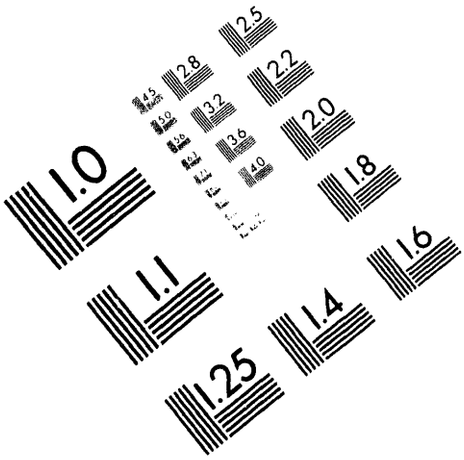

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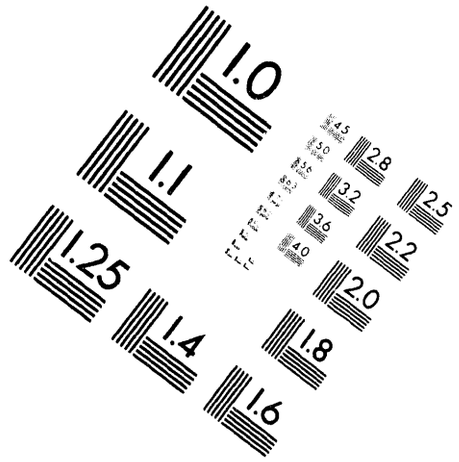

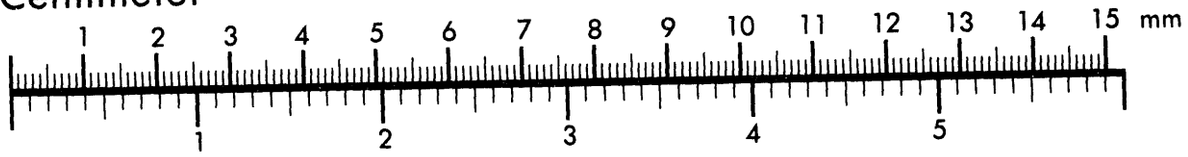

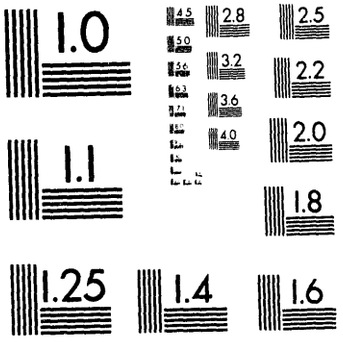

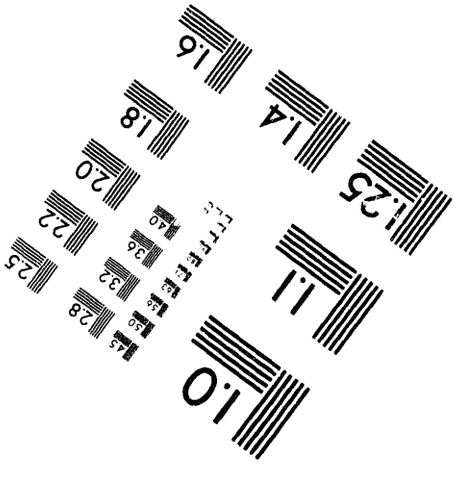

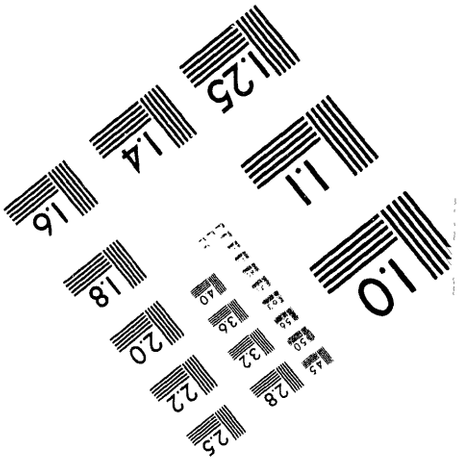

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EXPERIMENTAL MEASUREMENTS AND MODELING OF IMPURITY TRANSPORT IN THE DIVERTOR AND BOUNDARY PLASMA OF DIII–D

by

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EXPERIMENTAL MEASUREMENTS AND MODELING OF IMPURITY TRANSPORT IN THE DIVERTOR AND BOUNDARY PLASMA OF DIII–D*

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Analysis of trace impurity injection experiments on DIII–D during a beam power scan is presented. Spectroscopic measurements indicate that as beam power is increased, and concomitantly ELM frequency and scrape-off-layer thickness increase while energy confinement decreases, the core impurity content decreases only slightly. Modeling of the edge plasma using the UEDGE 2D and NEWT1D plasma fluid codes indicate that as beam power is increased, the parallel forces on an impurity ion increase in the direction from the divertor and toward the core plasma. Experiments using the divertor cryopump to induce higher parallel particle flow toward the divertor demonstrate significant reduction in core impurity content. These results indicate that parallel forces on impurity ions in the scrape off layer are playing a significant role in core impurity content.

Introduction

Containment of impurities within the divertor of a tokamak has long been an important issue, since the large heat and particle flux to the divertor plates naturally generates large impurity influxes which would be deleterious to the core plasma. With the recent effort to demonstrate the ability to actively reduce and control the heat flux to the divertor plates, in order to demonstrate realistic operating scenarios for the next generation long pulse tokamaks, there is renewed interest in impurity containment. This interest is focused on containment of impurities which are intentionally injected in order to enhance radiated power in the divertor and thus reduce the heat flux carried along field lines to the divertor plate. Since the real need for heat flux reduction is in long pulse and/or steady state operation, injection of recycling impurities, such as rare gases, is needed. The purpose of this paper is to briefly examine some experiments on DIII–D in which trace levels of rare gas impurities were puffed into the plasma, and through modeling to examine the various transport mechanisms that were contributing to the observed impurity core content.

The ability to maintain a high concentration of a recycling impurity in the divertor while maintaining low core plasma impurity levels is related to a number of transport mechanisms. The primary mechanism in the scrape off layer (SOL) that keeps the impurity ions from migrating back to the core plasma is the flow of the background plasma toward the divertor plate. Working against the flow is the thermal gradient force.[1] For recycling impurities, the flight of neutrals in the tenuous plasma region between the SOL and the vacuum wall is also important. When the neutral impacts the SOL plasma, the mean free path for ionization is important. Once an ion has reached the core plasma, it will remain there until is diffuses back to the SOL or is expelled by an ELM.[2] The distribution of the impurity within the divertor and core plasma will thus be determined by these various transport mechanisms.

Experiment

To begin exploring this important physics area on DIII–D, an experimental run was carried out in which a trace amount of argon or neon was injected into steady ELMing H–mode discharges. Parametric scans of beam power, plasma current, and toroidal field strength were conducted on a shot to shot basis. Spectroscopic measurements of line emission from the core plasma using the SPRED VUV instrument in the wavelength range of 100 to 1100 Å provided information on the core content of argon and neon. In the case of neon, charge exchange emission from a neutral heating beam which crosses the SPRED viewing cord near the central axis was observed. By modulating the neutral beam, and modeling its attenuation,[3] accurate core neon densities could be obtained. With argon, such charge exchange emission was not observed and core densities are obtained

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with the aid of modeling using the MIST transport code.[4] Electron density and temperature profiles of the core plasma, needed for the MIST modeling, are obtained using the multipulse Thomson scattering system. A six chord visible spectrometer (MDS),[5] with a spectral window of about 140 Å, setable from 3900 Å to 7100 Å views the divertor from above. The view chords are fixed in position, viewing 2 cm diameter spots placed at about 15 cm intervals across the floor of DIII–D from near the inner wall to beyond the typical outer strike point. This spectrometer was set to view emission from either ArII or NeII ions.

Here we will focus on the beam power scans with neon and argon injection. The effect on the core content for both species as a function of beam power is shown in Table 1. For both species, the core content is not observed to change dramatically with beam power. The neon content, which is derived from charge exchange emission, is more accurate than the argon content, which is obtained using emissivities derived from MIST. The neon data indicate some drop in core content as the beam power is increased. ArII line intensities as a function of beam power measured with MDS for two chords, one viewing through the vicinity of the X-point into the private flux region and one viewing near the outer strike point, are also given in Table 1. As beam power is increased, the ArII emission near the strike point does not change appreciably, indicating that the recycling of Ar at the plate is not affected by increasing beam power. However the emission from near the X-point drops dramatically as beam power increases, which reflects the fact that the electron temperature predicted by UEDGE[6] at the 1 cm flux surface begins to exceed the ionization potential of ArII near the X-point..

TABLE 1

Impurity	Beam Power (MW)	τ_E (ms)	Integral n_e Across SOL (a.u.)	ELM Frequency (Hz)	Core Impurity Density (a.u.)	MDS X-point (a.u.)	MDS OSP
Argon	4.6	165	4.2	30	0.83	230	315
	9.1	130	8.4	85	1.00	120	340
	13.2	100	12.4	220	1.01	50	340
Neon	7.0	190	8.4	45	1.15	190	88
	9.0	160	10.9	60	1.00	100	58
	13.5	110	13.3	215	0.88	30	73

Modeling

The UEDGE two dimensional fluid model and the NEWT1D[7] one dimensional fluid model have been used to investigate the effects of plasma flow and thermal gradient terms in the beam power scan. Both codes are based on the Braginski equations.[8] The UEDGE code input includes the power flux across the separatrix and the recycling coefficient at the plate. The electron and ion particle and thermal diffusivities are also inputs, and are adjusted until reasonable agreement is obtained with available midplane plasma data, such as Thomson scattering electron densities and temperatures and charge exchange spectroscopy ion temperatures just inside the separatrix and in the SOL. In previous work, the UEDGE results have been benchmarked against DIII–D discharges by comparing the resulting plasma density, temperature, and heat flux profiles against measured values. Best agreement is usually obtained when the ambipolar field is included in the model, and when an ad-hoc model for impurity radiation (constant carbon fraction of a few percent) is included. At the present time, UEDGE does not routinely include impurity transport, so the NEWT1D code was used to investigate impurity phenomena.

The predicted forces from the plasma flow and the thermal gradients along a flux tube lying about 6 mm outside the separatrix at the midplane for the 9.1 and 13.2 MW beam power discharges are shown in Fig. 1. These forces are calculated from the UEDGE predicted plasma following Neuhauser et al.[7] In this case, although the fluid flow is every where toward the plate, the ion thermal gradient force away from the plate becomes dominant just a few centimeters poloidally away from the plate. Impurity ions in this region will be forced toward the midplane, and thus toward the core plasma. As expected, this thermal gradient term is seen to increase as the beam heating power is increased. This effect can be dramatically illustrated using the NEWT1D code. In Fig 2, the predicted neon ion poloidal distribution is shown for two cases of trace impurity injection. In both cases the neon injection is very small, and the resulting background plasmas are essentially identical.

In case 1 the neon is injected into the divertor along a 1 cm long region just above the plate. The injection is assumed to be steady state and to achieve a steady state solution an impurity recycling coefficient at the plate of 0.985 is assumed. In the injection region the viscous force strongly dominates and essentially no neon is able

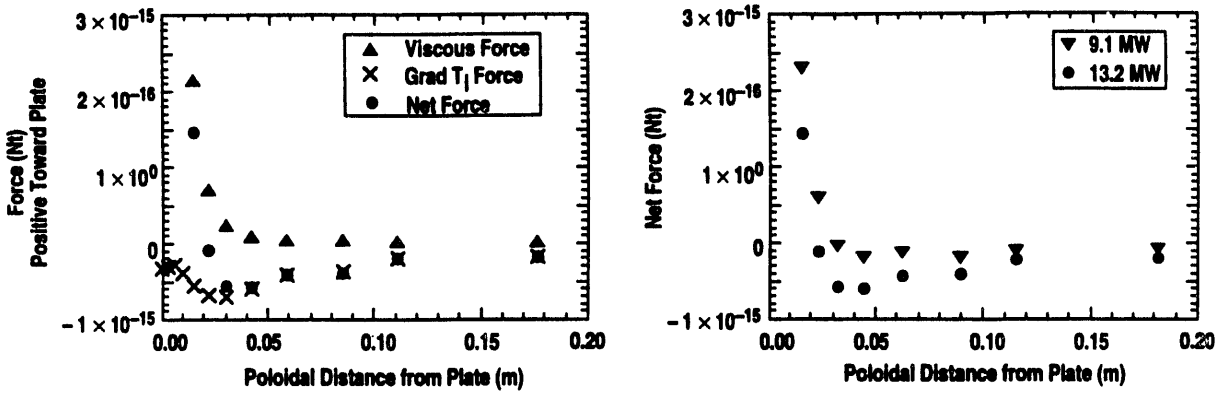

Fig. 1. The forces on a test ion (Ar+6) with zero velocity in the lab frame due to the plasma flow and thermal gradient terms are shown as a function of poloidal distance from the outer strike plate. On the left are the three most important terms using plasma parameters are obtained from the UEDGE code, for an injected beam power of 13.2 MW. On the right the net forces are shown for discharges with 13.2 and 9.1 MW of injected beam power.

of 0.985 is assumed. In the injection region the viscous force strongly dominates and essentially no neon is able to reach the SOL above the X-point. In case 2 the same neon throughput is injected along a 5 cm length poloidally above the plate. The injection reaches into the region where the thermal gradient force dominates, and a significant neon density is seen to build up above the X-point. In the open divertor configuration of DIII–D, normal recycling of neutral neon on the divertor plate should result in a significant flux of neutral neon reaching the divertor plasma a few centimeters above the plate, this net force away from the divertor and toward the core could be quite deleterious.

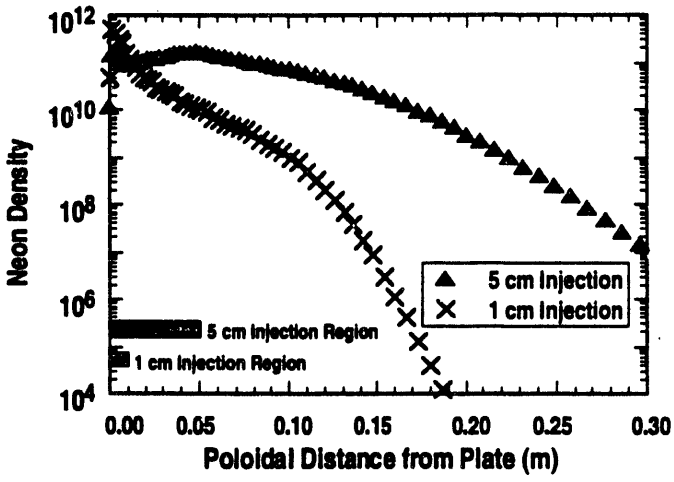

Fig. 2. Neon distribution along flux tube modeled using NEWT1D for plasma forces similar to those shown in Fig. 1(a). The circles are for injection of neon along a 1 cm distance just above the divertor plate, the crosses are for injection along a 5 cm distance above the plate.

Induced Flow Experiment

Direct experimental evidence has been produced on DIII–D that indicates a strong flow can be induced in the SOL and can keep the core plasma clean in the presence of a strong, steady argon puff.[9] A lower single-null configuration is used with a plasma current of 1.5 MA and neutral beam injection of 8.5 MW. In this case, the plasma is positioned such that a strong pumping condition is achieved with the cryopump which lies within a pumping plenum near the divertor floor at the outer wall. Deuterium can be steadily puffed in at the midplane and pumped at the outer strike point at a rate of 200 torr liters/s and a steady plasma density maintained. Simultaneously, argon can be puffed at the midplane, yet very little argon is observed in the core plasma with SPRED and little effect on radiated power is seen. Table 2 gives the observed core Ar content of four pumped discharges on DIII–D, with and without deuterium puffing and at two levels of Ar puffing. Also given is an effective Ar confinement time, given by the core plasma Ar content divided by the Ar puffing rate.

TABLE 2

	Case 1	Case 2	Case 3	Case 4
D_2 puff (torr-l/s)	200	0	200	0
$n_e(0)$ (10^{20} m^{-3})	1.0	0.7	1.0	0.7
Ar puff (torr-l/s)	0.5	0.5	1	1
Puff location	Divertor	Divertor	Midplane	Midplane
Central (r=0) Ar (10^{15} m^{-3})	2.9	56	20	190
τ_{Ar} (ms)	1	20	4	40

Using the plasma electron temperatures and densities from the UEDGE model as shown in Fig. 1, a rough estimate of the flow required to overcome the thermal gradient forces can be obtained by artificially increasing the plasma flow velocities until the viscous force toward the plate equals the temperature gradient forces away from the plate at a location just below the X-point. This adjusted flow can then be used to estimate the additional particle throughput required to provide a net force toward the plate. For this case an increased throughput of about 400 torr·l/s is required, in reasonable agreement with the experiment where 200 torr·l/s was observed to profoundly influence the core Ar content.

Discussion

The measurement of neon core plasma content during trace neon injection using charge exchange recombination radiation indicates that as beam power is increased (resulting in decreased core energy confinement time, increased ELM rate and a thicker SOL) the neon concentration in the core drops only slightly. Edge plasma modeling using both the UEGDE and NEWT1D codes indicates that the parallel ion temperature gradient from the divertor plate to the midplane is sufficiently strong to overcome the viscous drag and results in a net force on an impurity ion driving it toward the midplane (except very near the plate). As beam power is increased, the ion temperature gradient also increases, and may be limiting the beneficial effects discussed above. Using the cryopump on DIII–D, direct experimental evidence has been obtained that increased particle flow can reduce significantly the core argon content during argon injection experiments.

These results indicate that baffling of the divertor region to block the passage of recycling impurity neutrals around the plasma boundary may not be sufficient to provide good radiative divertor operation. Increased particle flow to overcome parallel thermal gradients may also be required. Along with new baffling structures, the radiative divertor configuration currently planned for installation on DIII–D willl include new cryopumps, two each in the lower and upper divertors. The combination of baffling and increased pumping speed should provide enhanced particle throughput and improved impurity containment.

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