Fusion Technology

ISSN: 0748-1896 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/ufst19

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To cite this article: D. N. Ruzic & D. B. Hayden (1997) Momentum and Energy Transfer Via Neutral Atoms and Molecules in an International Thermonuclear Experimental Reactor Low-Pressure (10-mTorr) Gas Target Divertor, Fusion Technology, 31:2, 123-127, DOI: 10.13182/FST97-A30814

To link to this article: https://doi.org/10.13182/FST97-A30814

Published online: 09 May 2017.

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MOMENTUM AND ENERGY TRANSFER VIA NEUTRAL ATOMS AND MOLECULES IN AN INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR LOW-PRESSURE (10-mTorr) GAS TARGET DIVERTOR

DIVERTOR SYSTEMS

KEYWORDS: *gas target, Monte Carlo modeling, ITER*

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Received August 11, 1995
Accepted for Publication July 16, 1996

One option for particle and power handling in the International Thermonuclear Experimental Reactor (ITER) is the creation of a low-pressure (~10-mTorr) gaseous divertor. The divertor would have a long channel over which energy would be removed from the plasma by radiation, and the plasma pressure would be balanced by a change in flow velocities and neutral pressures entering the sides of the channel. This combination should substantially reduce the ion energy and ion flux that impact the eventual end of the divertor channel. For this concept to work, momentum must be removed from the plasma by the neutral atoms and molecules. Plasma parameters were taken from a DDC83 code solution. A Monte Carlo treatment of the plasma-neutral interactions has been obtained using DEGAS, which includes charge-exchange, recombination, ion-neutral, and neutral-neutral elastic collisions. Results show that the momentum transferred to the side walls is insufficient by two orders of magnitude to achieve the pressure reduction needed. Each molecule that enters the plasma makes hundreds of elastic and inelastic collisions in the plasma and then is more likely to be ionized (transferring the momentum back to the plasma) than to travel to a wall.

INTRODUCTION

The International Thermonuclear Experimental Reactor[1] (ITER) divertor is required to handle 300 MW of power from particles flowing along the field lines without causing serious erosion of the divertor target plates or contaminating the core plasma. One proposed solution is a gaseous divertor in which the electron temperature drops to less than a few electron volts at all the walls. This may be accomplished by designing a long, closed channel in the divertor. Power could be conserved by introducing impurities such as neon, which will radiate to the walls. Momentum (pressure) could be conserved by either a high neutral pressure (several Torr) or the transfer of the momentum across field lines to the side walls via charge-exchange and elastic-scattering events.

A number of edge plasma fluid codes have been used to predict the electron and ion temperatures, densities, and flow rates in such a divertor. In many of these codes, neutrals are also treated as fluids—an incorrect assumption. Neutrals exist both as molecules and atoms, have a varying mean free path for a number of interactions, and have a very non-Maxwellian energy and flow distribution due to Franck-Condon dissociation, wall reflection, and recombination. As a result of these discrete events, Monte Carlo solutions of the neutral atoms and molecules are often considered a more accurate representation. This paper uses the DEGAS 62.9+ code. It is the latest version of DEGAS (Ref. 2), which includes an updated atomic physics package that is valid down to 0.1 eV and contains the ion-neutral and neutral-neutral elastic collision routines from DEGAS+ (Ref. 3).

A companion paper using DEGAS+ models a PLANET (Ref. 4) plasma solution for the high (10-Torr) neutral pressure regime.[5] The Monte Carlo results show that an order of magnitude lower neutral pressure was all that was needed and that the ion and neutral flux to the side walls near the entrance of the divertor throat was excessive.

The lower pressure solution that relies on momentum transfer to the side walls to account for pressure balance was also modeled using DEGAS+. A plasma from the high neutral pressure regime was used since no independent plasma solution existed at the time.[6] It was found that little momentum transfer to the louvered side wall structures occurred and that the efficacy of a stable low-pressure plasma solution may be in doubt. However, the plasma used was not necessarily consistent with the lowered neutral density.

In this paper, a consistent fluid plasma solution for the low-pressure dynamic gas target divertor was utilized as an input.[7] To detail the effect of momentum transfer to the walls, a variable width divertor was simulated. Momentum transfer from the plasma (or the lack thereof) is computed, analyzed, and explained.

MODEL

The grid for the calculation was the same as used in the DDC83 fluid code.[8] It includes Monte Carlo neutral atoms and molecules but does not explicitly account for elastic collisions. The outer divertor is simulated as a 50-cm-wide slot, wrapped toroidally around the machine the connection length of the field lines. Our work uses the 2-m-long poloidal projection of this geometry but maintains the toroidal and poloidal plasma flow rates. Neutrals are followed in all three dimensions. Three widths were simulated—the standard 50-cm-wide channel and two runs with closer walls at 25 and 13 cm. All of these runs had the same plasma conditions. The ability of the neutral atoms and molecules to transfer momentum a variable distance away from the plasma is compared.

Figure 1 illustrates the three wall locations. Figures 2 and 3 show the electron temperature and density from the fluid code in the simulated region. The flame front is extinguished approximately one-third of the way down the divertor channel. The ion density is equal to the electron density, and the ion temperature is very close to that of the electrons.

The source of neutrals for this simulation is a louvered or open gas box that would supply a uniform molecular pressure of 10 mTorr. Accordingly, neutral molecules at 700 K are randomly launched from the sides of the box. These neutral molecules are tracked by DEGAS+ until they are ionized. Once a molecule is dissociated into an atom, possible collisions include charge exchange, elastic scattering from ions, and elastic scattering from neutral molecules.

Since the molecular density is both a result and a necessary input, the results of the code must be iterated. However, the molecular density varies little over the simulated region, and atom-molecule collisions are rare in comparison to the other simulated collisions. Therefore, one iteration sufficed.

RESULTS

Figure 4 shows a typical flight from the Monte Carlo DEGAS 62.9+ run for the 50-cm-wide channel. While the particle remains a molecule, it travels in a straight line. Once it becomes an atom, the flight path deviates by predominantly small-angle collisions during the elastic-scattering events and large-angle collision during charge exchange. It is also these charge-exchange and elastic collisions with the ions that impart a net flow velocity and energy transfer to the atoms and, as envisioned, eventually to the walls.

Examination of the figure, however, shows that the number of charge-exchange collisions dwarfs the number of wall collisions for a given flight. Since the statistical weight of the particle is decreased by the ionization probability at each step, an atom that does eventually

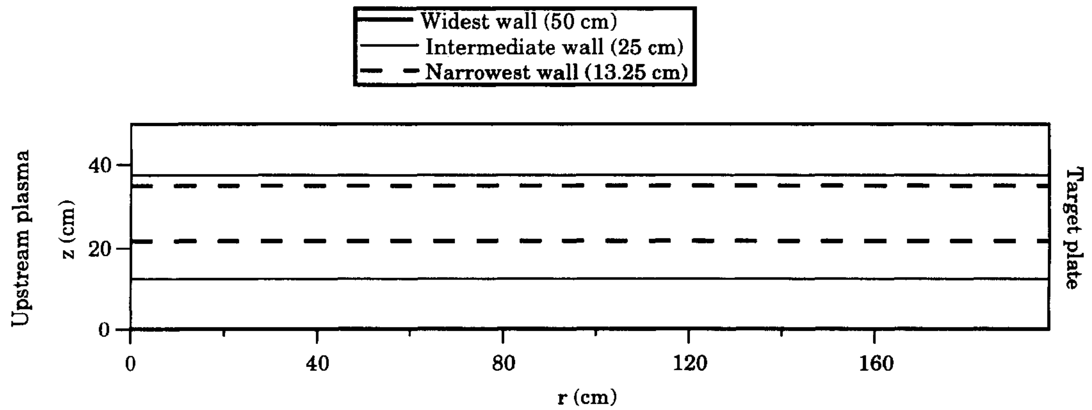

Fig. 1. The model geometry with the three simulated wall locations.

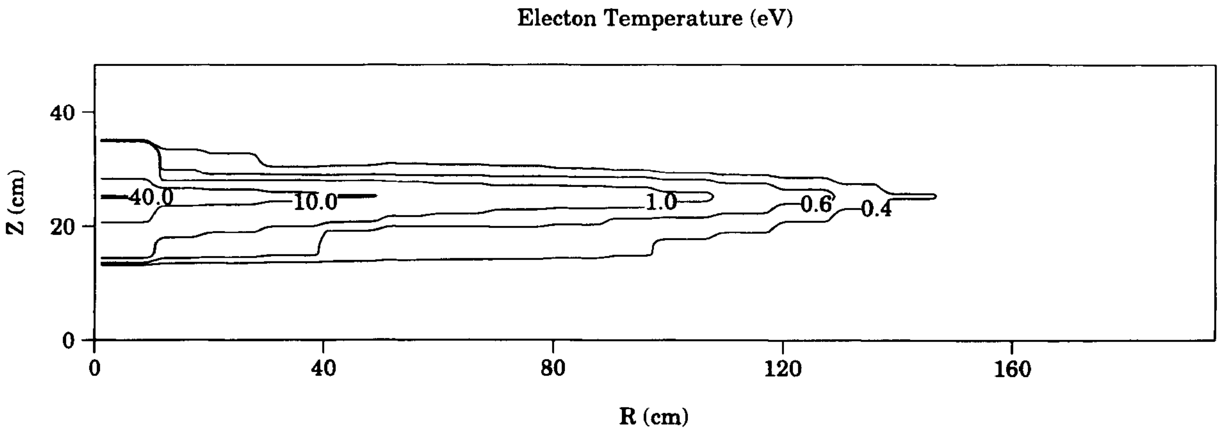

Fig. 2. Electron temperature in the divertor channel.

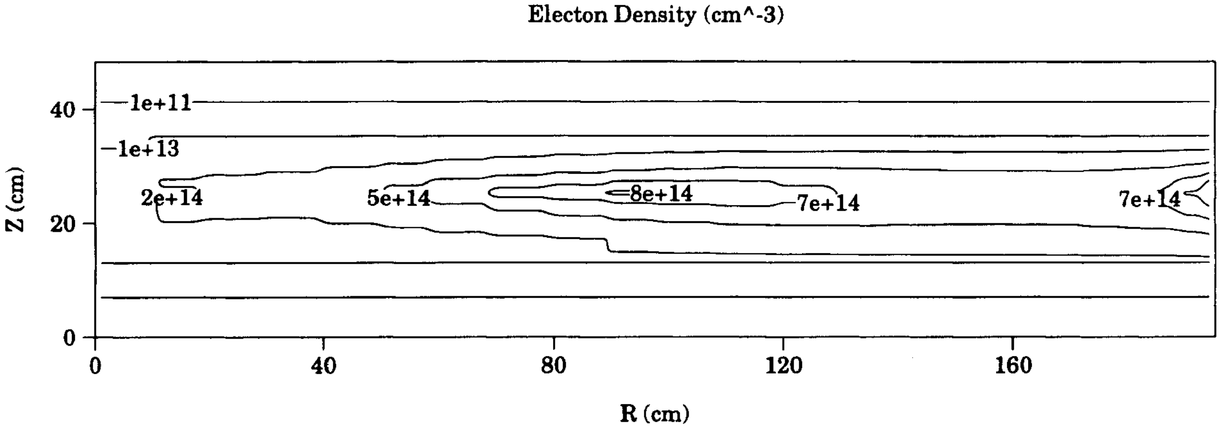

Fig. 3. Electron density in the divertor channel. Note that the density peaks in the center and drops about four orders of magnitude toward the side walls (the top and bottom of the plot).

strike the wall and imparts momentum to it is only a shadow of its former self.

The cross section for ionization and for charge exchange (Fig. 5) explains the phenomenon. Neutral atoms born at the 4- to 5-eV Franck-Condon energy from molecular dissociation have a relatively constant chance of charge exchange and a very small (<1 cm) mean free path. Although the ion flow is toward a region of lower temperature, the sheer number of collisions within the plasma and the Maxwellian tail of the electron energy distribution make an ionization event much more likely than the removal of the atom from the plasma stream and its impact on the wall. The presence of the elastic collisions with molecules just serves to further hinder the atoms' progress to the wall.

TABLE I

Statistical Collision Data per Flight for the DEGAS 62.9+ Computer Runs

Type of Collision	Channel Width		
	50 cm	25 cm	13.25 cm
Ionizations	1000	1000	1000
Charge exchanges	1634	5180	4570
Ion-neutral elastic	706	1648	1501
Molecule-n elastic	77	137	114
Wall collisions	3.8	6.9	16.0

Table I shows the statistical results per flight for each of the three widths. There are always 1000 ionizations per flight since the minimum weight is set at 0.001. The statistics are equivalent to launching 1000 particles from the same spot and allowing an ionization to terminate a flight.

As expected, moving the wall closer to the plasma increases the number of wall collisions per ionization event. The number of charge-exchange and elastic collisions

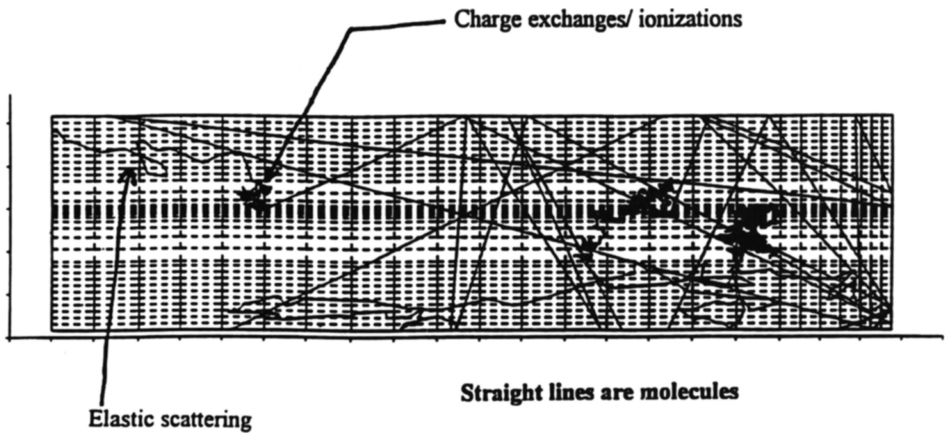

Fig. 4. A typical DEGAS 62.9+ neutral flight.

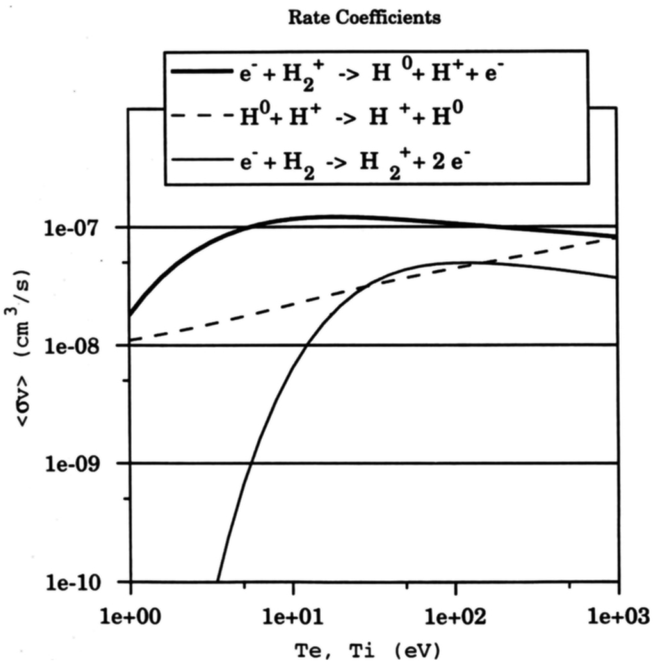

Fig. 5. Rate coefficient for charge exchange and ionization of molecules and atoms.[9]

TABLE II

Momentum Flux to the Walls for the Three Different Widths

Momentum Flux to Walls (mTorr)	Channel Width		
	50 cm	25 cm	13.25 cm
From atoms	0.9	2.0	3.7
From molecules	11.7	18.9	32.4

increases as well since the particles that do exit the hotter part of the plasma can return after a wall collision. The drop in charge-exchange and elastic collisions for the narrowest width is likely due to a competing effect between being returned to the hotter plasma where collisions can occur and spending proportionately more time in the hottest region where ionization is most likely.

Table II shows the momentum flux, which is equivalent to pressure since $mv\Gamma = nkT$, transferred to the side walls. If there were no plasma present, the momentum transfer (pressure) to the walls from the molecules would be 10.0 mTorr, and the momentum transfer to the walls from atoms would be zero. By comparison, the starting plasma pressure at the opening of the divertor channel from an electron temperature of 50 eV and density of 10^{20} m^{-3} is ~10 000 mTorr. The narrowest channel is effective at raising the temperature (and therefore the pressure) of the molecules by a factor of 3 due to the elastic collisions. However, it still falls short of anything near the 10-Torr pressure drop envisioned for the dynamic gas target divertor. Diffusive momentum transfer through molecules is insufficient to account for the required momentum loss.

DISCUSSION

Moving the walls closer to the plasma flame front succeeds in transferring more momentum to the side walls but still falls short of transferring a significant fraction of the plasma's momentum. A closer channel has the drawback of increasing the number of ion sputtering events at the side wall as well as increasing the energy deposition to a localized area.

The Monte Carlo neutral code's inability to show the existence of sufficient momentum transfer calls into question the very existence of a low-pressure unattached dynamic gas target divertor solution. In the fluid codes, the neutrals are also treated as a fluid and retain their equilibrated ion temperature all the way to the wall in a diffusive manner. In other Monte Carlo codes, viscous effects with the molecules are assumed instead of calculated. This paper shows that upon more careful examination, the neutrals are reionized, and they redeposit that momentum in the plasma rather than carry it to the boundary structures. As shown by moving the boundaries closer, momentum transfer is increased. An attached plasma, at least on one side, may be necessary to provide a momentum sink that allows a stable ionization front to exist in a low-pressure (10-mTorr) gas target divertor.

ACKNOWLEDGMENTS

This work was supported by U.S. Department of Energy ITER Physics contract DEFG02-89-ER52159 and NERSC computer time.

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