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A comparison of impurity screening between limiter and divertor plasmas in the Alcator C-Mod tokamak

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Abstract

A series of experiments has been carried out on Alcator C-Mod to compare impurity penetration between similar limiter and divertor discharges. Known amounts of recycling impurities (Ar and Ne) and non-recycling impurities (N_2 and CH_4) are injected by gas puffing, and the fraction ending up in the plasma is deduced from spectroscopic measurements. The poloidal location of the gas injection is also varied. It is found that during the most recent run campaign, limiter plasmas have 1-3 times higher impurity penetration than divertor plasmas which detached, but 5-20 times higher penetration compared to divertor plasmas which remained attached. During the previous run campaign, limiter plasmas had only 1-3 times higher penetration than attached divertor plasmas. These ratios are the same for both recycling and non-recycling species. There are strong dependencies on gas puff location as well. The reason for the difference in the two run campaigns is not understood, but may be related to gas leakage paths behind the divertor structure, which were plugged up between the two campaigns.

Keywords: Alcator C-Mod; Impurity transport; Poloidal divertor; Limiter

1. Introduction

One of the primary functions of a divertor is to reduce the impurity content of plasmas to levels substantially below that of limiter discharges. It is important to verify this performance, since divertors come with a very high penalty in terms of increased machine complexity, severe difficulties with heat removal, less efficient use of *B*-field volume, etc. The impurity content in a plasma depends on a combination of the generation rate (for intrinsic impurities) and the screening properties (for both intrinsic and non-intrinsic impurities). Here the phrase 'screening properties' refers to the ability of a plasma to prevent the penetration of an impurity atom from the outside to inside the plasma boundary. This paper is concerned primarily with comparison of the screening properties of limiter and divertor plasmas, and therefore only non-intrinsic impurities have been used in order to separate out issues dealing with impurity generation.

2. Experimental setup

The Alcator C-Mod tokamak is equipped with several gas fueling inlets controlled with fast piezo-electric valves, as well as a system of capillary tubes for puffing in a variety of gases [1,2]. The capillary tubes are distributed around the interior surfaces of the vessel first wall (i.e., relatively close to the plasma surface), whereas the fast valve inlets are located at port flanges far from the plasma. For the work reported here, three capillary locations were used: (A) inboard wall at the midplane, (B) bottom of vessel (divertor region), and (C) outboard side near the midplane in addition to one of the fast valve inlets (D), as shown in Fig. 1a. The gas injection systems have been calibrated in situ by measuring the pressure rise while puffing into the empty vacuum vessel, so the atomic inflow rates and total atoms injected are known absolutely as a function of time.

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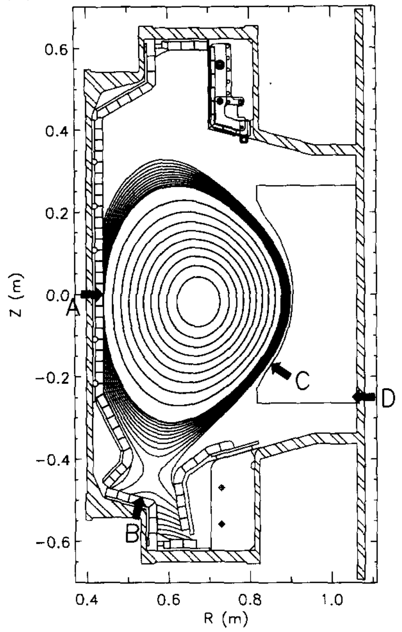
(a) Limiter Plasma

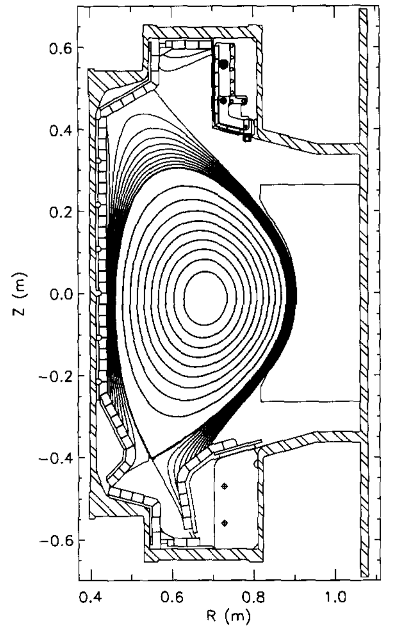
(b) Divertor Plasma

Fig. 1. (a) Typical limiter plasma, with gas puff locations pointed out. Note that the inboard midplane capillary injects gas directly into the plasma edge, bypassing the SOL. (b) Typical lower single-null divertor plasma.

To determine the impurity screening, it is also necessary to know how many of the injected impurities end up inside the plasma. In Alcator C-Mod this is deduced from spectroscopic measurements. X-ray line intensities from high Z ions (such as Ar^{+16} and Ar^{+17}) are measured by an array of high resolution X-ray crystal spectrometers [3], while UV line intensities from lower Z ions (N, C, Ne, etc.) are measured by a single-chord VUV spectrometer [4]. Both spectrometer systems are absolutely calibrated. The chord brightness data from the spectrometers are used by the MIST 1D impurity transport code [5] to determine the impurity density profiles for each charge state, as well as the total number of impurity ions within the plasma volume. Other inputs to MIST include n_e and T_e (mapped to magnetic flux surfaces), as well as profiles of the impurity diffusion coefficient, $D(r)$, and pinch velocity, $V(r)$. These transport parameters have been determined empirically from other impurity injection experiments.

Typical magnetic equilibria for limiter and divertor configurations used in this study are shown in Fig. 1a, b respectively. For the results described here, all of the divertor plasmas are lower single-null configurations with elongations, $\kappa \sim 1.6$. The limiter plasmas are somewhat less elongated, with $\kappa \sim 1.3$. Although more highly elongated limiter plasmas can be run, they invariably have more of the outboard scrape off layer (SOL) going down to the divertor instead of wrapping around to the inboard wall. To do an unambiguous comparison, only limiter plasmas with at least 15 mm of SOL (i.e. several e-foldings) wrapping around to the inboard wall have been used for this study. Each set of limiter/divertor comparisons were done on the same day, with similar plasma parameters (I_p, B_ϕ, $\bar{n}_e$, etc.)

3. Recycling versus non-recycling impurities: Definition of penetration factors

Ideally, we would like to know the probability of a neutral impurity atom penetrating into the plasma core. This probability presumably depends on properties of the SOL, such as n_e and T_e, as well as neutral densities, and the geometry of the first wall and/or divertor. However, to just compare limiter and divertor performance, it is sufficient to use simpler empirical measures of impurity screening. An important distinction must be made between recycling impurities (such as argon and neon) and non-recycling impurities (nitrogen and carbon). As shown in Fig. 2, for recycling impurities such as argon, the total number of impurity ions residing in the plasma is proportional to the total number of atoms that have been puffed in. Therefore we define an empirical penetration factor for recycling impurities, PF_R:

$$PF_R = \frac{\text{total number of impurity ions in the plasma}}{\text{total number of impurity atoms puffed into the vacuum vessel}}$$

PF_R is thus a dimensionless quantity.

In contrast, for non-recycling impurities such as carbon, the total number of ions residing in the plasma as a function of time is proportional to the gas injection *rate*, and *not* the total number of atoms puffed in, as shown in Fig. 3. Therefore an empirical penetration factor for non-recycling impurities, $\mathrm{PF}_{\mathrm{NR}}$, can be defined as:

$$\mathrm{PF}_{\mathrm{NR}} = \frac{\text{total number of impurity ions in the plasma}}{\text{rate at which impurity atoms are puffed into the vacuum vessel}}$$

Note that $\mathrm{PF}_{\mathrm{NR}}$ has the units of time. Intuitively, this behavior makes sense, since carbon sticks quite well to the vessel walls (non-recycling). Each incoming carbon atom has essentially only one chance to penetrate the SOL and enter the plasma as an ion. If the carbon ion does not make it in, its parallel motion along field lines in the SOL quickly carries it to a limiter surface or strike plate, and it is essentially lost from the system. Those carbon ions that do get into the plasma have a finite residence lifetime, τ_{imp}. As they leak out into the SOL, they also travel to the wall and are lost. Therefore, for non-recycling impurities, the total number of ions in the plasma, N_{pl}, is determined by the balance between the penetration rate and the impurity confinement time:

$$\frac{\mathrm{d}N_{\mathrm{pl}}}{\mathrm{d}t} = \text{penetration rate} - \text{loss rate}$$

$$= \text{atom puff rate} \times \text{penetration probability} - \text{loss rate}$$

$$= \frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}t} \times P - \frac{N_{\mathrm{pl}}}{\tau_{\mathrm{imp}}}$$

where N_{inj} is the total number of non-recycling impurities puffed in, and P is the penetration probability. It is therefore possible to derive the true penetration probability from the screening measurements:

$$P = \left(\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}t}\right)^{-1} \frac{\mathrm{d}N_{\mathrm{pl}}}{\mathrm{d}t} + \left(\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}t}\right)^{-1} \frac{N_{\mathrm{pl}}}{\tau_{\mathrm{imp}}}$$

Except for fast transients near valve turn-on/turn-off times, the first term is negligible in Alcator C-Mod compared to the second term. Thus the penetration probability, P, is just $\mathrm{PF}_{\mathrm{NR}}$, as defined above, normalized by τ_{imp}:

$$P \simeq \frac{\mathrm{PF}_{\mathrm{NR}}}{\tau_{\mathrm{imp}}}$$

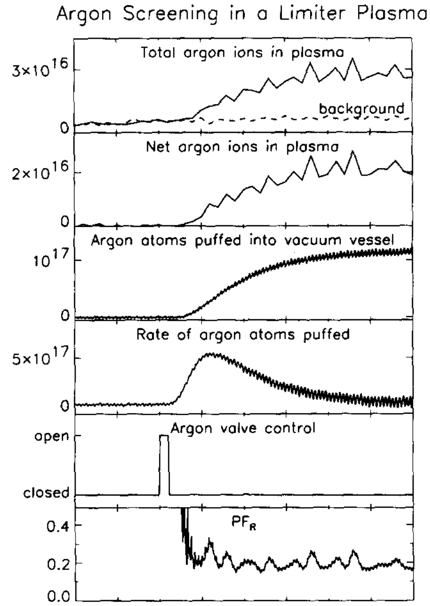

Fig. 2. Example of argon screening measurements in a limiter plasma (#941206018). A 20 ms puff of argon is injected from valve D at $t = 0.5$ s. The background level of argon is determined from an identical shot with no impurity puffing. For recycling impurities, the total number of impurity ions in the plasma is seen to be proportional to the *total number* of atoms puffed into the vacuum vessel (second and third traces). The bottom trace shows the ratio of these two signals, which is about 0.2 for this shot.

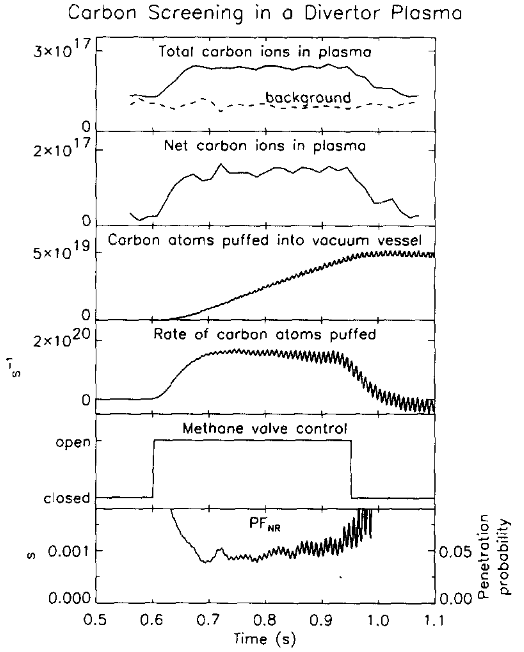

Fig. 3. Example of carbon screening measurements in an attached divertor plasma (#950526035). A 0.35 s puff of methane was injected starting at $t = 0.6$ s. Note that the plasma carbon content is proportional to the *rate* at which carbon is puffed into the vessel (second and fourth traces), rather than the total number of atoms puffed. The bottom trace shows the ratio of these two signals, which is about 0.001 s for this example. This gives a penetration probability of ∼ 0.05, assuming $\tau_{\mathrm{imp}} = 0.020$ s.

Furthermore, with the notable exception of H-mode plasmas, $\tau_{imp} \simeq 0.020$ s ±25% in C-Mod, so P is essentially proportional to PF_{NR}. In practice we tend to use PF_{NR}, however, the true penetration probability is presumably useful for direct comparison to other tokamaks.

4. Limiter and divertor screening comparisons

The screening measurements for nitrogen, which is a non-recycling impurity, are shown in Fig. 4 for a series of limiter and divertor discharges with $I_p = 0.8$ MA, $B_\phi = 5.3$ T, $\bar{n}_e = 1.7–3.2 \times 10^{20}$ m^{-3}, and $P_{rf} = 0$. These data were taken during the most recent run campaign. The PF_{NR} values plotted here are derived by averaging over suitable steady state portions of the shots. It is seen that limiter plasmas are generally about 1–3 × worse than comparable divertor plasmas which detach. However, those divertor plasmas which remain attached have much better impurity screening [6], with PF_{NR} values about ~ 5–20 × lower than the limiter plasmas. It is also apparent that gas puffing at the inboard midplane (location A in Fig. 1a) into a limiter plasma tends to result in greater impurity penetration compared to other puffing locations. This is not surprising, since gas atoms injected here essentially bypass the SOL. Although not shown here, no consistent dependence of screening of non-intrinsic impurities with $\bar{n}_e$ has been observed.

Fig. 5 shows the screening measurements for argon, which is a recycling impurity. Data from two different series of limiter/divertor comparisons from two different run campaigns about one year apart (December 1994 on the left and December 1995 on the right) are shown. Plasma parameters were $I_p = 0.8$ MA, $B_\phi = 5.3$ T, $\bar{n}_e = 0.7–2.1 \times 10^{20}$ m^{-3}, and $P_{rf} = 0$. In the most recent run campaign, limiter plasmas had 10–20 × worse screening performance than comparable divertor plasmas, all of which were attached. This is consistent with the nitrogen data discussed previously, which also came from the most recent run campaign. Again it is apparent that puffing gas from the inboard wall into a limiter plasma results in more impurity penetration than puffing from the bottom or outboard regions.

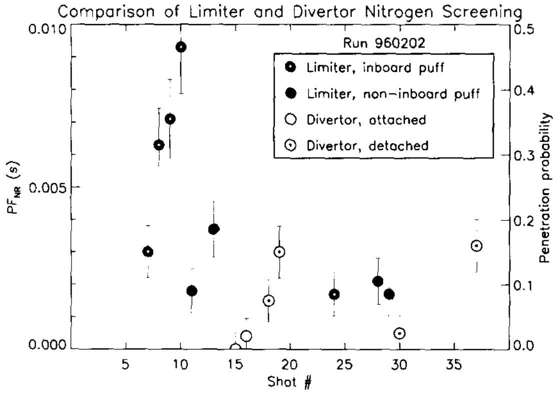

Fig. 4. Comparison of nitrogen screening in limiter and divertor plasmas. These discharges are all from the same day, during the most recent run campaign. Limiter plasmas are seen to have 1–3 × greater impurity penetration than detached divertor plasmas, and ~ 5–20 × greater than attached divertor plasmas. Puffing into limiter plasmas at the inboard midplane (i.e., bypassing the SOL) tends to result in higher PF_{NR} values.

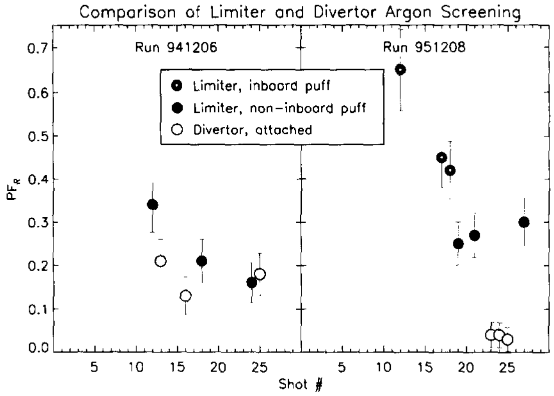

Fig. 5. Comparison of argon screening in limiter and divertor plasmas. Two sets of data are shown from two different run campaigns about one year apart. Although impurity screening in limiter plasmas has remained about the same in the two campaigns, the screening by divertor plasmas (all of which were attached) has apparently improved between the two campaigns. Again it is seen that puffing into limiter plasmas at the inboard midplane tends to result in higher PF_R values.

In contrast, the screening data from the previous run campaign (left half of Fig. 5) show that argon penetration into limiter plasmas was only 1–3 × higher than into attached divertor plasmas. Apparently the impurity screening of attached divertor plasmas in the most recent run campaign has improved compared to the previous run campaign. The reason for this is not understood, but may be related to gas leakage paths behind the divertor structure which were plugged up between the two campaigns.

5. Dependence of impurity screening on gas puff location in limiter plasmas

The screening measurements with both recycling and non-recycling species show that injection of impurities from the inboard midplane location directly into a limiter plasma tends to have greater impurity penetration compared to puffing from other locations. The histogram plots in Fig. 6 show this more quantitatively. In order to combine the data from the different gases, it is necessary to define a 'normalized' penetration factor, PF*:

$$PF^* = PF_i / \langle PF_i \rangle$$

where $i = \{R, NR\}$ and $\langle PF_i \rangle$ is the average of the respective limiter dataset. Therefore PF* = 1 is the mean for

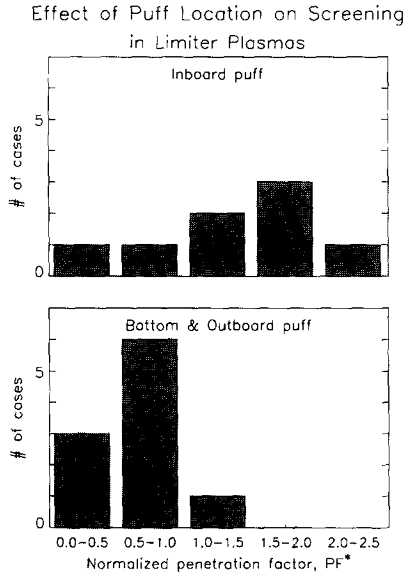

Fig. 6. Histogram plots of 'normalized' penetration factor, PF*, for inboard and non-inboard puffing into limiter plasmas. Data from both recycling and non-recycling species are included. It is seen that inboard puffing tends to give above average impurity penetration, while puffing from the bottom or outboard locations (which are outside the SOL) results in below average values.

both the limiter PF_R and PF_{NR} datasets. It is seen that on average, about 2–3 × more impurities penetrate into the plasma when injected directly at the last closed flux surface compared to injection outside the SOL. However, there are a couple of examples of inboard puffing which did not show enhanced impurity penetration. No reason for this has been identified yet. (The magnetic configurations were identical, as was the density.)

6. Summary

During the most recent run campaign, limiter plasmas had 1–3 times higher impurity penetration than divertor plasmas which detached, but 5–20 times higher penetration compared to divertor plasmas which remained attached. During the previous run campaign, limiter plasmas were only 1–3 times worse than attached divertor plasmas. These findings are the same for both recycling and non-recycling species. The reason for the difference in the two run campaigns is not understood, but may be related to gas leakage paths behind the divertor structure which were plugged up between the two campaigns.

Screening of impurities in limiter plasmas was also found to vary with the location of the gas puff. Inboard midplane puffing, which bypasses the SOL, typically results in 2–3 × greater penetration than puffing from other locations well outside the SOL.

As stated in the introduction, the impurity content in the plasma is determined by the combination of both the production rate (for intrinsic impurities) and the penetration behavior. The results described in this paper have concentrated on the penetration behavior only. Although a detailed study of intrinsic impurities (molybdenum in C-Mod) in these limiter/divertor comparison experiments has not been done yet, it is clear that molybdenum levels are noticeably higher in limiter plasmas at lower densities, and that this enhancement becomes less pronounced as the plasma density is raised.

In future work it is intended to model the impurity transport using the DIVIMP Monte Carlo code [7] for both limiter and divertor discharges, hopefully leading to a better understanding of the physics involved in the screening of impurities.

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