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The Relation between Impurity Neutral and Impurity Ion Compression in the Alcator C-Mod Divertor

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Abstract

The effect of divertor baffling on impurity neutral and impurity ion compression in the Alcator C-Mod tokamak is explored. Experiments are performed using a novel divertor “bypass” which allows *in situ* variations to the divertor baffling. The results indicate that divertor baffling in C-Mod plays an important role in impurity neutral compression, but little role in impurity ion compression. The apparent separation between neutral compression and ion compression is surprising, but is consistent with a model where the neutral compression (both deuterium and argon) is determined by a leakage flux through the baffle structure from the divertor region to the main chamber which is independent of the leakage conductance. Instead, the leakage fluxes appear to be determined by the divertor plasma conditions (including impurity and fuel ions), which are not influenced by the baffle structure.

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1. Introduction

It has long been the goal in tokamak research to compress impurities in the divertor, both with respect to impurity ion density in the local divertor plasma and with respect to the impurity neutral density in the surrounding gas [1-3]. Enhanced impurity ion concentrations in the divertor plasma would increase the dispersal of plasma power via radiation processes, thus reducing the power density incident on the target plates, whilst enhanced impurity gas pressures in the region adjacent to the divertor would increase the rate of impurity extraction via vacuum pumps. Intuitively, one would expect a close relationship between the two.

We have performed experiments on the Alcator C-Mod tokamak exploring the relationship between impurity neutral compression and impurity ion compression. We make use of the novel divertor bypass [4-6], which allows in situ variations to the baffling surrounding the divertor plasma, where we define baffling to be any mechanical structure that impedes the flow of gas from the divertor region to the main chamber. In contrast to the intuitive relationship mentioned above, we find a separation between divertor impurity neutral compression and impurity ion compression.

2. Experiment

Alcator C-Mod [7] is a compact, high-field tokamak, with a single-null (bottom) divertor, ICRF heating and molybdenum first-walls which are routinely boronized. A poloidal cross-section of the machine (at a vertical port location) appears in Fig. 1. The conductance between the divertor plenum and the main chamber (which we call the “leakage conductance”) is altered in these experiments using the Alcator C-Mod divertor bypass, Fig. 1 [4-6]. The bypass conductance is ~ 23 m^3/s, which is approximately equal to the intrinsic leakage conductance with the bypass closed. Thus, the bypass, when open, approximately doubles the leakage conductance.

In this experiment, impurity compression experiments are performed using the recycling impurity argon, which is monitored in the core plasma by spectroscopic means from high charge states (typically Ar^{+16}), in the divertor plasma using visible spectroscopy from Ar II emission, and in the divertor gas using a residual gas analyzer (RGA) separated from the divertor region by a ~ 1.7 m long tube [8]. The Ar II (440.1 nm) divertor emission is measured with a visible spectrometer using 8 chords which cover the shaded region in the divertor indicated in Fig. 1. We assume that for given plasma conditions the Ar II emission is directly related to the argon ion flux, which in turn is directly related to the argon ion density. In addition, Langmuir probes (not shown in Fig. 1) built into the divertor plates monitor the local divertor plasma electron density and temperature.

3. Experimental Results

Fig. 2 gives results for the argon and deuterium neutral compressions as functions of the line-average discharge density for Ohmic discharges. According to convention, we define impurity neutral compression c_Z as,

$$c_Z \equiv \frac{n_Z^{div}}{n_Z^{core}} \qquad [1]$$

where n_Z^{div} is the impurity gas density in the divertor and n_Z^{core} is the impurity ion density in the core plasma. The impurity neutral compression is compared to the deuterium neutral compression,

$$c_D \equiv \frac{n_D^{div}}{n_D^{core}} \qquad [2]$$

where n_D^{div} is the deuterium gas density derived with the RGA (or pressure gauge, indicated by "G" in Fig. 1) and n_D^{core} is the central deuteron ion density, derived from the core electron density and Z_{eff}. The relative neutral compression, or "enrichment" η_Z, of the impurity is simply the ratio, $\eta_Z \equiv c_Z / c_D$, and is also given in Fig. 2. The impurity and deuterium ion compressions are defined in an analogous way, simply by replacing the divertor neutral density in the above expressions with the divertor ion density.

In general, the argon neutral compression is very high, in the range of $c_Z \sim 100$ at moderate discharge density, which tends to be reduced at both the lowest and highest plasma densities. The deuterium neutral compression on the other hand is significantly lower, $c_D \sim 10$, and although it increases with density, it tends to saturate rather than decrease at the highest discharge density. In both the argon and deuterium cases, the divertor bypass reduces the neutral compression by a factor of two approximately. This is consistent with the factor of ~ 2 increase in divertor leakage conductance and the hypothesis that the leakage fluxes (of both argon and deuterium) are fixed at a given central density. The fixed flux appears to be the case for deuterium, as shown through experiment and simple analytic modeling [6]. More detailed modeling is in progress for both the argon and the deuterium.

Fig. 3 gives the outer divertor plasma conditions as deduced by the plate Langmuir probes for two discharges (one with bypass open, one with bypass closed) with identical main discharge parameters. Within experimental error, the divertor plasma conditions are similarly identical, despite a significant difference in the gas pressure immediately adjacent to the divertor plasma (20 mTorr with bypass open, 43 mTorr with bypass closed).

Fig. 4 gives the ratio of the Ar II signal in the divertor normalized by the core argon density for the Ohmic density scan with the bypass open and closed. Although we do not here derive the argon ion density in the divertor, the Ar II intensity at a given plasma density can be used to measure relative changes between bypass open versus closed, since the measurements with Langmuir probes indicate no influence of the bypass on either the divertor plasma density or temperature, or their radial profiles for a given discharge density, e.g. as in Fig. 3 [4,6]. The ratio of Ar II (divertor) to $n_{\mathrm{Ar}}^{\mathrm{core}}$ is therefore a measure of divertor argon ion compression. From this data, no effect of the bypass can be discerned, indicating no effect of the divertor baffling on the argon ion compression, despite the factor of ~ 2 reduction in argon neutral compression when the bypass is open. One notes that for a given argon inventory in the vessel the bypass does in fact change the Ar II and $n_{\mathrm{Ar}}^{\mathrm{core}}$ levels, since the divertor plenum is a significant reservoir of (neutral) argon and the bypass can alter the inventory residing there. We focus here, however, on the divertor/core ion compression ratio, which is not influenced by the bypass.

4. Discussion

In this letter we have demonstrated that divertor baffling in Alcator C-Mod plays a significant role in recycling impurity neutral compression. These results for neutral impurity compression are similar to those obtained on a number of other divertor tokamaks, where similar baffle changes have been made across different experimental campaigns [2,9]. In contrast, the argon ion compression in the divertor, appears to be independent of the baffling. The apparent separation between argon ions in the divertor plasma and argon atoms in the gas immediately adjacent is surprising, but is consistent with the deuterium behavior as indicated by the divertor Langmuir probes and the deuterium divertor gas pressure. In the deuterium case, experiments and simple modeling suggest that the leakage flux through the baffle structure (Fig. 1) is determined not by the leakage conductance but by the atom flux out of the divertor plasma fan, which in turn is determined by the ion flux to the plate and an escape probability for atoms to reach the private flux region—the leakage flux is therefore “flux-limited”, as opposed to “conductance-limited” [6]. Thus, changes in the divertor gas pressure are proportional to changes in the leakage conductance and the leakage flux is determined by the scrape-off-layer plasma conditions and not the mechanical baffle structure. The evidence presented here suggests that argon is similarly 'flux-limited', i.e. argon gas pressure is determined by the conductance, whilst the argon ion density in the divertor (or in this case the Ar II emission, which is more a measure of flux) is determined by the argon level in discharge and the divertor/core argon ion compression ratio which is determined by SOL plasma physics.

These findings thus demonstrate the importance of divertor baffling for the compression of gases in the divertor, but not necessarily for impurity ions, at least at present in Alcator C-Mod. Thus, reductions in leakage conductance, while they may increase impurity gas pressures in the divertor, may do little to enhance the local impurity ion density. The former of course is an advantage for impurity extraction (e.g. helium ash), while the latter means concomitant improvements in power dispersal will not necessarily occur.

Acknowledgements

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References

1. F Wagner and K Lackner, in ‘Physics of Plasma-Wall Interactions in Controlled Fusion”, editors D E Post and R Behrisch, NATO ASI Series, Plenum Press (1986), p. 931
2. C S Pitcher and P C Stangeby, Plas Phys Control Fusion 39 (1997) 779

3. P C Stangeby, “The Plasma Boundary of Magnetic Fusion Devices”, IOP Institute of Physics Publishing, Bristol, 2000
4. C S Pitcher, C J Boswell, J A Goetz *et al*, Physics of Plasmas 7 (2000) 1894
5. C S Pitcher, B LaBombard, R Danforth *et al*, Review of Scientific Instruments 72 (2001) 103
6. C S Pitcher, C J Boswell, T Chung *et al*, J Nucl Mat 290-293 (2001) 812
7. I H Hutchinson, R Boivin, F Bombarda *et al.*, Phys Plasmas 1 (1994) 1511
8. J A Goetz, B Lipschultz, C S Pitcher *et al.*, J Nucl Mat 266-269 (1999) 354
9. H-S Bosch, J C Fuchs, J Gafert *et al.*, Plas Phys Control Fusion 41 (1999) A401

Figure Captions

1. Poloidal cross-section of the lower half of Alcator C-Mod showing the location of the divertor bypass and various edge/divertor diagnostics. “G” denotes pressure gauge, “RGA” denotes residual gas analyzer. The circulation of gas through the bypass is indicated. The region viewed by 8 chords which monitor Ar II emission is indicated.

2. Argon neutral compression C_{Ar}, deuterium neutral compression C_D and argon neutral enrichment η_{Ar} in the Ohmic density scan. Comparison between bypass open and closed.

3. Outer divertor plasma conditions as deduced by the plate probes in two identical discharges, one with bypass open, one with bypass closed. The corresponding divertor gas pressures are 20 mTorr and 43 mTorr, respectively. Discharge conditions, $\bar{n}_e = 1.8 \times 10^{20}\,\mathrm{m}^{-3}$, B_t = 5.4 T and I_p = 1 MA, Ohmic heating only.

4. A measure of the argon ion compression as indicated by the ratio of the divertor Ar II intensity normalized by the core argon density.

Fig. 1

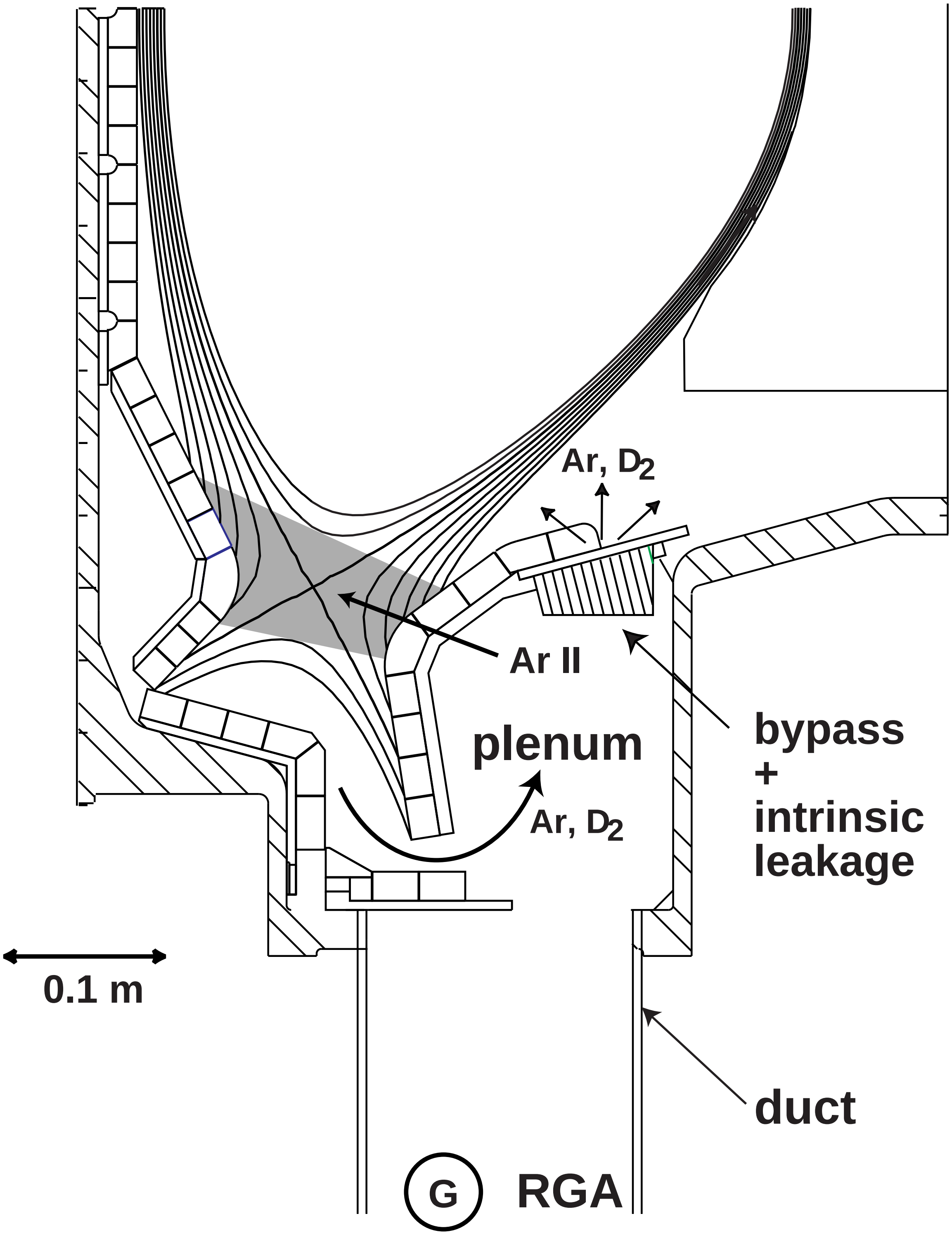

Ar, D2
Ar II
bypass
+
intrinsic
leakage
plenum
Ar, D2
0.1 m
duct
G
RGA

Fig. 2

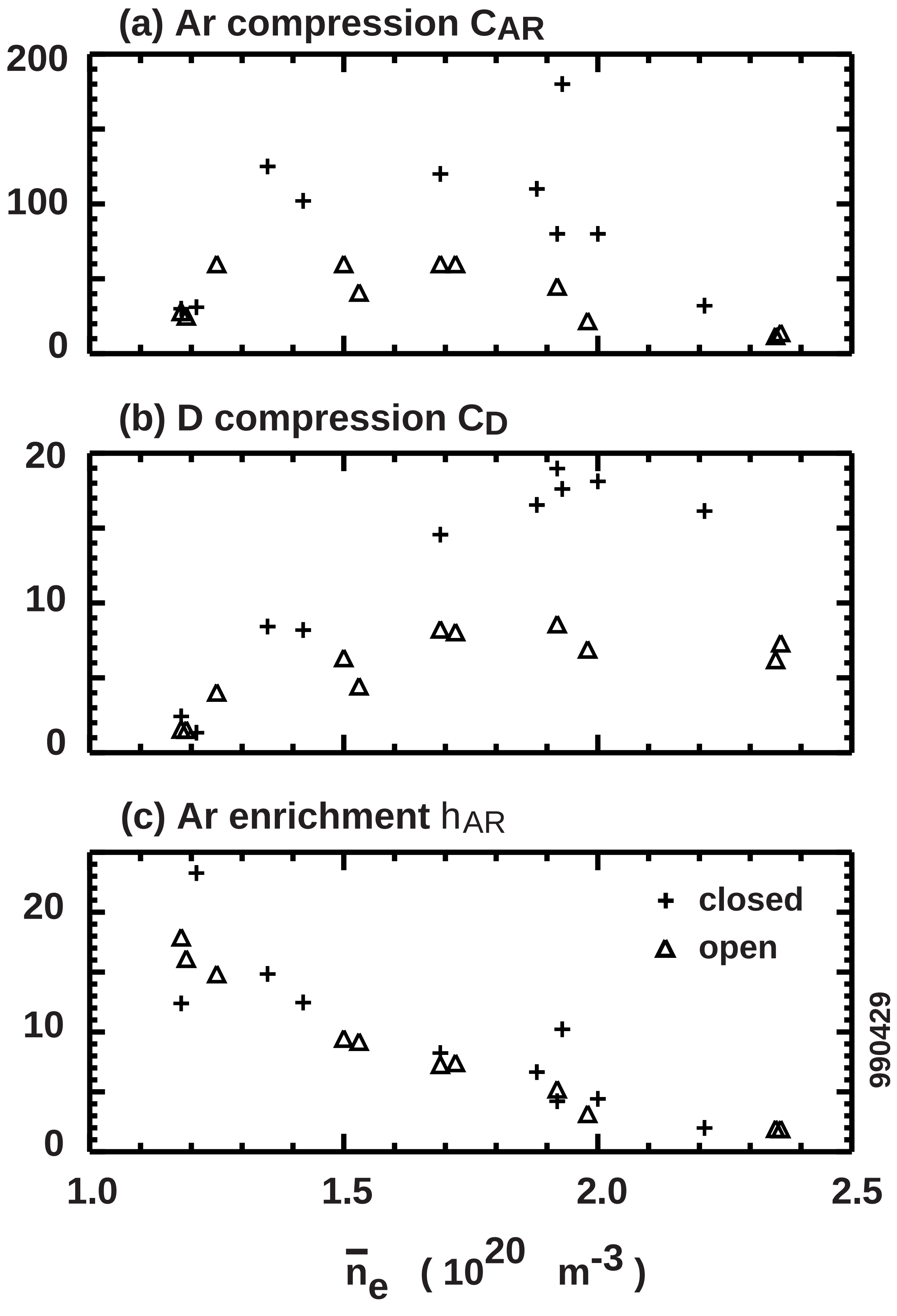
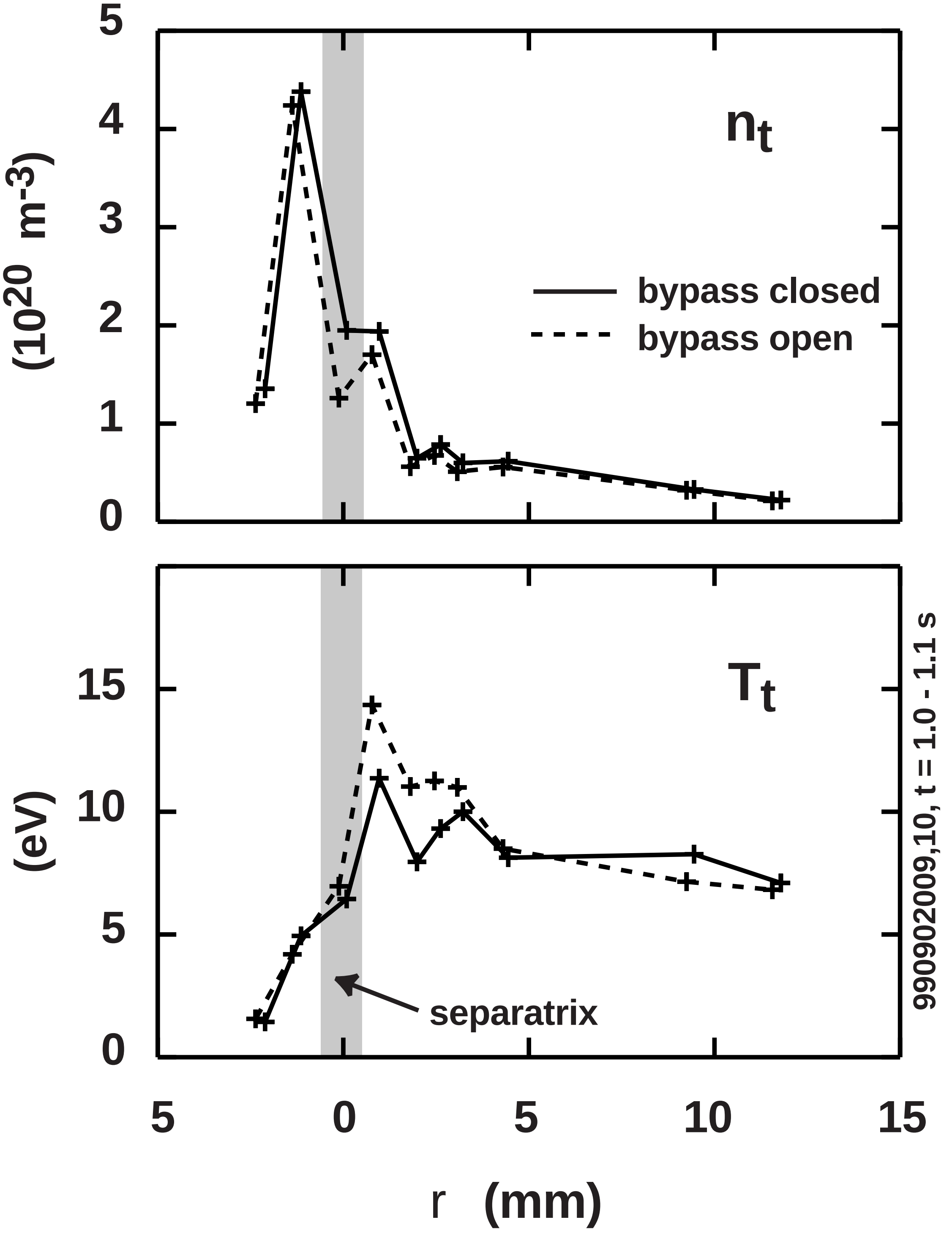
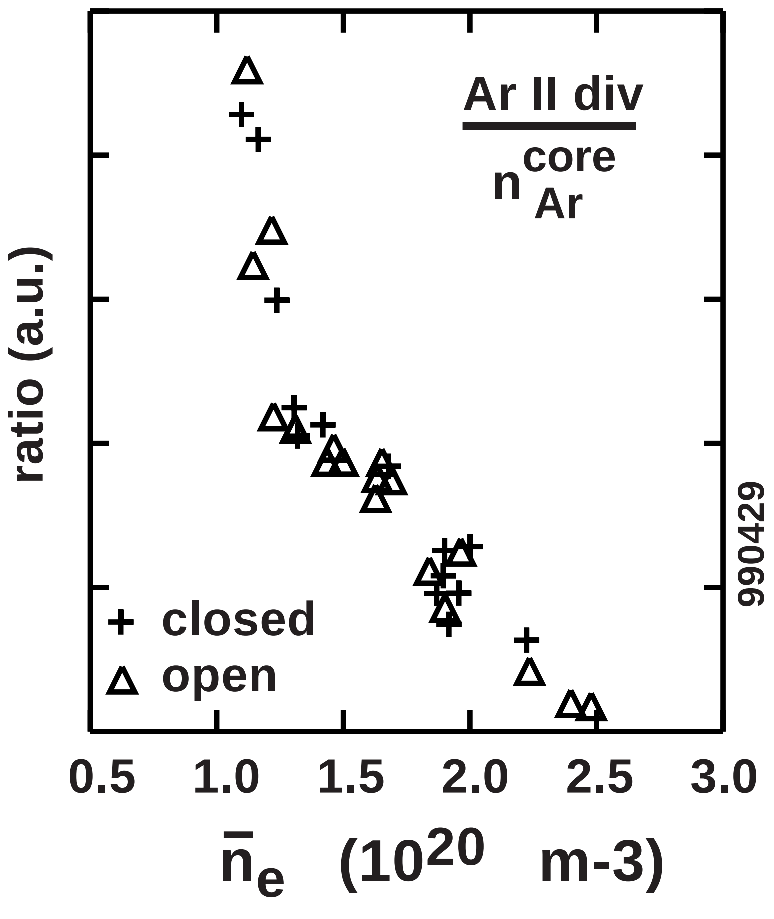

(a) Ar compression C_{AR}
200
100
0
(b) D compression C_D
20
10
0
(c) Ar enrichment h_{AR}
20
10
0
+ closed
Δ open
1.0
1.5
2.0
2.5
$\bar{n}_e$ (10^{20} m^{-3})
990429

Fig. 3



5
4
3
2
1
0
$(10^{20}\ m^{-3})$
n_t
bypass closed
bypass open
15
10
5
0
(eV)
T_t
separatrix
990902009,10, t = 1.0 - 1.1 s
5
0
5
10
15
r (mm)

Fig. 4


Ar II div
n_{Ar}^{core}
ratio (a.u.)
+ closed
△ open
0.5
1.0
1.5
2.0
2.5
3.0
$\bar{n}_e$ (10^{20} m-3)
990429