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Modeling of Alcator C-Mod divertor baffling experiments

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Abstract

A specific Alcator C-Mod discharge from the series of divertor baffling experiments is simulated with the DEGAS 2 Monte Carlo neutral transport code. A simple two-point plasma model is used to describe the plasma variation between Langmuir probe locations. A range of conductances for the bypass between the divertor plenum and the main chamber are considered. The experimentally observed insensitivity of the neutral current flowing through the bypass and of the D_α emissions to the magnitude of the conductance is reproduced. The current of atoms in this regime is being limited by atomic physics processes and not bypass conductance. The simulated trends in divertor pressure, bypass current, and D_α emission agree only qualitatively with the experimental measurements, however. Possible explanations for the quantitative differences are discussed.

Keywords: Alcator C-Mod; DEGAS code; Neutral gas modeling

1. Introduction

Experiments on Alcator C-Mod have directly addressed the effectiveness of divertor baffling on plasma performance. A bypass in Alcator C-Mod can be opened and closed to essentially double the gas conductance between the divertor plenum and the main chamber in as little as 20 ms. A principal result of these experiments is that opening the bypass leads to a reduction by factor of two in divertor neutral pressure [1]. The current flowing through the bypass from the divertor to the main chamber is thus inferred to remain constant. Even more surprisingly, the plasma parameters, D_α emissions, global energy confinement and H-mode power threshold, do not change significantly either.

The conclusion drawn is significant and surprising: the Alcator C-Mod divertor effectively operates as if it were an open divertor [1]. Simple qualitative arguments and a one-dimensional model [2] lead to a hypothesized explanation. Establishing the validity of these arguments requires an examination of the experiments with a more complete, quantitative model.

Analysis of the neutral transport behavior can be carried out with a fixed plasma since the experimental result is that the plasma does not respond to changes in bypass conductance. The extensive diagnostic set present on Alcator C-Mod permits the plasma parameters to be specified almost entirely by direct experimental measurements.

A detailed representation of the geometry of the problem is required to adequately model the conductances of the pathways between the divertor and main chamber. The neutral species must be treated kinetically to correctly reproduce momentum exchanges between the plasma, atoms, and molecules, at least in the vicinity of the plasma. Even in vacuum regions, the mean free paths of the neutral species may be long enough to invalidate a fluid treatment. Only a Monte Carlo neutral transport code like DEGAS 2 [3] can incorporate this physics and the details of the geometry into a practical simulation.

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2. Experimental data

The complete set of ohmic discharges used in the divertor baffling experiments has been described in [1]. For this paper, we focus on a single discharge in the high recycling regime having a line average density $\bar{n}_e = 1.46 \times 10^{20}$ m^{-3}. With the bypass closed, the pressure in the divertor plenum measured by an absolute capacitance pressure gauge is 30 mTorr. With the bypass open, a pressure of 15 mTorr is measured. Upstream plasma conditions are obtained from fast-scanning Langmuir–Mach probes at midplane and divertor throat. Fixed Langmuir probes in the target provide the plasma density and temperatures there as well as the ion fluxes striking the target. We will also make comparisons with an array of divertor-viewing D_α detectors.

The plasma density and temperature over the entire volume must be specified as input to DEGAS 2. For high recycling plasma conditions, the variation of the plasma parameters between the probe locations can be obtained using a simple, one-dimensional 'two-point' model [4]. The plasma pressure is taken to be constant (at the value obtained from the midplane probe) along flux surfaces. The pressure drop between this value and the one measured by the target probes is assumed to occur over a small distance representative of the neutral deuterium recycling region. The plasma pressure on surfaces in the private flux region is varied smoothly between the values measured on the inner and outer targets. For the purpose of modeling with DEGAS 2, we take $n_e = n_i$ and $T_e = T_i$.

An ad hoc source of deuterium molecules is specified in the DEGAS 2 model to simulate recycling on limiter surfaces in the main chamber [5]. The strength of this source is set equal to the random thermal flux corresponding to the measured main chamber neutral pressure of 0.15 mTorr. The plasma density in regions outside the volume treated with the two-point model is computed using an exponential radial fall-off length of 4 cm. The temperature at these locations is assumed to be radially constant at the value obtained from the two-point model.

3. Description of simulation

The geometry used in DEGAS 2 is built up from a simple outline of the vacuum vessel, including the divertor plenum and RF limiter, and an equilibrium computed for the Alcator C-Mod shot and time of interest. A two-dimensional plasma mesh of the sort used by fluid plasma codes is established using the DG and CARRE packages [6]. The resulting hardware elements and the plasma mesh are loaded into a DEGAS 2 preprocessor as a set of polygons covering the entire problem space. Larger polygons such as those comprising solid and vacuum regions are broken up into triangles [7]. Each of the triangles and quadrilaterals comprising the vacuum and plasma regions is assigned a unique 'zone' number for bookkeeping use by DEGAS 2. The end result of the preprocessor is DEGAS 2's internal description of the toroidally symmetric geometry in terms of quadratic surfaces [3].

The geometry for this series of simulations is shown in Fig. 1. The region labeled 'duct' is intended to rep-

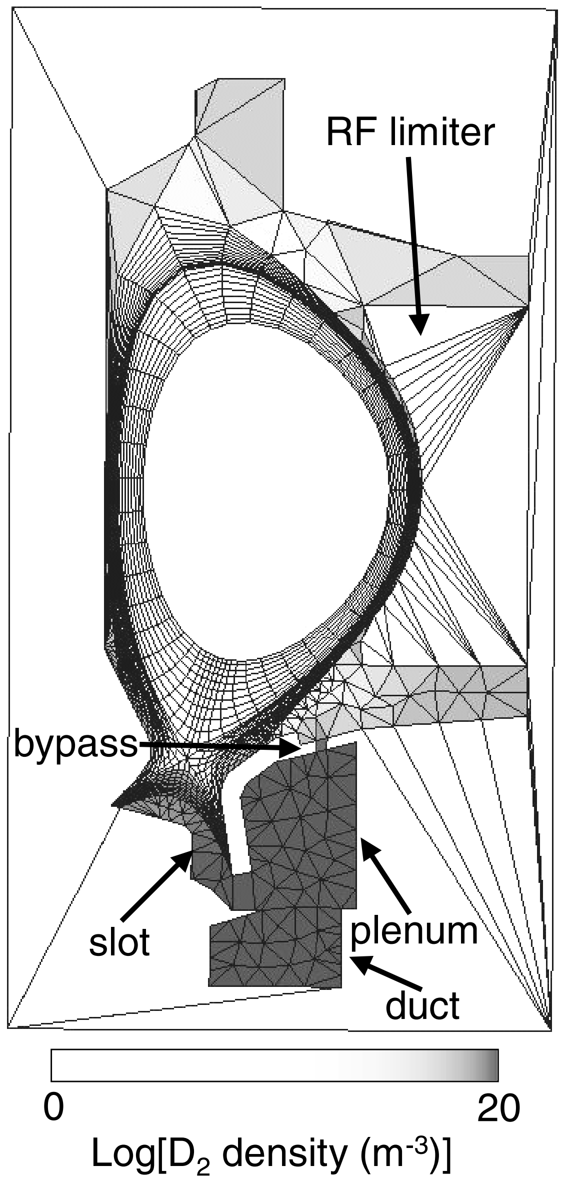

Fig. 1. Computational geometry used in DEGAS 2. The log of the molecular density from the run with $w = 16$ mm is plotted in the plasma and vacuum region. The triangulation of the solid regions is done only to facilitate definition of the geometry.

resent a series of 10 vertical ports around the torus. The actual three-dimensional conductance between the divertor slot, these ducts and the plenum will differ from the axisymmetric conductance represented by this geometry. However, the qualitative behavior of our results should not be affected.

The width of the bypass region will be varied. A width of 16 mm and a toroidally integrated area of 0.075 m^2 correspond to the leakage conductance which persists even with the bypass closed [1]. Having the bypass open provides another 0.075 m^2 of area, modeled here as a gap 32 mm wide. Gap widths of 0, 8, and 64 mm will also be considered to establish trends over a wider range of conductances than are available experimentally. The case with no gap corresponds to the ideal of a completely closed divertor. All hardware surfaces are assumed to be molybdenum for the purpose of treating atom and ion reflection. Typical reflection coefficients are between 0.5 and 0.6. Nonreflected atoms and ions are assumed to thermally desorb as molecules.

A collisional-radiative model is used to obtain the multi-step deuterium ionization and recombination rates [8,9]. The collision cross-sections used in the model were taken from [10]. The collisional-radiative model assumes that the divertor plasma is optically thin. However, the absorption of Lyman series lines in the divertor will quantitatively alter the ionization balance [11]. A subsequent paper will use an escape factor formalism (see, e.g., [11]) to assess the magnitude of the effect of opacity on these results. The rates and kinetic treatment of molecular dissociation and ionization are described in [12]. Balmer-α photons arising from the dissociation process are not significant in these simulations and are not included.

Scattering of deuterium atoms and molecules off deuterium ions is treated using differential cross-sections calculated using state-of-the-art quantum mechanical techniques [13]. The interaction between deuterium atoms and ions incorporates both classically identifiable charge exchange and elastic scattering channels. For computational efficiency, a minimum scattering angle is enforced with a constraint that the momentum transport cross-section be unaltered [14]. The differential scattering is handled using cumulative probability tables for the cosine of the scattering angle [14,15].

A simple, iterative, BGK treatment of neutral–neutral elastic scattering is used [14,16,17]. For the observed pressures, the ratio of the neutral–neutral mean free path relative to a typical length scale, the Knudsen number, can be as low as $\sim$0.01 for molecules in the plenum and >1 for atoms in the divertor slot. If the Knudsen number were smaller than 0.01 everywhere (the so-called 'viscous flow' regime), a fluid treatment of the neutral transport would suffice. If it were well above 1 everywhere ('molecular flow' regime), we could neglect the neutral–neutral collisions in the Monte Carlo treatment. The transitional conditions occurring in this problem demand a nonlinear kinetic treatment similar to the one being used here. Run times for a single DEGAS 2 iteration are of the order of a few minutes on a cluster of 18 PC processors [18]. A few to several iterations are required for the neutral distribution to converge.

4. Results

Fig. 2(a) shows the variation of the plenum pressure and bypass current with the width of the bypass, w. The current of neutrals through the bypass is a small fraction of the ion recycling current at the outer target,

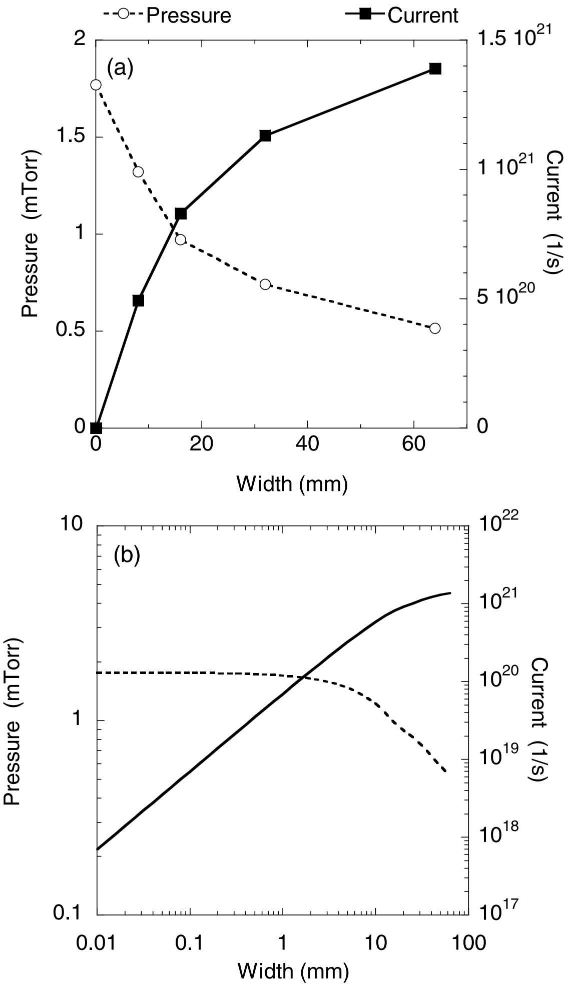

Fig. 2. Simulated plenum pressure (left scale, dashed line) and equivalent neutral atom current through the bypass (right scale, solid line) plotted as a function of the bypass width w. The actual data are indicated by the points in (a). These curves are linearly interpolated onto a finer scale for w and then replotted on a log–log scale (b).

$1.60 \times 10^{22}\ s^{-1}$, even with the largest bypass width. The simulated main chamber neutral pressures are of the order of 0.1 mTorr and are thus comparable to the measured values.

The D_α emission from the runs with $w = 0$ and $w = 64$ mm are compared with the experimental values in Fig. 3. The difference between the two simulated results is difficult to discern. The main reason for this is that the signal is dominated by emissions well away from the divertor slot, the region most affected by changes in the bypass. Secondly, the total number of atoms passing through the bypass in these simulations is small compared to the total atom current in the problem.

The plenum pressures in Fig. 2 are roughly an order of magnitude smaller than the measured values. The baseline curves in Fig. 3 are a factor of 3–10 smaller than the experimental results. No clear explanation exists for these discrepancies. The possibility of misinterpretation of the target probe fluxes must be discounted since those fluxes match well the corresponding upstream measurements. There are no reasons to suspect the Langmuir probes to be off by more than a factor of two. An earlier attempt at computing a divertor neutral particle balance in Alcator C-Mod encountered similar difficulties in reconciling these diagnostic signals [19].

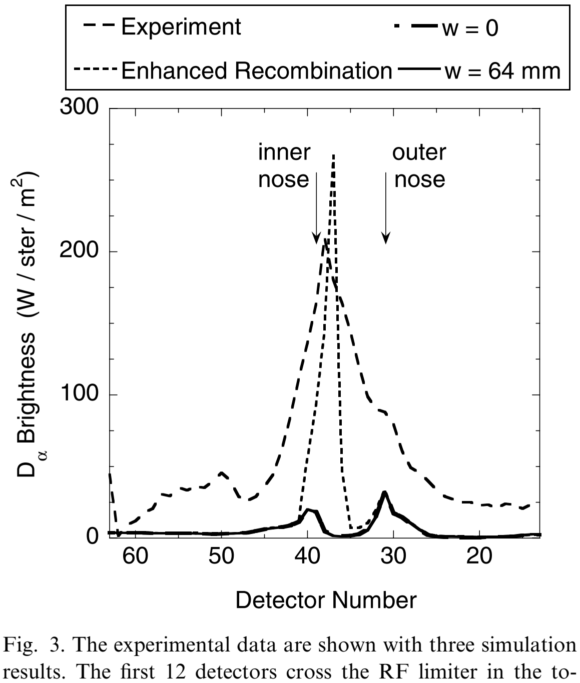

Fig. 3. The experimental data are shown with three simulation results. The first 12 detectors cross the RF limiter in the toroidally symmetric DEGAS 2 simulation, but not in the experiment, and, thus, cannot be directly compared with the measurements. The chord numbers progress from larger major radius to smaller. The detectors viewing the inner and outer divertor noses are labeled. The innermost detector strikes the inner limiter near midplane. In addition to the two baseline simulation results having bypass widths $w = 0$ and $w = 64$ mm, a third result that incorporates enhanced private flux region recombination is included to demonstrate its effect on the D_α emission.

Larger recombination rates in the private flux region may be partially responsible. Tomographic reconstruction of the D_γ emission indicates much more recombination than is predicted with this simple plasma model. The D_γ emission peaks in the private flux region between the inner target and the X-point. To assess the impact of recombination of this magnitude on the plenum pressure, we manually lower the plasma temperature and increase the plasma density in the private flux region and near the inner target in an attempt to reproduce this peak. The resulting recombination current is comparable to the outer target current. The simulated D_α signal reproduces a central peaking behavior (Fig. 3) similar to that seen in the experiment. Conceivably, most or all of the remaining D_α discrepancy can be eliminated by inclusion of an appropriate amount of recombination.

The addition of the recombination in this case raises the plenum pressure from 0.97 mTorr ('closed' bypass case) to 1.88 mTorr, still well below the measured value of 30 mTorr. No similar attempt has been made to force better agreement of the simulated and measured D_γ/recombination away from the peak region. Smaller, but perhaps significant, emissions are indicated throughout the private flux region. In particular, recombined neutrals created near the outer target may make larger contributions to the plenum pressure than those generated near the D_γ peak.

The plenum pressure and D_α discrepancies may also arise in part from the approximate treatment of the recycling region in the plasma model [4]. The size of this region and the magnitude of the plasma density peak are only estimated. Errors in these values could overemphasize ionization of neutral atoms and molecules near the target, preventing them from making contributions to the plenum pressure and/or the D_α signal. To establish the magnitude of the effect, we examine a series of runs in which the plasma densities and temperatures are everywhere capped at $1 \times 10^{20}\ m^{-3}$ and 4 eV, respectively. The results are qualitatively similar to those of Figs. 2 and 3. The plenum pressures and bypass currents are roughly a factor of two larger. The effect on the D_α signal is smaller. The ion source rate computed by DEGAS 2 could be used in an iterative process to specify the plasma variation in these regions.

The observed high plenum pressures must arise in part as the result of elastic scattering collisions that transfer momentum between the atoms and molecules in the slot [2]. Errors in the implementation or algorithm used for the neutral–neutral scattering could be contributing to the discrepancy. An initial sensitivity test has been performed in which the target fluxes are artificially increased by a factor of 10, resulting in a plenum pressure of 12.5 mTorr. Turning off neutral–neutral scattering results in a drop to 6.3 mTorr, confirming that these reactions are having a significant effect in the simulations. Additionally removing ion–molecule elastic scattering causes it to decrease to 5.4 mTorr. Nonetheless, detailed tests confirming the accuracy of the treatment of neutral–neutral scattering must still be done.

5. Conclusions

The experimental results [1] indicate that opening and closing the bypass strongly affects divertor neutral pressure. The current through the bypass, estimated as the product of the plenum pressure and the conductance, is insensitive to the state of the bypass. Moreover, the plasma conditions in the divertor and the D_α emissions do not change significantly.

The principal result of this paper is the qualitative reproduction of these trends with a sophisticated kinetic neutral transport code under the assumption of constant plasma conditions. The insensitivity of the current through the bypass to the width of the bypass indicates that some other process is limiting the flow of neutral atoms and molecules between the divertor target and the bypass. From an experimental design point of view, the conclusion is that the divertor is effectively open, even with the bypass closed.

Pitcher et al. [2] propose a simple one-dimensional model that yields these same qualitative tendencies. To facilitate comparisons with Fig. 7 of [2], we linearly interpolate the data of Fig. 2(a) onto a finer mesh of w values and replot on a log–log scale in Fig. 2(b). The experimentally relevant 'flux-limited' regime arises for $w \gtrsim 10$ mm. The magnitude of the bypass current represents a competition between ionization in the divertor and escape to the main chamber via the bypass. As the bypass widens, the likelihood of escape to the main chamber increases. For a sufficiently wide gap, atomic physics processes (principally ionization and elastic scattering) limit the escaping current, and the curve begins to turn over, as in Fig. 2. Other geometric factors neither varied here nor included in the model of Pitcher et al. [2] also play a role in determining the limiting current. The 'conductance-limited' regime [2], characterized by a nearly linear variation of the bypass current with w and relatively insensitive plenum pressures, occurs for $w < 10$ mm.

Subsequent work will focus on reducing the quantitative differences between the experimental and simulated pressures. A method of combining the D_γ measurements with the probe data to describe recombination in the private flux region plasma will be investigated. In addition, more sophisticated plasma models, including two-dimensional fluid plasma codes could be incorporated into the simulations.

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