Divertor Bypass Experiments in Alcator C-Mod

C S Pitcher, J A Goetz, B LaBombard,
B Lipschultz, J L Terry and M V Umansky

MIT, Plasma Science and Fusion Center, NW17, Cambridge, MA, 02139, USA

1 Introduction

Since the early 1980's it has been suggested that tight divertor baffling can improve the performance of tokamak discharges, for example, in the achievement of high energy confinement times [1]. It was further believed that tight baffling could result in better neutral compression/helium exhaust and in improved impurity screening. All of these would ultimately improve the performance of an energy-producing tokamak reactor. Over the intervening years, virtually every divertor tokamak has attempted to optimize baffling by arranging the mechanical divertor structure to restrict the leakage of gas out of the region. One problem with this activity, and one of the reasons that definitive answers on many aspects of the subject have yet to be obtained, is that mechanical changes typically take of order one year to institute and thus, before and after comparisons are made across years, under varying machine conditions, magnetic geometry and diagnostic calibrations (see for example [2, 3]).

2 Alcator C-Mod Divertor Bypass

To improve this situation, we have executed a series of experiments on the Alcator C-Mod tokamak [4] where in situ changes to the divertor baffling can be made between, or even during discharges. Experimental comparisons are thus performed under identical operating conditions. The Alcator C-Mod divertor bypass design consists of louvered flaps, magnetically-actuated using small solenoids which interact with the toroidal magnetic field (see Fig. 1). The large available torque allows the coils to open or close the divertor bypass in times as short as $\sim 20\ ms$. The bypass(es) reside at 10 discrete toroidal locations. The total cross-sectional area of the bypasses is 750 cm^2, giving an estimated free-molecular conductance between the divertor plenum and the main chamber of $\sim 23\ m^3 s^{-1}$. This conductance is enhanced by factors as large as ~ 3 due to viscous flow effects at the high gas pressures present in the Alcator C-Mod divertor.

All experiments reported here were performed in 0.8 MA, 5.4 T, deuterium discharges, with grad-B drift towards the single lower null divertor. A number of discharge densities and heating powers were used.

3 Neutral Pressures

Figures 2a,b give typical results for the effect of the bypass on neutral pressures at the outside mid-plane in the main chamber and in the divertor as functions of the line-average density in Ohmic discharges. The bypass was either open or closed for the entire duration of the discharge so to attain true steady-state conditions. In general, the divertor pressure is a factor of 2 to 3 lower with the bypass open, while no corresponding effect is observed for the mid-plane pressure within an experimental error of $\sim 20\%$.

4 Impurity Screening

The results of Fig. 2a,b indicate a change in divertor to mid-plane neutral deuterium compression ratio between bypass open compared with closed. We observe a corresponding change in compression for recycling impurities, e.g. in discharges seeded with argon or krypton. In this case the compression is quantified by the neutral deuterium and impurity densities in the divertor compared with the deuterium and impurity ion densities in the confined plasma [5]. The relative compression between impurities and deuterium is the enrichment factor η_Z, defined as,

$$\eta_Z = \frac{n_Z^{div}/n_Z^{core}}{n_D^{div}/n_D^{core}} \tag{1}$$

where, the divertor ('div') densities are for neutral species and the 'core' densities are for ion species. Fig. 2c gives the argon enrichment factor as a function of discharge density for open and closed divertor bypass. Discharges with a line-average density above $\overline{n}_e \sim 2 \times 10^{20} m^{-3}$ are detached from the outer divertor plate. The argon enrichment decreases with increasing discharge density, qualitatively similar to previous results [5]. No change is observed due to the divertor bypass. Thus, the argon compression, while being strongly affected by the bypass, is influenced to the same degree as the deuterium compression.

5 Energy Confinement

We have found no discernable effect of the divertor bypass (within an accurancy of $\sim$10%) on energy confinement. This includes Ohmic, L-mode and Enhanced D-Alpha (EDA) H-mode discharges. Fig. 3 gives an example – experimental results from an EDA H-mode discharge with 1.5 MW of ICRF power. Shortly after the start of ICRF heating the discharge density rises (Fig. 3a) and comes within a period of $\sim 150\ ms$ to a steady state, this being a signature of EDA H-mode behaviour [6]. Identical density traces are observed for bypass closed and bypass open. The same is true of the mid-plane pressure (Fig. 3b), with virtually no dependence on the bypass. As found above in Sect. 3, the divertor pressure (Fig. 3c) is a factor of ~ 2 lower with the bypass open. Despite this strong effect on neutrals in the divertor, the stored energy (Fig. 3d) for the two discharges are nearly identical.

6 Discussion

The main result of this preliminary study is that divertor baffling in Alcator C-Mod, while having a strong effect on the fuel and recycling impurity compression in the divertor, has only a minor influence on conditions outside of the divertor. The factor of 2 to 3 decrease in divertor pressure with the bypass open is roughly consistent with the large increase in conductance between the divertor plenum and the main chamber. This is estimated to increase by a factor ~ 2.5, from $\sim 15\ m^3s^{-1}$ with the bypass closed to $\sim 38\ m^3s^{-1}$ with the bypass open. The closed conductance is primarily determined by toroidal gaps in the divertor plate structure, which amount to $\sim 8\%$ of the toroidal circumference.

The small change in mid-plane pressure is surprising given the large magnitude of the flux through the divertor bypass. This flux is in fact comparable to the level of main chamber recycling based on the mid-plane pressure and D_α measurments (not given). The high level of main chamber recycling in Alcator C-Mod (off of limiters and walls) has recently been documented [7]. It still remains to explain the resilience of the mid-plane pressure to the leakage through the bypass.

The fact that the argon impurity compression in the divertor is affected to the same degree as the deuterium compression, giving an enrichment which is independent of the bypass, suggests that both fuel and impurity species are 'leaking' to the main chamber through the bypass. An alternative explanation might ascribe the changes in impurity screening to changes observed in the SOL plasma conditions which result from the redistribution of neutral particles in the boundary. We are presently studying this inherently two-dimensional transport problem.

It appears that our results, while demonstrating that divertor baffling does not have a significant influence on energy confinement in Alcator C-Mod, can neither deny nor confirm the conclusion that main chamber neutrals influence confinement.

Acknowledgement

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References

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Fig. 1

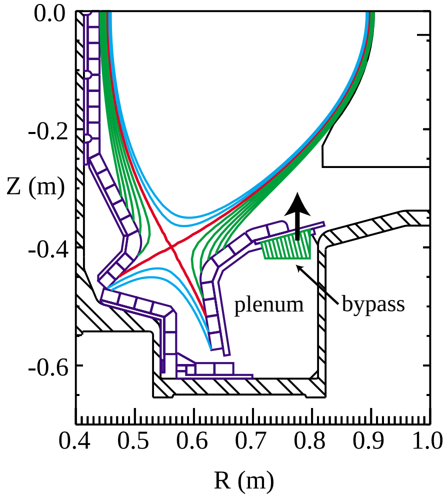

Fig. 2

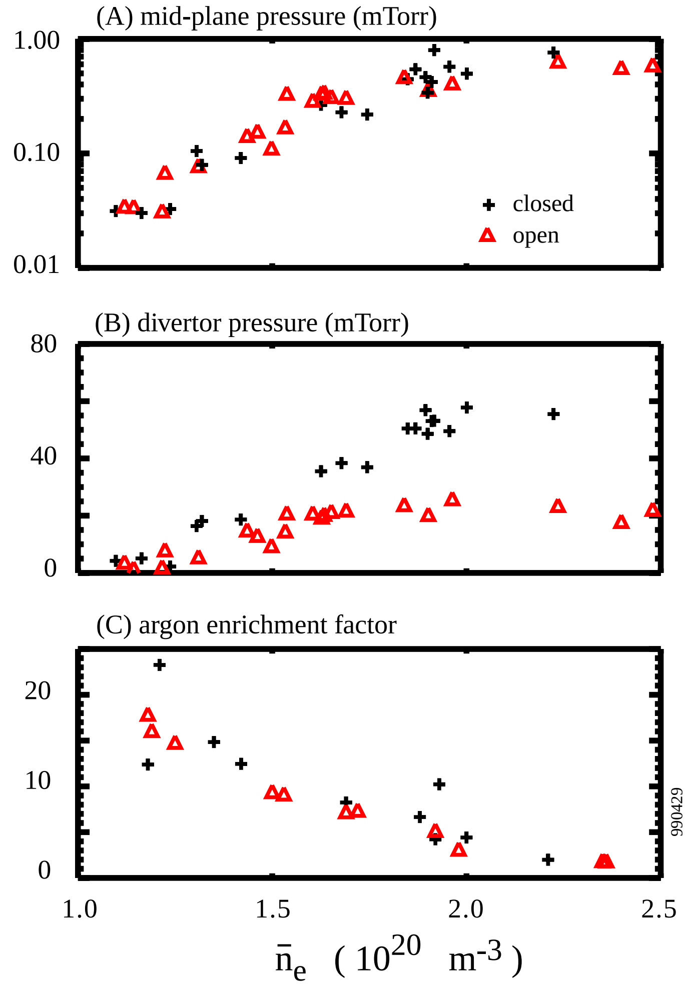

Fig. 3