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Neutrals studies on Alcator C-Mod

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Abstract

The high neutral densities and short neutral mean free paths in the Alcator C-Mod divertor have provided a unique testing ground for our understanding of the role of neutrals in a tokamak. The high neutral pressures found in the C-Mod divertor can only be reproduced in models by including such collisional processes as ion-neutral and neutral-neutral collisions, neutral viscosity, as well as taking into account the plasma in the private flux region. After detachment, when the divertor plate ion flux has dropped by over an order of magnitude, the divertor pressure still remains high. High neutral collisionality and the plasma in the private flux region again help keep neutrals in the divertor along with the large source of neutrals due to recombination. Likewise, diffusive neutrals are the explanation for the divertor neutral pressure's insensitivity to strike point position. Closure of neutral leakage pathways did not lead to a decrease in neutral pressures in the region outside the divertor – the main chamber. This observation prompted further research which showed that ion fluxes to main chamber surfaces rival those reaching the divertor plates; the main chamber pressure can be primarily determined by the level of ion transport perpendicular to the magnetic field. This finding has spawned a host of studies (active and passive) both at C-Mod and other tokamaks to understand how radial transport can be so large.

I. Introduction

The role of neutrals in the divertor, their sources, ionization and control are emphasized in the Alcator C-Mod program. Divertor neutrals play a central role in divertor pumping throughput, in assisting divertor detachment and in fueling the core plasma. It is less clear how they affect the core plasma performance (e.g. confinement, structure of the H-mode pedestal) and what the most important 'neutral leakage' pathway is, i.e., via direct escape from the divertor or via leakage to the midplane/SOL. In addition, the role of neutrals recycling on main-chamber wall surfaces needs to be considered.

Predictions of divertor plasma performance for a Burning Plasma Experiment (BPX) such as ITER will remain uncertain unless the physics in the predictive codes can be checked against divertor experiments with relevant plasma conditions. The neutral mean free paths in ITER, normalized to the size of the divertor, are smaller than for any currently operating tokamak. This is also true for the level of hydrogen-resonance line radiation trapping (Ly_α) in the divertor, which strongly affects the ionization/recombination balance. The plasma density (and accompanying ion fluxes and n_0) in the C-Mod divertor, and the Ly_α trapping (proportional to n_0L), are closest to that predicted for ITER among existing tokamaks. Thus the benchmarking of predictive codes against C-Mod plasmas is a crucial test. Until recently, the correspondence between code results and experiment has been poor in that the predicted divertor pressures for C-Mod were low by an order of magnitude (e.g.[1]). However, recent modelling of the C-Mod divertor plasma and neutrals has been more successful. This is due to the inclusion a number of previously neglected physical effects and forcing a better match between an interpretive plasma model and measured plasma background parameters [2]. Yet, as will be discussed later, this is just the first of many neutral modelling comparisons with C-Mod data that are needed.

Central to the discussion of the neutral species in Alcator C-Mod are measurements of the neutral pressure. Pressure gauges are placed at a number of locations in C-Mod, both toroidally and poloidally, as shown in Figure 1. The pressure gauges used include absolutely-calibrated baratron capacitance gauges and Bayard-Alpert gauges (nude, but magnetically-shielded) on ports. In addition, there are a number of Penning gauges mounted on internal vessel surfaces. The inner divertor plate shape as shown in Figure 1 was changed in 2002 (see [3] for a figure showing the new shape). The period prior to 2002 corresponds to the majority of the data included herein. In addition, the physics of neutral transport discussed herein does not appear to be changed by the change in geometry.

II. Scaling of divertor neutral pressures in sheath limited, high recycling and detached regimes

Divertor characteristics vary considerably as the core conditions are varied. In the simplest Ohmic-heated plasmas, the divertor plasma goes from sheath-limited to high-recycling to detached regimes as the core density is increased[4]. Accompanying the changes in plasma characteristics are changes in the divertor neutral pressures [5-7]. An example is given in Fig. 2 for the original C-Mod divertor geometry (Fig.1). As will be discussed, modifications were later made to the divertor which increased the divertor pressure. In the sheath-limited regime [5] the divertor pressure is found to be fairly constant or slowly increasing with plasma density, but rises rapidly when the divertor transitions into the high-recycling regime. Finally, when the outer-divertor detaches, the divertor pressure continues to rise, but much more slowly. The neutral pressure dependence on density parallels the non-linear variation in plasma characteristics measured at the divertor plate up to the density of deteachment onset. Thus, as the detachment threshold is modified (e.g. by changing input power or injecting impurities, [8,4]), the curve shown in Fig. 2 shifts to lower or higher densities [7]. We note particularly that as the power flowing to the divertor is increased the detachment threshold and maximum divertor pressure increase as well[8].

At first glance the observed neutral pressure behavior appears quite straightforward. For the lowest densities, the low ion fluxes incident on the divertor plates (source of neutrals) and their long mean free path allow them to easily escape the divertor; both effects lead to low neutral densities in the divertor. In the high recycling regime the combination of rapidly increasing ion fluxes and shortening neutral mean free path leads to a positive feedback mechanism raising the neutral pressures. Power flow to the divertor is what supports the increase in divertor ion recycling and neutral pressures observed[8]. On the other hand, in detached regimes the divertor ion fluxes drop by a factor of 10 or so, yet the divertor pressure continues to increase. This lack of connection between the neutral source (ion fluxes) and the neutral pressure during detachment indicates that additional physics plays a role in this regime.

It has been pointed out that the divertor plasma is very cold over a large region ($T_e < 5$ eV) in C-Mod detached plasmas [7]. In this limit, the neutral mean free path for ionization, λ_{ioniz}, is larger than that for momentum transfer (charge-exchange and elastic collisions), λ_{mt}. In addition the mean free path for momentum transfer is short compared to the divertor dimension, L_D, which means that the neutral transport through the background plasma is diffusive ($\lambda_{mt} < \lambda_{ioniz} < L_D$). In this regime, the albedo of the divertor plasma, A, for neutrals trying to penetrate through it, can be approximated as $A = 1- \lambda_{mt}/L_D$. Thus, as the plasma detaches, the albedo of the divertor plasma increases, reducing the leakage of neutrals from the divertor region allowing a similar divertor pressure to be sustained with a smaller source of neutrals (i.e., ion flux to the divertor target). The model used [9,7] did not include the effect of recombination in the plasma, which, because it is an additional neutral source, would increase the neutral pressure in the divertor further. However, it was hypothesized that it would have a significant effect. Later volume recombination estimates derived from spectroscopic measurements of the Balmer series showed that the recombination neutral source (sink for ions) can be large when the outer divertor is detached [10]. However, the recombination neutral source does not quite make up for the large (factor of 10 drop) loss in ion current to the divertor plate, and so the total neutral source in the divertor does indeed drop during detachment [10].

III. Effect of geometry on divertor pressure

The neutral pressure in the divertor was found to be remarkably insensitive to the divertor and strike-point geometry in Alcator C-Mod. The pressure measurement data shown in Fig. 2 are indicative of the pressure in the plenum located behind a ‘closed’ section of the outer divertor plate (see Fig. 1) [7]. Thus, with the outer divertor strike point in its standard vertical plate position (Fig. 18a of [4]), the measurement plenum is connected to the Private Flux Zone (PFZ) below the x-point. As the outer divertor strike point is shifted to the top of the outer divertor plate (‘flat-plate’ divertor, Fig. 18c of [4]) the pressure gauge still samples the PFZ. However, in this configuration, the recycling occurs on the top of the divertor such that neutrals are generally launched in a direction towards the core plasma and away from the divertor. If the strike point is shifted down past the bottom of the outer divertor to the floor (‘slot’ divertor, Fig. 18b of [4]) the recycling still occurs in the divertor but the pressure gauge samples the common flux zone (CFZ) of the SOL. Figure 3 shows the result of these variations in magnetic geometry, with the x-axis indicating the location of entrance to the plenum with respect to the separatrix, referenced to midplane. The pressure has a mild maximum when the outer divertor strike point is located near the entrance to the measurement plenum behind the plate (at the bottom of the outer plate). The lack of a strong dependence on strike point location is in contrast to results from other lower density devices [11-13] where, unlike C-Mod plasmas, the neutral collisional mean free path in the divertor (cx and elastic), λ_{MFP}, is long compared to the divertor dimensions and ionization length, λ_{IONIZ} ($\lambda_{MFP}/L_D > 1$, $\lambda_{MFP}/\lambda_{IONIZ} > 1$); the neutral transport is 'ballistic' and neutrals only reach the pressure measurement plenum if they enter it on the first bounce.

IV. Modeling of the divertor neutral pressure

The development of numerical tools to model the C-Mod divertor, and by extension the ITER divertor, is still in its infancy. As mentioned above, the effort to match the C-Mod divertor conditions [1] led to simulated divertor pressures that were a factor of 10 below the measurements. That effort relied on a simple model for the divertor plasma.

More recently, the problem has been attacked again with the aim to develop a more accurate plasma description for the C-Mod divertor and to include a more extensive set of neutral physics, including radiation trapping effects [14,2]. This effort led to a better match between model and experiment. The plasma under investigation was a medium density C-Mod discharge (also used in [1]) where the inner divertor and PFZ plasmas were detached but the outer divertor plasma was attached. The EIRENE neutral transport code was used [15]. The modeled divertor plasma 'solution' was reconstructed from experimental measurements using the Onion Skin Method [16]. In particular, a simple, parameterized model for the profile of plasma conditions along the flux tube through the detached region was used. The plasma solution was forced to match, in an overall sense, the data from a host of plasma diagnostics ranging from Langmuir probes in the plates to spectroscopic measurements of D_γ emissivity, which is indicative of the occurrence of volume recombination, and the local density and temperature in the detached/recombining regions. The match of D_γ emission between experiment and modeling is shown in Figure 4. The two recombination zones correspond to the high emission regions in the PFZ paralleling the inner and outer legs.

A number of factors were found to be essential to obtain the observed high neutral pressures in the divertor. Neutral viscosity (arising from neutral-neutral collisions) is important inside the pressure measurement plenum; it supports a gradient in the D_2 density which extends from the PFZ into the plenum volume. However, neutral viscosity was found to be significantly less important outside the plenum where plasma-neutral interactions dominated instead.

$D^+ - D_2$ elastic collisions in particular were found to be a necessary element for achieving higher divertor neutral pressures. Molecules traveling to the PFZ from the plenum volume have a high probability to scatter off the cold, dense plasma in the PFZ. This leads to an effective *albedo*, A, of the PFZ plasma to the incident molecules. A flux balance can be assumed between hot neutrals entering the plenum and cold neutrals returning from the plenum to the PFZ. For a given "primary influx" of neutrals into the PFZ from the plenum (particles entering the PFZ for the first time), Φ_0, a fraction, $A\Phi_0$ is reflected back into the plenum. That flux then tries to enter the PFZ again leading to $A^2\Phi_0$ returning towards the plenum. This infinite series can be expressed as the total influx, Φ_{tot}, by:

$$\Phi_{tot} = \frac{\Phi_0}{1-A}, \qquad (1)$$

which is highly nonlinear as $A \to 1$. We can see evidence of the plasma-neutral collisions in the gradient in the density profile, Fig. 5. The density gradient at the entrance to the plenum is due to: (a) the conversion of D to D_2 via wall collisions; (b) the temperature gradient between the higher energy molecules outside the plenum (which have partially thermalized with the plasma via D^+–D_2 elastic collisions) and the colder gas inside the plenum that has thermalized with the walls; and (c) the higher energy neutrals "pushing" on the colder plenum gas via neutral-neutral collisions.

While neutral viscosity and plasma neutral collisions are important for *increasing* the divertor plenum pressure in the model, photon trapping has an important effect in *lowering* the divertor pressure. If a Lyman series photon emitted during a volume recombination event leaves the system either directly, or through multiple absorptions and re-emissions, the result is the creation of a ground state neutral atom. We call this a 'complete recombination'[17]. However, if that photon is absorbed by a neutral atom before leaving the system, *and* that neutral is ionized before re-emitting the photon, then there is no net gain in neutrals due to the volume recombination event (no complete recombination). This is termed photon 'trapping'. Thus, for a fixed plasma solution, which is the case here, proper accounting of the radiation transport and subsequent re-ionization leads to a reduction in the calculated recombination rate compared to the un-trapped case. The modelling of the photon transport was done with EIRENE and included Doppler and natural broadening, taking into account Ly_α through Ly_ε trapping. Zeeman splitting and Stark broadening have recently been incorporated into the modelling but are only expected to introduce a 10-20% change in trapping rates. Finally, the existence of openings (leakage) in the outer divertor structure were included in EIRENE which lowered the divertor pressure by roughly 60%. The relative importance of three of the above effects is shown in Figure 6.

Overall, the modeled discharge produced pressures around 11 mTorr, a factor of five above what was achieved previously[1], but still a factor of ~2 below that measured in experiment (25±3 mTorr). It is unclear at present whether the remaining discrepancy is due to deficiencies in the neutral model or inaccuracies in the plasma solution. This effort is continuing with improvements to the plasma and radiation transport models as well as modeling of higher density discharges where the outer divertor is detached leading to a higher level of photon trapping and shorter mean free paths (neutrals and plasma). These divertor plasma conditions are even closer to an ITER-like device, and provide an important test for the code's capabilities.

V. Effect of divertor closure on neutral pressures

A high divertor neutral pressure is desirable in a reactor since He ash removal is required and gas throughput is proportional to pumping speed times neutral pressure. One would expect that any neutral leakage from the divertor might lower the pressure below that of the ideal 'sealed' divertor. In addition, it is desirable to minimize the neutral pressures in the main-chamber. In reducing the neutral levels near the vessel walls outside the divertor, the main chamber impurity sources arising from charge exchange neutral sputtering of the wall should be reduced. Moreover, better control of core fueling should result. In practice, any divertor structure has intrinsic pathways (e.g., gaps for thermal-expansion) through which neutrals can 'leak' out of the divertor. These pathways are difficult to seal because of the complex mechanical structure. Nevertheless, the overall expectation has been that any success in reducing those leaks should lead to increases in the divertor pressure simultaneous with decreases in the main chamber pressure. With this view in mind, efforts were undertaken in C-Mod to close these intrinsic neutral pathways. However, the efforts led to some unexpected results.

Based on the simple modeling of divertor pressures outlined the previous section [9], it was predicted that if the toroidally semi-continuous gap (poloidal gap) between the largest major radius edge of the outer divertor and the vessel wall were closed (see Figure 1a), then the divertor pressure should rise by a factor of 1.7 and the midplane pressure should be halved. A further suggestion was made that if one changed the outer divertor geometry such that a larger fraction of the outer SOL impacts the vertical plate section of the divertor, then more neutrals would be created in the divertor instead of the main chamber, and thus increase the divertor pressure (and lower the midplane pressure).

Acting on the first of the above suggestions for modifying the divertor, the poloidal gap between the outer divertor and the vessel was filled with fiberglass insulation which, when compressed, drops the conductance through the gap to a small fraction of its original value. In fact the closure of the poloidal gap did lead to an *increase* in the divertor to midplane neutral pressure ratio by a factor of ~ 2-3 (see bottom panel of Fig. 7). This increase was almost entirely due to an increase in the divertor pressure; there is little or no evidence for a corresponding decrease in main chamber pressure as a result of closing the leak (top panel of Fig. 7) [18], suggesting that the main-chamber neutral pressure is set primarily by some other physical mechanism. The leakage through the poloidal gap represented approximately half the overall leakage out of the divertor with the remaining leakage due to the toroidal gaps between sections of the outer divertor plate required for diagnostic access.

VI. Main chamber recycling

The minimal, if any, reduction in main chamber pressures after the closure of the divertor leakage foreshadowed a radical rethinking of the plasma transport physics in the C-Mod SOL, in particular, the relative strengths of cross-field versus parallel ion transport [3]. Based on Mach probe measurements at the entrance to the outer divertor, the integral ion flux into the throat of the divertor is small compared to the amount of ionization occurring outside the divertor and fueling the plasma [19]. Since any neutrals escaping from the divertor must return as ions or neutrals back into the divertor, the level of divertor neutral leakage could not by itself account for the level of neutral ionization observed in the main chamber. The implication was that the source of neutrals in the main chamber must be from ions recycling on main chamber surfaces. To support these conclusions it was argued that there must be very strong radial ion transport in the SOL with an effective diffusion coefficient increasing strongly with distance from the separatrix [19].

Modeling, using UEDGE [20], was brought to bear on the above set of experimental data [21-23] with the same end result – divertor leakage (and thus divertor closure) does not have a large effect on main chamber neutral levels. An example of the match to experimental data is shown in Figure 8 (from [22]). As stated above, the amount of main chamber ionization, which is equivalent to the total flux of neutrals 'attacking' the plasma, is much greater than the ion flux into the divertor. It can certainly be argued that for scenarios where the divertor neutral leakage is very large, it could indeed affect the observed main chamber neutral levels. However, the action of closing the divertor to neutral leakage beyond a point where the leakage is small relative to the integral of ion fluxes to main chamber surfaces obviously has little effect on the main chamber pressure. This appears to be the case in C-Mod and for high densities in JET [12]. Modelling of ASDEX-Upgrade plasmas led to a similar conclusion regarding the role of radial plasma transport [24]. More recently, studies of DIII-D and JET SOL transport also indicate that strong radial transport exists in a number of devices [25-27] and that the 'main-chamber recycling' effect can be an important contributor to neutral pressures outside the divertor.

VII. Active experiments to determine the importance of main chamber recycling

Even though the concept of main-chamber recycling appeared to explain the disparity between the effect of divertor closure on the midplane and divertor pressures, doubts remained. In particular there was a concern that conditions of the chamber walls (neutral retention characteristics, wall-recycling levels) or of the plasmas themselves could have been different between the run periods with and without the divertor closure. Based on this concern, a divertor bypass valve system was designed and built [28]; see item #8 in Figure 1. The conductance between the divertor plenum and the main chamber is altered by the bypass, which consists of 10 discrete structures equi-spaced in the toroidal direction. The locations in the divertor structure are shown in Fig. 1. A single unit consists of seven louvered flaps. The total area of the bypass (10 units) is therefore 0.08m^2, giving a free-molecular conductance of ~ 23 m^3/s. This amount of conductance is comparable to the intrinsic leakage conductance through the open ports as well as the leakage through the toroidally semi-continuous gap that had been closed. The bypass is controlled using a small embedded coil. When energized, the resulting interaction with the ambient toroidal magnetic field produces a torque which rotates all seven flaps of the bypass. The bypass can open or close in a time as short as ~20 ms.

Experiments showed that bypass valve affected only the divertor pressure, not the mid-plane pressure – the same response seen previously when the toroidally, semi-continuous, leakage gap (item #11 in Figure 1a) was closed by a ‘glass-sock’ material. Figure 9 shows the divertor and midplane pressures as a function of $\overline{n}_e$ for both open and closed bypass conditions. All plasmas are with ohmic heating only. The midplane pressure increases strongly with $\overline{n}_e$, roughly as $\overline{n}_e{}^4$. The divertor pressure also increases strongly. We see that the opening of the bypass lowers the divertor pressure by ~ factor of 2. The saturation in divertor pressure above

$\overline{n}_e$=1.8x10^{20} m^{-3} is due to detachment.

The divertor and main chamber plasma parameters were carefully compared with and without the bypass open. There were no significant differences seen in the profile of plasma across the divertor plate, the plasma across the SOL, or the flows in the SOL.

One initial aim of the bypass experiment was the investigation of the effect on the main chamber SOL of changing the flux of neutrals escaping the divertor. Measurements of D_α just above the bypass indicated that a portion of the flux of neutrals through the bypass is ionized in the main chamber relatively close to the bypass. Such a particle flux must re-circulate as ion flow in the SOL in steady state, ultimately returning to the divertor. The probe at the entrance to the divertor shows a well-defined net flux into the outer divertor, which does not depend on the state of the valve. In addition, that flux into the divertor is smaller than, but similar to, the flux estimated (based on molecular flow) to pass through the bypass. The probe and D_α measurements suggest that most of the particles going through the bypass return directly to the outer divertor, and are not transported as ions around the plasma periphery. Apparently, the influence of the bypass valve state tends to be lost in the presence of a relatively large amount of main-chamber recycling.

Alternatively, the observation that the mid-plane pressure and flux into the divertor is insensitive to the bypass valve state might be explained by a tendency for the plasma to maintain a constant leakage flux from the divertor plenum to the main chamber. In other words, when the bypass is opened, the conductance out of the divertor increases, the divertor pressure decreases, and the net flux (conductance times pressure) might stay approximately constant. It was argued that such a ‘fixed-flux’ of neutrals might be set by a rate-limiting process, such as the ion flux to the divertor, which is the primary source of neutrals in the divertor [29]. Based on these considerations, the relative contributions to the mid-plane pressure of main chamber recycling and neutral leakage from the divertor remained uncertain.

As a result of this ambiguity, further experiments were conducted in an attempt to unfold the relative roles of divertor leakage and main chamber recycling [30]. These involved a comparison of the pressures in the upper divertor (locations 1 and 2 of Fig.1), the mid-plane (location 5) and the lower divertor (location 9 and 10). Location 9 corresponds to toroidal location where the lower divertor is fully 'closed', i.e. with no local toroidal opening, while location 10 is at a diagnostic port opening ('open') – a location where a 6 degree toroidal sector of divertor is removed for diagnostic access. Figure 10 summarizes the results. Mid-plane pressure is plotted as a function of the three divertor pressure measurements (lower divertor 'closed', 'open' and upper divertor). These data exhibit a linear correlation between the midplane pressures and the lower open divertor and/or the upper divertor pressures; a non-linear relationship between midplane and 'closed' divertor pressures is found [30]. Thus, it is unlikely that the 'closed' divertor plays a direct role in determining the midplane pressure, except indirectly through neutrals traveling to the 'open' divertor. We note that the upper divertor neutral pressure is the result of recycling there of plasma on flux surfaces in the SOL far outside the separatrix, in the region of the second separatrix. The gap between first and second separatrices, mapped to the midplane, SSEP, is in the range 1.5-2 cm for most C-Mod experiments.

The linear scaling between the lower divertor (open port) pressure (P_{LD}), upper divertor pressure (P_{UD}) and the midplane pressure ($P_{0,Mid}$) is consistent with a simple model [30] which balances the number of neutrals outside the divertor attacking the core plasma per unit time ($\Gamma_{\perp,0}$) through the plasma surface area, A_{Plasma}, with the neutral flux through lower (open) and upper divertor leakage areas, $A_{L,Leak}$ and $A_{U,Leak}$.

$$P_{0,Mid} \approx f(P_{UD}R_{UA} + P_{LD}R_{LA}) + P_{MCR} \qquad (2)$$

The contribution of main chamber recycling at outer wall surfaces to the midplane pressure is denoted by P_{MCR}. The ratio of $A_{L,Leak}$ to A_{Plasma}, R_{LA} =.0136, and $R_{UA} \sim 8xR_{LA}$. f is the probability that an escaping neutral will reach the midplane before being ionized.

Since $P_{LD}R_{LA} \sim P_{UD}R_{UA}$ then the contribution to the midplane pressure due to main chamber recycling at the top of the chamber is already similar to the effect of leakage from the lower divertor. Allowing main chamber recycling at the outer wall (P_{MCR}) will reduce the relative contribution of lower divertor leakage still further.

Using a plausible upper limit for f (0.5), P_{MCR} was estimated. Substituting in the scaling relationships of Fig. 10bc between P_{UD}, P_{LD} and $P_{0,Mid}$ we find $P_{MCR} \sim 0.67xP_{0,Mid}$. If we assume that the upper chamber contribution to the midplane pressure is really just part of main chamber recycling then main chamber recycling contributes ~80% of the midplane pressure.

The data of Figure 10 show that it is difficult to separate out the effect of the different divertor geometries (lower or upper) on the midplane pressure because of the strong correlation with $\bar{n}_e$. One strategy used to separate out the effect of the different divertors is to vary the magnetic equilibrium from single-null x-point at the lower divertor (LSN) to double-null (symmetric up-down x-points). We use SSEP, as a measure of x-point balance. Figure 11 includes data from the upper divertor, midplane and lower divertor (closed and open ports) pressures versus the SSEP parameterization. The curves in Fig. 11 show the result of fitting the pressure data from the divertors and using that as input to the model prediction (simpler version of Eq. 2) of the midplane pressure. The contributions to the midplane pressure are $\boldsymbol{P_{MCR} / P_{0,Mid}}$ ~ 0.9 and $\boldsymbol{P_{L,Leak} / P_{0,Mid}}$ ~ 0.1. We note that this estimation of $P_{MCR}/P_{0,Mid}$ is not dependent on knowing the values of $\boldsymbol{f}$, R_{LA} and R_{UA}.

Finally, a third method of determining $P_{MCR}/P_{0,Mid}$ was used in this study [30]. The lower divertor pressure was changed by changing the inner wall gap (keeping the gap to the outer limiters constant). This lowered the lower divertor pressure by a factor of 4 with ~ 10-25% drop in the midplane pressure. This again shows that the lower divertor leakage plays a minor role in determining the midplane pressure. In summary, the techniques utilized for examining the relative effects of divertor leakage and main chamber recycling in determining the midplane pressure give essentially the same result, $\boldsymbol{P_{MCR}/P_{0,Mid}}$ ~ 0.8-0.9 and the transmission of neutrals to the midplane, f, in the range 0.1 - 0.5.

Although the preceding analysis examines the role of divertor leakage in determining the midplane pressure, the question of the relative roles of mechanical (baffling) versus plasma blockage (or ‘plasma-plugging’) of the neutral flows was not addressed. Neutral pressures in the toroidally and poloidally-open upper divertor during upper x-point discharges are found to be comparable to neutral pressures in an short (toroidally) open section of the lower divertor during lower x-point discharges. These results suggest that plasma baffling must make a significant contribution in reducing the overall leakage conductance (i.e., ‘effective conductance’). A study was undertaken to address this question [31]. A novel experimental technique was employed, using capillaries to puff known flow rates of D_2 gas into different parts of the lower divertor (open and closed sections) as well as the upper, open divertor with and without plasma present. Localized pressure measurements were also made nearby, allowing the gas conductance and flow through the various structures to be measured directly. It was found that the presence of a lower single-null plasma (LSN) in the vacuum vessel lowers the effective neutral conductance out of the open sections of the lower divertor (diagnostic openings) by a factor of ~ 4 relative to the vacuum conductance value. Conductances out of the ‘closed’ sections of the lower divertor are also reduced by the presence of this plasma, but only by a factor of ~2. The LSN plasma was even found to influence the overall neutral conductance from the upper divertor chamber, dropping the conductance there by a factor >2. When the plasma magnetic equilibrium was switched to USN, a dramatic drop in effective leakage conductance from the upper divertor was seen – a reduction of a factor of ~5 relative to the vacuum conductance value. Recently, Stotler has used these data to help benchmark the DEGAS2 neutral transport code [32], simulating C-Mod's 3-D vacuum vessel structure and resulting vacuum conductances. The ultimate goal is to use direct neutral conductance measurements such as these to further constrain plasma and neutral transport modeling of the divertor.

VIII. Summary

The divertor characteristics of Alcator C-Mod lead to neutral densities and mean free paths approaching those predicted for ITER, thus providing essential tests of neutral and plasma models. C-Mod research shows that in addition to divertor recycling, three-body recombination can be an important neutral source affecting divertor pressures. Experimental results and simple models show that the diffusive nature of neutrals in C-Mod reduces their chance of escape from the divertor during detachment. That, together with recombination, are key reasons the divertor pressure does not drop even though the ion flux to the divertor plates drops by a factor of 10. The short neutral mean free path in C-Mod (normalized to the size of the divertor), approaching ITER, leads to an absence of an effect of divertor strike point geometry on neutral pressure, unlike other tokamaks where neutrals are more kinetic in nature. The testing of plasma-neutral codes on C-Mod divertor conditions proved very difficult as they had only been tested under kinetic neutral conditions. Careful comparison of the models with experiment showed that the physics associated with short neutral mean free paths (e.g. viscosity) and trapping of hydrogenic Lyman alpha radiation play an important role in determining the neutral pressure. Of equal importance is the result that the private flux region must be modeled properly, including detachment effects, to recover the neutral pressure.

Neutrals studies of regions outside the divertor proper have also led to ground-breaking results. The minimal reduction of the C-Mod main chamber pressure after leaks of neutrals from the divertor were significantly reduced (and the divertor pressure increased) became essential to the shift in understanding of the role of perpendicular transport in the SOL: Only larger than expected ion fluxes to surfaces outside the divertor could support recycling and neutral sources comparable to that in the divertor. This realization led to a number of active and passive experiments and modelling to support this hypothesis. The end result is that the C-Mod research has played an important role in characterizing the phenomena of radial transport and its consequences.

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Figure Captions

Figure 1: Poloidal (a) and toroidal (b) cross-sections of Alcator C-Mod showing the lower closed divertor and open upper divertor. Baratron capacitance manometer pressure gauges are located in the vertical ports at locations 1,9 and 10. A shielded Bayard-Alpert gauge is at location 5 in a horizontal port. Penning gauges are attached the wall of the vessel at locations 3 & 6. Scanning probes are inserted horizontally (4) and vertically (7). Divertor bypass valves are located at 10 points toroidally (8). Two thin plates/gussets (#2, shown as dotted lines) of ~ 1.25 cm toroidal extent, are located on either side of each of 10 vertical ports with protection tiles on the edge facing the plasma. The gap between the outermost edge of the outer divertor and the vessel is indicated by location 11 (cf discussion under section V).

Figure 2: Divertor neutral pressure versus line-averaged plasma density, spanning different divertor plasma regimes (from [7]).

Figure 3: Divertor pressure as a function of outer strike-point location. The horizontal axis gives the distance of the entrance to the pressure measurement plenum from the strike point (referenced to the midplane). When the strike-point is at smaller major radius than the plenum the geometry is labeled ‘slot’ divertor and the plenum is sampling neutrals from the common-flux zone. In the ‘flat-plate’ and standard ‘vertical-plate’ divertor configurations the measurement plenum samples neutrals from plasma in the private flux zone. See [4] for more details of the divertor geometries.

Figure 4: Dγ emissivity patterns derived from experiment (a) and modeling of the same discharges (b) from [2].

Figure 5: (a) The neutral molecule density distribution for the standard case (linear scale). (b) The neutral molecule pressure for the standard case (linear scale). (c) Radial variation (along the dashed horizontal line in [a]) of the molecule density with (solid) and without (dashed) viscosity included in the model. (d) Radial pressure variation, as in (c). Figure from [2].

Figure 6: The change in the calculated neutral pressure when various processes are removed from the standard (with all effects except neutral leakage) neutral model in EIRENE (from [2]).

Figure 7: a) Main-chamber and divertor neutral pressures before and after closing a neutral leakage pathway in the C-Mod divertor; b) Compression ratio of divertor to midplane pressures.

Figure 8: Rough estimates of ionization fluxes in the main chamber from midplane D_α (green diamonds), ion fluxes towards the divertor from the scanning Langmuir/Mach probe (purple stars) and ion fluxes onto divertor surfaces from divertor probes (red squares) as a function of an estimate of the neutral flux from the wall. UEDGE simulations of two discharges yield similar results: fluxes from the main-chamber ionization (open diamond) are much higher than fluxes directed towards the x-point (open star). Figure from [22].

Figure 9: Midplane pressure (a), divertor pressure (b) and their ratio (c) as a function of line-averaged density for cases with bypass valve open and closed (from [28]).

Figure 10: Correlations between midplane pressures and (a) lower ‘closed’ divertor, (b) lower ‘open’ divertor, and (c) upper divertor pressures (from [30]).

Figure 11: Dependence of neutral pressures on the x-point balance (SSEP) in otherwise identical discharges. SSEP = 0 corresponds to a balanced double-null case. SSEP < 0 corresponds to lower single-null divertor. Symbols indicate measurements. Lines indicate model results. See Figure 1 for locations of pressure gauges. Figure from [30].

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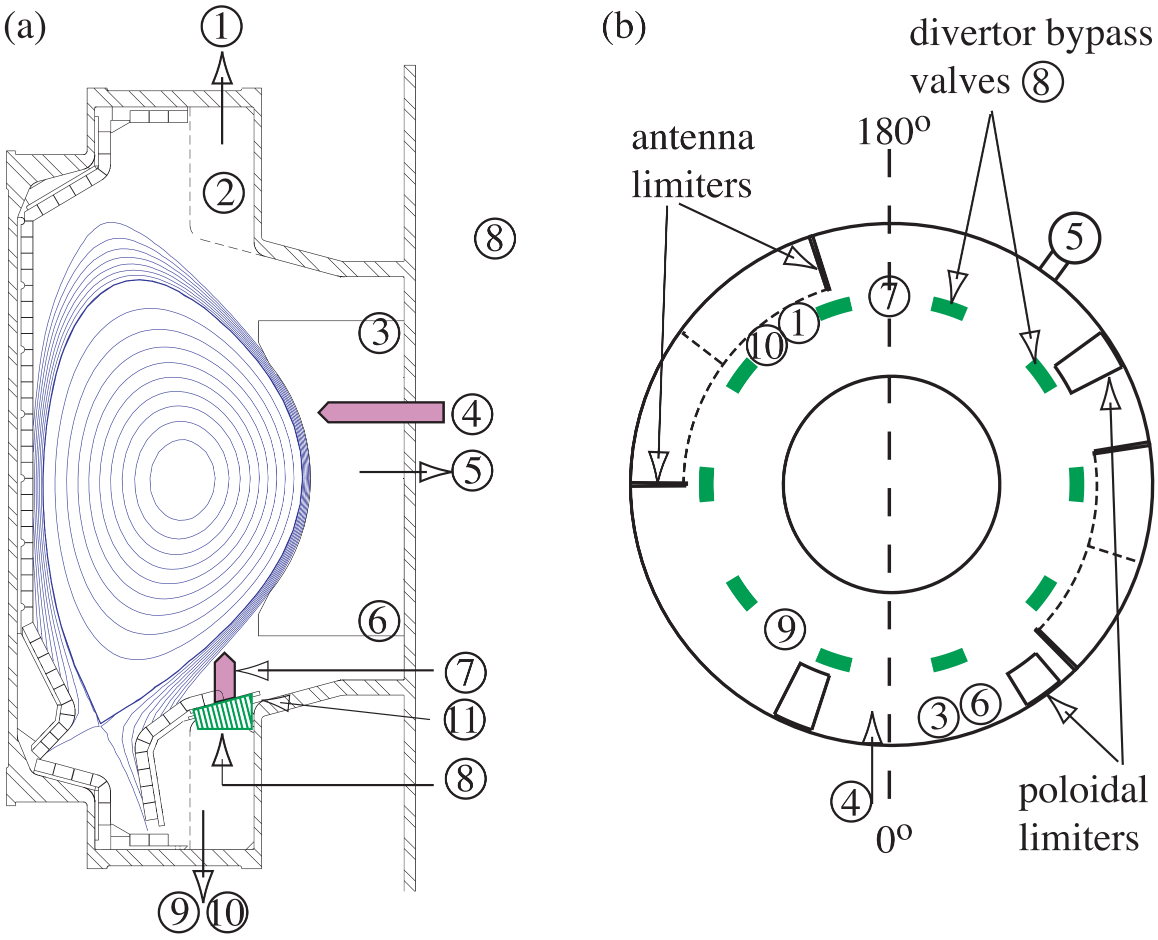
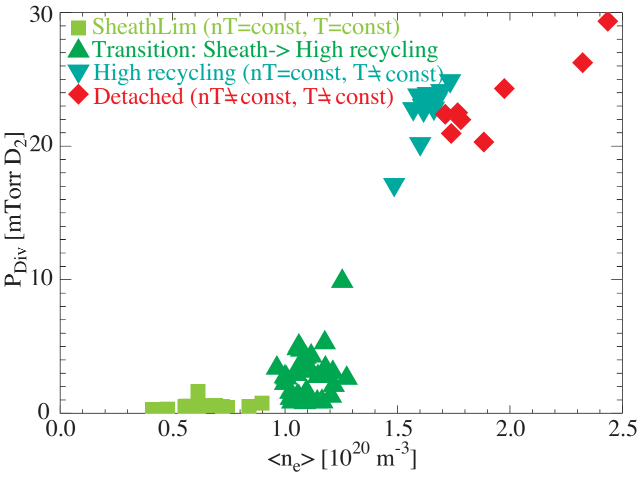


Figure 1: Neutrals studies on Alcator C-Mod, Lipschultz et al.



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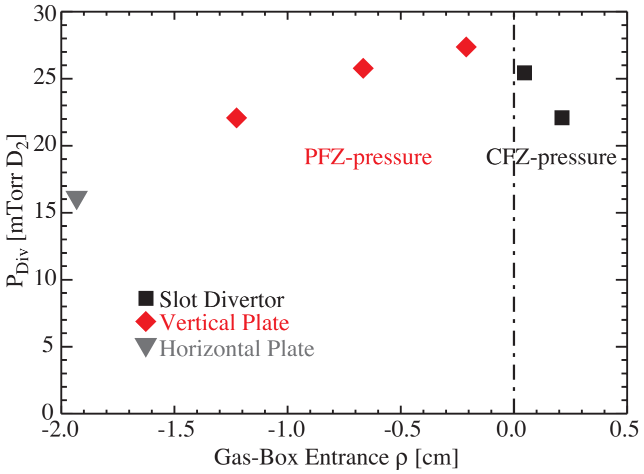

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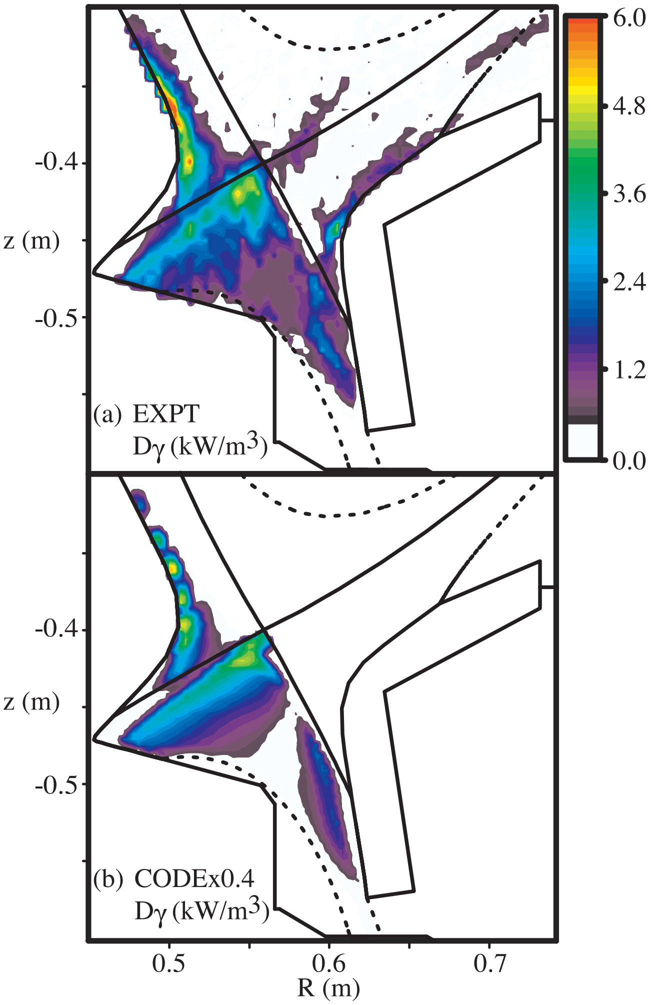

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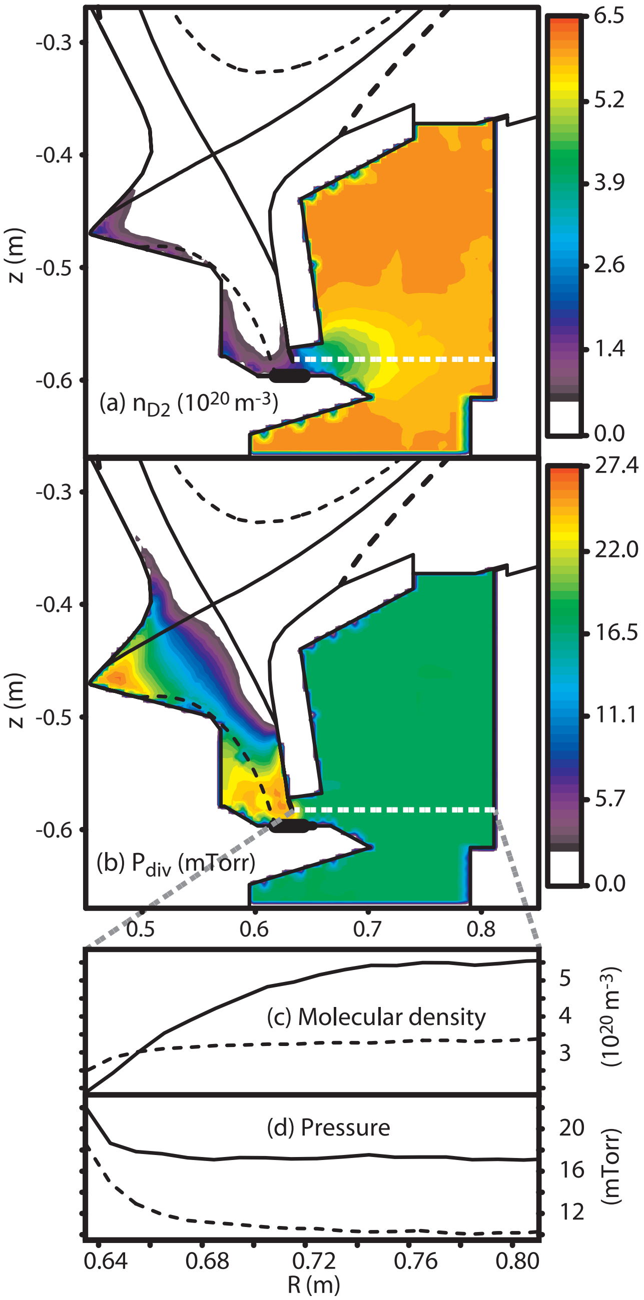

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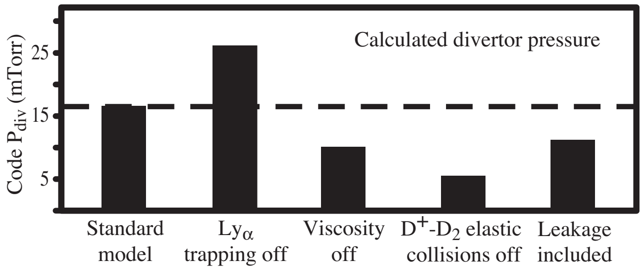


Figure 6: Neutrals studies on Alcator C-Mod, Lipschultz et al.

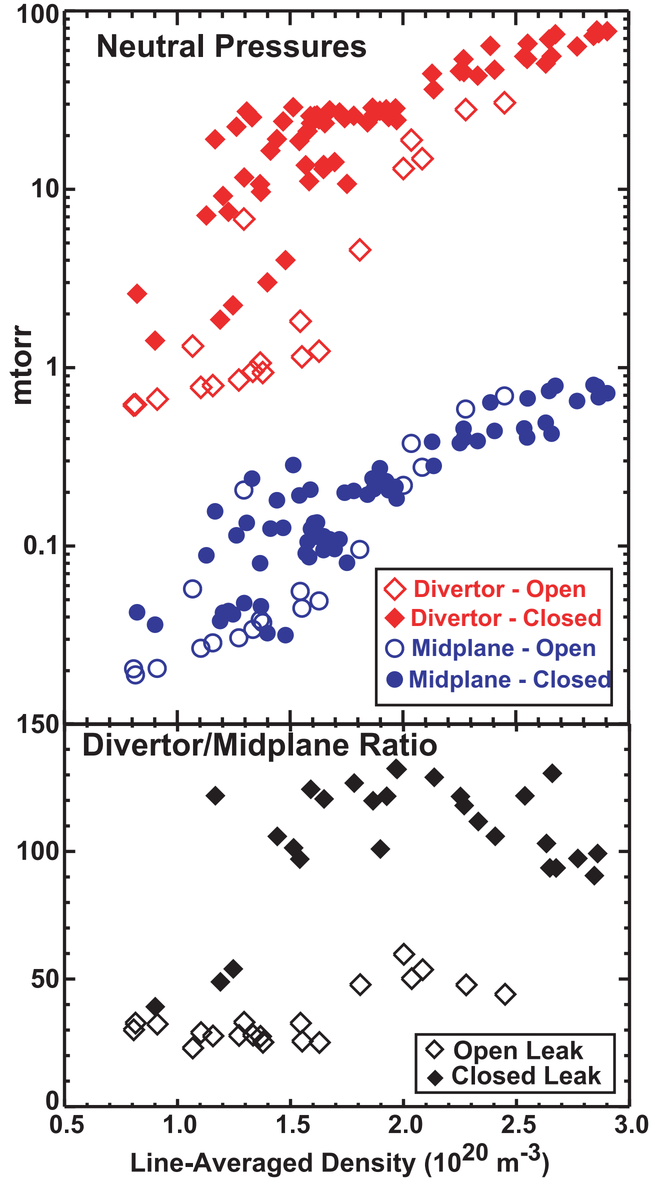
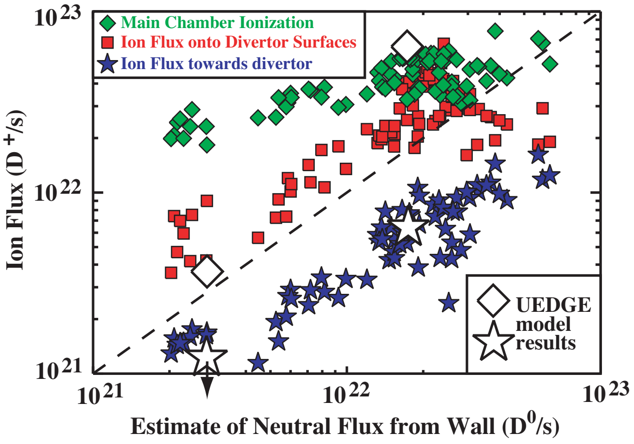


Figure 7: Neutrals studies on Alcator C-Mod, Lipschultz et al.



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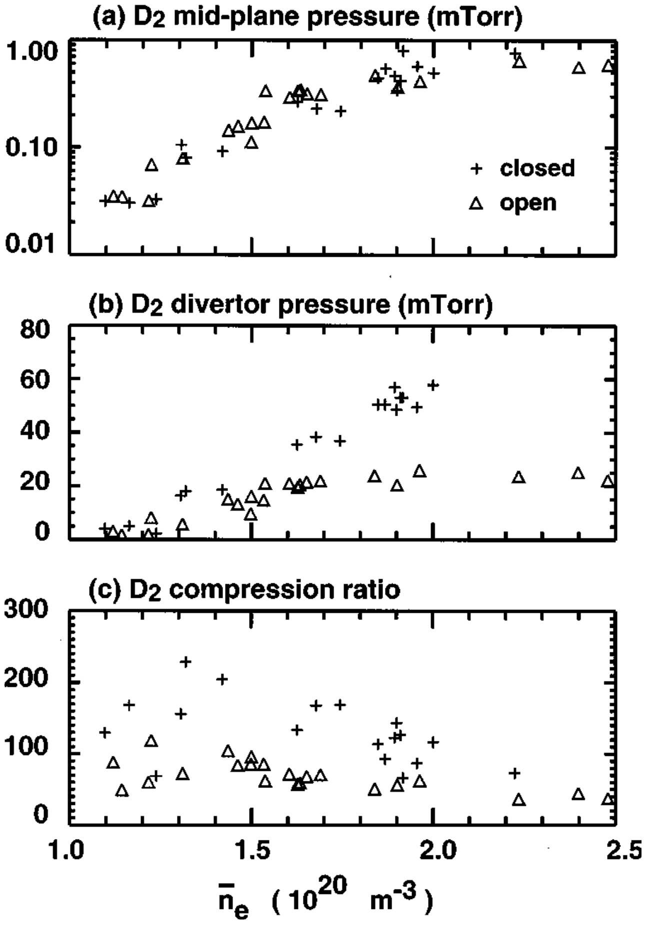

Figure 9: Neutrals studies on Alcator C-Mod, Lipschultz et al.

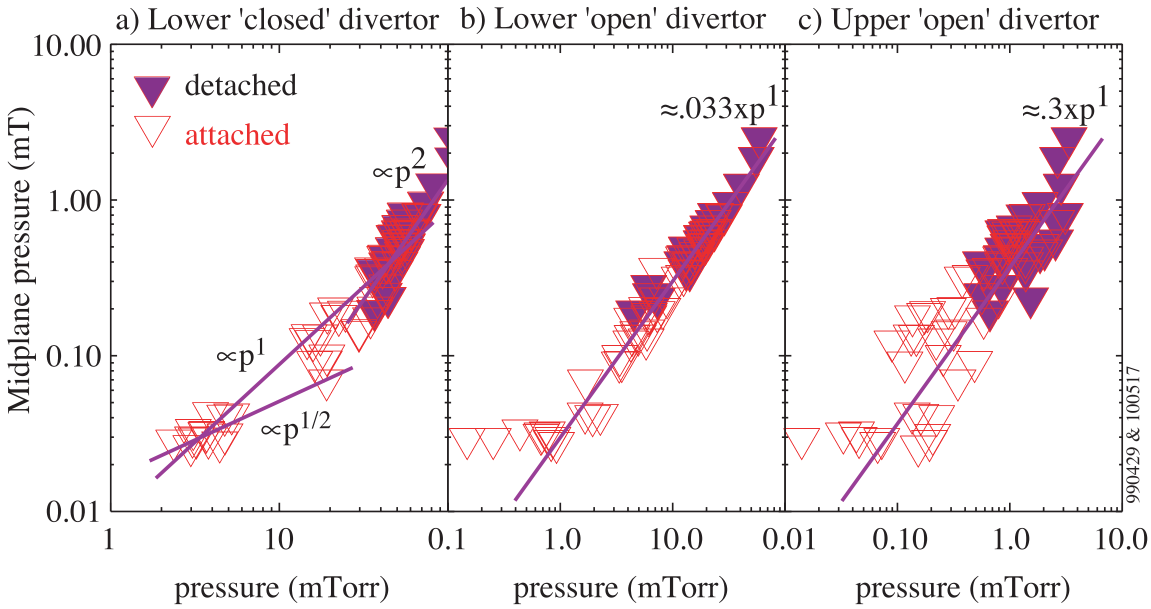

Figure 10: Neutrals studies on Alcator C-Mod, Lipschultz et al.

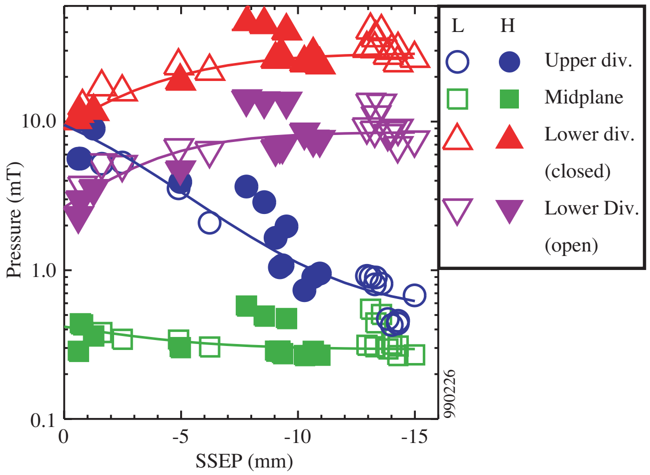

Figure 11: Neutrals studies on Alcator C-Mod, Lipschultz et al.