measurements for PFZ plasma). DIVIMP extracts data for atomic processes from the ADAS database [7]. The compuational grid for C-Mod is shown in Fig. 2. Impurity neutrals are launched initially at a point in the main chamber and move freely in space until they are ionized. Then spatial displacement of impurity ion both for parallel and perpendicular to the field is calculated as follows

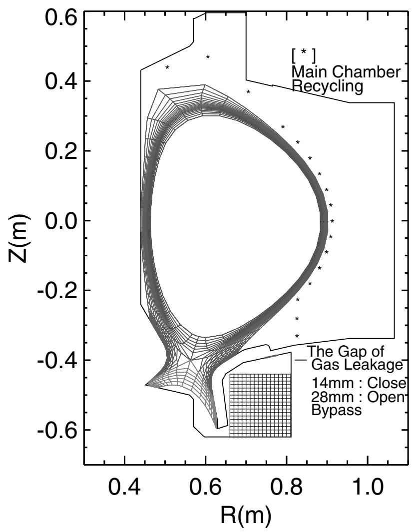

Fig. 2. DIVIMP grid for a typical equilibrium magnetic field in C-Mod. The gas leakage is implemented with an equivalent gap width. The impurity ions are relaunched as neturals at designated points in main chamber.

- Parallel

$$\delta s_\parallel = \frac{1}{2}\left\{ v_{\rm th}\left(\frac{2\delta t}{\tau_\parallel}\right)^{1/2} + \frac{v_p - v_z}{\tau_s} + \frac{1}{m_z}(ZeE + \alpha_e \nabla T_e + \beta_i \nabla T_i)\right\}\delta t^2, \qquad (2)$$

- Perpendicular

$$\delta s_\perp = \pm\sqrt{2D_\perp \delta t}, \qquad (3)$$

where δt is a computational time step (0.08 μs) and τ_s, $\tau_\parallel$ are Spitzer's stopping time and parallel diffusion time for impurity ions, respectively. The first term in RHS of Eq. (2) represents the parallel diffusion equivalent to the pressure gradient force (Ch. 6 in Ref. [6]), the second term is the frictional force, the third is the electric field force and the last two terms are the temperature gradient forces. $D_\perp$ is a parameter to simulate anomalous perpendicular transport of impurity ion.

4. Modeling results

The interpretation of the result is divided into two parts: impurity neutral transport and impurity ion transport resulting in impurity compression in C-Mod.

4.1. Gas leakage and impurity shielding by the plasma

Fig. 3 shows both the experimental and modeling results for the argon compression and its trend for various Ohmic L-mode discharges in C-Mod.

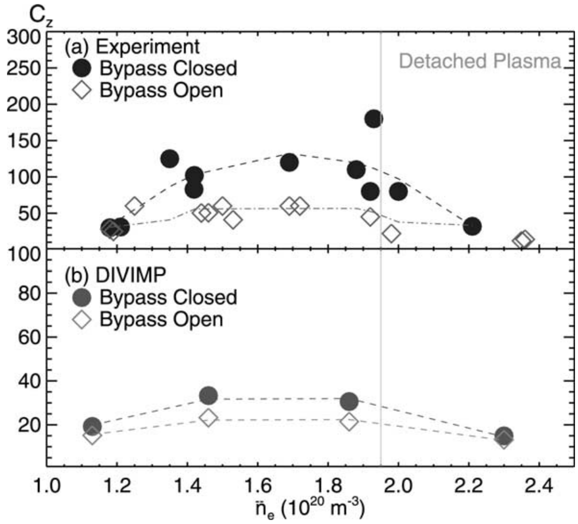

Fig. 3. c_z changes as plasma conditions vary in discharges: c_z increases as plasma density increases then drops at detached plasma. The open bypass reduces c_z. Modeling results in c_z are lower than experiments by a factor of 2–3.

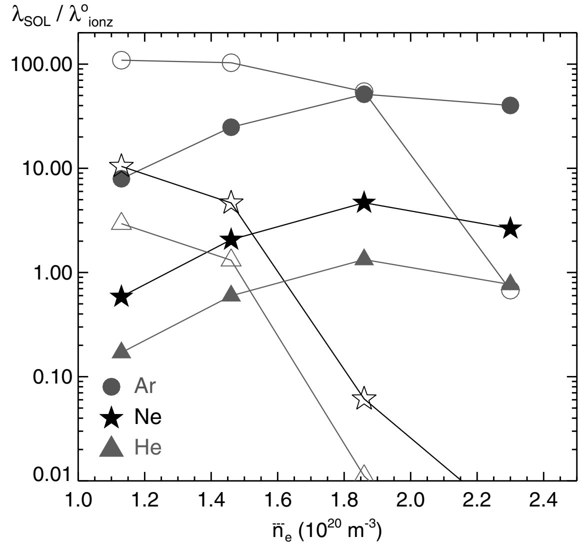

Fig. 4. DIVIMP calculation of impurity shielding factor in the outboard midplane and target ($\bar{n}_e = 1.46 \times 10^{20}$ m^{-3}). The open symbols represent target values and closed symbols represent midplane values.

The argon impurity compression increases as the plasma density increases and then drops in detachment regime at the highest plasma density. The modeling indicates that the changes in plasma conditions (n_e and T_e) changes the impurity shielding by plasma. The impurity shielding can be estimated by a shielding factor, S_0, defined in this paper as the ratio of the width of local SOL (at the midplane or in the divertor), λ_{SOL}, to the impurity neutral ionization mean-free path, $\lambda^o_{\mathrm{ionz}}$,

$$S_0 = \frac{\lambda_{\mathrm{SOL}}}{\lambda^o_{\mathrm{ionz}}}. \tag{4}$$

As the density increases within the modest range (below the detachment regime), $\lambda^o_{\mathrm{ionz}}$ at the midplane decreases more rapidly than $\lambda^o_{\mathrm{ionz}}$ at the plate increases. Therefore, S_0 for argon impurity increases. On the other hand, at the highest density, $\lambda^o_{\mathrm{ionz}}$ at target plates decreases very rapidly due to the low plasma temperature there. In this case the impurity penetration into core from the divertor region becomes substantial and causes c_z to drop for detached plasmas ($T_e \leqslant 1$ eV). The variation of S_0 at the outboard midplane and target plates is plotted in Fig. 4. The typical value of λ_{SOL} is $\sim$1 cm at the midplane and $\sim$4 cm at the target. Note that for the same plasma condition, heavier impurities are screened more effectively. This modeling analysis is consistent with the observation and argumentations made that lighter impurities have lower c_z values [5].

The divertor open bypass reduces the measured c_z by a factor of $\sim$2 as it reduces the neutral density in the divertor plenum (by a factor of $\sim$1.5) by opening the leakage path to the main chamber and increases the ion density in the core plasma (by a factor of $\sim$1.2) by providing a path for impurity neutrals to enter the SOL and then to the core plasma from the plenum. The modeling results are qualitatively similar to the experiments. The differences in magnitude between the experiments and the modeling could be explained by the assumption used in this modeling – toroidal symmetry of the plenum pressure and the calculation of leakage conductance strictly based on free molecular flow [8].

In DIVIMP, c_z is estimated based on an assumption that the impurity neutral pressure in the plenum is toroidally symmetric. However, the real divertor and bypass structure in C-Mod has a number of structures which breaks this symmetry; namely, a number of gaps which increase the conductance between the plenum and main chamber exist, so called, in *open ports* used for the diagnostics accesses. Otherwise the ports are closed with no diagnostics connections and have no gaps (called *closed ports*). In addition, there are structures which impede the flow of gas in the plenum in the toroidal direction. The experimental c_z that is measured in a closed port, therefore, has a higher value than the modeling one. Recent experiments have found the evidence of substantial asymmetries in the plenum gas pressure in C-Mod [9]. Those same experiments also indicate that the divertor leakage conductance may be lower than assumed. Both lower average pressures and lower leakage conductances would bring the modeling c_z closer to experiment. Fig. 5 shows how the correction made on the plenum pressure measured in experiment changes c_z to be closer to the modeling. Although the

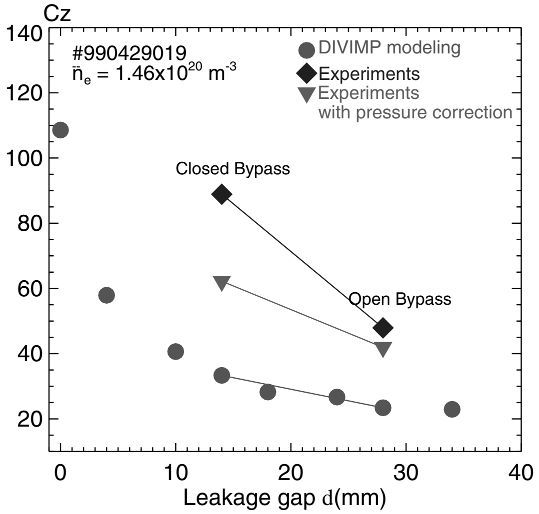

Fig. 5. Comparison of c_z for short #990429019 ($\bar{n}_e = 1.46 \times 10^{20}$ m^{-3}). The leakage gaps of 14 mm for closed bypass and 28 mm for open bypass in the modeling are estimated to correspond to the equivalent area to leakage conductance of free molecular in C-Mod divertor [8]. The correction made on the plenum gas pressure measured reduces the magnitude differences in c_z between the modeling and experiments.

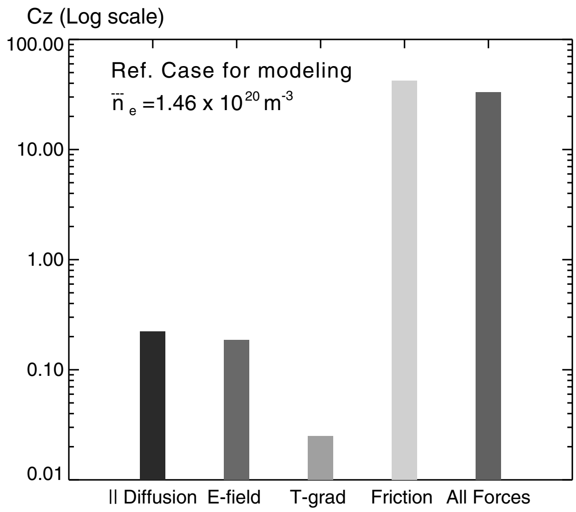

Fig. 6. DIVIMP calculates and compares the effect of each force on c_z for argon. Among the competing forces the frictional force is dominant over the ∇T forces in determining c_z.

pressure corrections have been made, the magnitude difference still remains. The remaining quantitative discrepancy may be associated with the lack of precise description of radial transport in DIVIMP. For example, cross-field transport of ions are determined only by the diffusion (in Eq. (3)) which omits the possibility of radially outward transport of ions. The study of cross-field transport in DIVIMP remains as the future work.

4.2. Plasma flow and frictional force

With respect to forces acting on the impurity ions in the divertor plasma, DIVIMP modeling indicates that the frictional force is dominant over the temperature gradient forces in determining c_z. The contribution of each force to c_z is compared in Fig. 6. The frictional force due to plasma flow parallel to the field drives impurity ions toward the targets and enhances the impurity retention in the divertor (an exception to this occurs in regions where flow reversal is present). Opposing this is the temperature gradient force that drives impurity ions away from the targets and therefore increases the probability that the impurity ions will reach the core, thereby reducing c_z. Shown in Fig. 6 is that the frictional force is dominant over the temperature gradient force in determining c_z. One may estimate the ratio of the frictional force (the second term of RHS of Eq. (2)) to the temperature gradient force (the last two terms of RHS of Eq. (2)) in the divertor region (near the X-point). For example, the typical parameters of plasma flow velocity of $v_p \simeq 0.2$ (Ma) and the temperature gradient of $\nabla T \simeq 11$ eV/m result in the ratio of ~ 10 ($v_z = 0$ and $T_e = T_i$ assumed).

One would expect c_z to increase monotonically as one increases the plasma flow. On the contrary, however, DIVIMP modeling indicates that the frictional force due to parallel plasma flow does not increase c_z linearly. Fig. 7 shows the variation of c_z as plasma flow varies. c_z for argon follows the flow change within the modest range

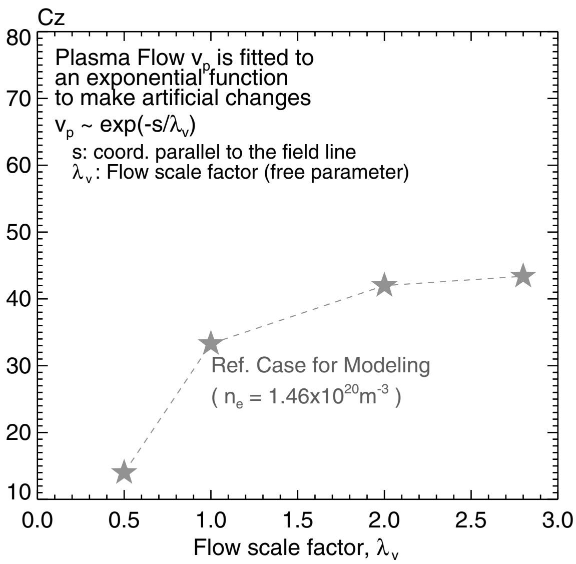

Fig. 7. The effect of frictional forces due to parallel plasma flow on c_z. Frictional force (or plasma flow) is effective in increasing argon c_z linearly in the modest flow regime.

(in this range the flow stagnation point locates far below the outboard midplane).

5. Summary

The qualitative behavior of c_z has been reproduced by the DIVIMP code. Absolute agreement is to within a factor of 2–3, with modeling underestimating the experiment c_z values. The potential explanations to the discrepancies are the overestimation of leakage conductance and the assumption of toroidal symmetry of plenum gas pressure in modeling. On the other hand, the recent studies [10,11] suggest that the radially outward transport of impurity ion which is omitted in current modeling should be considered, which remains as the future work.

Recycling impurity compression in C-Mod is in general high ($c_z \geqslant 100$ for argon) at modest densities, and reduces at lower density and higer density (detachment). This trend is explained by the change of impurity neutral screening by the plasma. At lower density, the impurity screening is poor at the midplane. At detachment, the cold divertor condition reduces the impurity screening significantly at the target plates.

The code demonstrates the importance of friction in retaining impurity in the divertor. With respect to forces acting on impurity ions in the divertor plasma, the frictional force parallel to the field is dominant over the temperature gradient force and enhances impurity retention. Outside of the divertor, the cross-field penetration by the impurity is a factor determining c_z.

Acknowledgements

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