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The role of friction in SOL pressure balance in Alcator C-Mod

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Abstract

We assess the importance of ion–neutral friction in parallel plasma pressure balance in Alcator C-Mod. For a high-powered N_2 seeded case, a large plasma pressure drop is observed along the magnetic field, coincident with a significant parallel velocity differential between the plasma ions and the neutral particles in the divertor. The observed pressure loss is consistent with the inferred friction and cannot be explained by volume recombination.

Keywords: Detached plasma; Detachment; Charge-exchange momentum loss; Flow; Flow reversal

1. Introduction

The parallel power density q_u flowing in the scrape-off-layer (SOL) upstream of the divertor in a burning or ignited magnetic fusion device is expected to be very large, i.e. > 1 GW m^{-2}, much larger than can be transferred in an acceptable way across a plasma-material interface, i.e. < 5 MW m^{-2}. Even with the glancing magnetic field angles present in divertors, which for example can reduce the heat flux incident on the surface by a factor as large as ~ 100 from the parallel field value, the resulting heat flux density is still too large to provide acceptable engineering margins.

One solution to this problem is the dissipative divertor, where a large fraction of the upstream power density is dispersed more uniformly by electromagnetic radiation, and possibly by neutral particles, see review [1]. Recent research has shown that the parallel power density at the target plate q_t can be reduced from the upstream value by factors as large as ~ 100, although factors of 5–10 are more typical. These latter values are adequate to bring the heat flux down to acceptable levels in a reactor. Discharges operated in this way are said to be 'detached' because they are usually accompanied by large plasma pressure reductions at the target plate in comparison to upstream values, i.e. typically, $p_t/p_u < 0.1$ and in extreme cases (e.g. in Alcator C-Mod) $p_t/p_u \approx 0.01$ has been found [2]. Since ion particle flux density on the plate ϕ_t is closely related to the local pressure p_t, large reductions in ion particle flux are simultaneously observed during detachment. Under these conditions, a key feature in the reduction of the power incident on the plate is the decrease of the ion flux and its associated flux of potential energy (ionization + molecular binding, [3]).

Two candidate processes may be responsible for the loss of plasma pressure along magnetic field lines – ion–neutral friction and volume recombination. In this paper we focus on the first, ion–neutral friction, and examine the experimental evidence for its presence in Alcator C-Mod. We refer the reader to a companion paper in this conference where recombination has been quantitatively addressed [4]. We start first with a simple model, comparing the relative magnitudes of the two processes under various assumptions. Following this we then present recent experimental results.

2. Simple model

In the case of ion–neutral friction, plasma momentum (i.e. pressure) is lost through elastic and charge–exchange (CX) collisions between ions and neutral

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atoms/molecules when a velocity differential exists between the plasma and neutral fluids, i.e.

$$\frac{d}{dx}[p_i + p_e + mnv^2] = -m(v - v_H)S_m, \quad (1)$$

where x is along the magnetic field line, $p_{i,e}$ are the ion and electron static pressures ($T_i = T_e$ is assumed, and is reasonably accurate in C-Mod's high density SOL [1]), m is the ion mass, n and v are the plasma density and velocity, v_H is the neutral velocity and $S_m = nn_H\langle\sigma v\rangle_m$ is the charge-exchange reaction rate [5]. We assume for simplicity that only atoms are present (no molecules).

In the case of volume recombination, plasma momentum is transferred to the neutral fluid by conversion of the ion to an atom,

$$\frac{d}{dx}[p_i + p_e + mnv^2] = -mvS_r, \quad (2)$$

where $S_r = n^2\langle\sigma v\rangle_r$ is the recombination rate (radiative and three-body assumed [6]). In this calculation, optically-thin conditions are assumed for the transport of Lyman radiation, and thus this calculation over-estimates the importance of volume recombination, i.e. radiation trapping effectively reduces the recombination rate [7].

The relative importance of the two sinks for momentum can be explored using their ratio,

$$R \equiv \frac{\langle\sigma v\rangle_r}{\left(1 - \frac{v_H}{v}\right)\left(\frac{n_H}{n}\right)\langle\sigma v\rangle_m} \quad (3)$$

given in Fig. 1 for a range of plasma densities and velocity ratios (v_H/v), assuming conditions typical of a detached divertor in Alcator C-Mod, i.e. $T_i = T_e = 1$ eV and $n_H = 0.1$ n. As shown, under most conditions momentum loss due to friction is dominant over recombination, except when the neutral–ion velocity ratio is close to unity, that is $v_H/v > 0.99$. Thus, a critical issue in detachment research is the relative velocities of the atoms and ions in the recycling region in the divertor. Unfortunately, such measurements are difficult, although we present new measurements here where parallel velocities have been deduced by spectroscopic Doppler shifts.

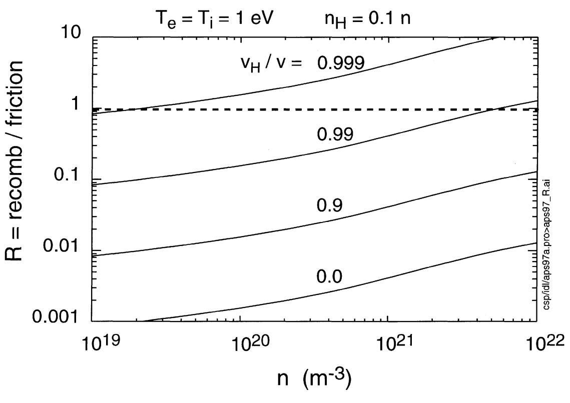

Fig. 1. The ratio R of recombination rate to friction rate for various conditions. v_H is the neutral velocity, v is the plasma velocity.

3. Experiment

Alcator C-Mod is a compact, high density, high field tokamak with a single (bottom) closed poloidal divertor with molybdenum armour as the primary first-wall component, Fig. 2. In this paper we use a variety of divertor diagnostics, including Langmuir probes built into the outer divertor plate and a fast scanning Langmuir/Mach probe (FSP) at an upstream location on the low-field side. The radiated power from the plasma is measured with a number of multi-chord bolometer arrays, which are able to deduce the 2D radiation pattern in the divertor and in the main chamber.

In the case of the above-mentioned Doppler measurements, a four chord tangential array viewing the divertor plasma from the bottom is utilized. The angle of the chords with the magnetic field is $\approx 30°$. Because of the toroidal curvature, the views trace out a curved path in a poloidal projection as shown in Fig. 2. The collected light is fed via optical fibers to a high resolution visible spectrometer. Doppler shifts, ion temperatures and magnetic field strength are derived by fitting the individual spectral lines using a multi-parameter optimization procedure [8,9].

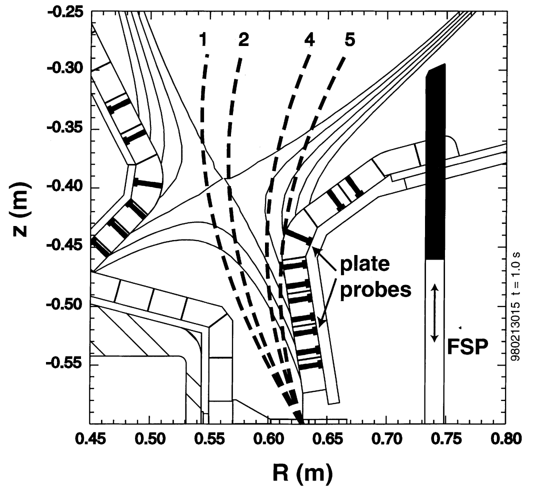

Fig. 2. Poloidal cross-sectional view of the Alcator C-Mod divertor, showing the plate probes, the fast-scanning probe (FSP) and the position of the tangential viewing chords.

4. Global discharge parameters

In this paper we focus on two Alcator C-Mod discharge scenarios – high-powered discharges, without and with nitrogen seeding, corresponding to attached and detached divertor conditions, respectively. The attached discharge scenario is similar to the 'EDA mode', discussed previously [10]. These discharges were fueled with deuterium, heated with H-minority ICRF heating, had a plasma current of $I_p = 1.0$ MA, a magnetic field of $B_t = 5.7$ T (favourable direction), no discernable ELMs, H-mode confinement ($H_{ITER89} \sim 1.5$) and had a small amount of helium puffing for divertor flow measurements.

At $t = 0.50$ s, 2.7 MW of ICRF heating is applied, which increases the total input power from the Ohmic value of $P_{tot} \approx 2$ MW to $P_{tot} \approx 4$ MW. Shortly after this, at $t = 0.67$ s, both types of discharge jump into H-mode. In the case of the detached discharge, nitrogen enters the vessel (from the divertor) at $t = 0.70$ s, resulting in an increase of the total radiated power P_{rad} and Z_{eff} over the attached case. By $t = 1.0$ s, the discharges reach a quasi-steady-state, which is maintained for the duration of the ICRF pulse (until $t = 1.4$ s). Comparing the attached and detached results during this steady-state period, for P_{rad}/P_{tot} we find 0.6 ± 0.1 and 0.9 ± 0.1, respectively, and for Z_{eff} we find 1.0 ± 0.1 and 1.4 ± 0.1. The 2 MW incremental radiation associated with the N_2 puffing originates in equal measure from the confined plasma and the divertor plasma, so that $P_{SOL}/P_{tot} \sim 0.7$ in the attached case compared with $P_{SOL}/P_{tot} \sim 0.5$ in the detached case. The corresponding upstream parallel power densities in the SOL are quite high, $q_u \sim 0.6$ GW m^{-2} and $q_u \sim 0.4$ GW m^{-2}, respectively.

5. Outer divertor pressure loss

In the detached discharge, the radiation level rises continuously after the start of the nitrogen puff until $t = 0.9$ s, by which time $P_{rad} \approx P_{tot}$ and the outer divertor is strongly detached. The effect on the SOL is given in Fig. 3, where upstream 'u' and target 't' conditions as measured by the fast-scanning probe and outer plate probes, respectively, are given in the attached and detached discharges, corresponding to a flux surface 1 mm outside the separatrix.

The upstream measurements of electron temperature T_u and electron pressure p_u are only slightly affected by the various phases of the discharge, and whether attached or detached, Fig. 3. In contrast, the target plate conditions are strongly affected by the discharge phase. In the case of the electron temperature, an abrupt decrease at the target to $T_t \approx 5$ eV is observed on entering H-mode at $t = 0.67$ s, which is maintained for the remainder of the attached discharge and is reduced to as low as $T_t \approx 1.5$ eV at $t = 0.9$ s for the detached discharge after N_2 puffing. In the case of the electron pressure at the target plate, no pressure reduction is observed for the attached discharge within experimental error (factor ~ 2), but a strong reduction is observed for the detached case, i.e. a factor of $p_t/p_u \approx 0.02$ at $t = 0.9$ s, coincident with the minimum in the electron temperature

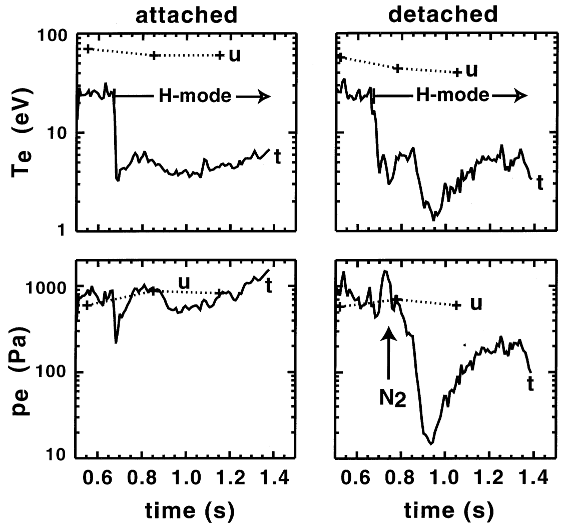

Fig. 3. SOL conditions (electron temperature and pressure) from the probes as determined at the upstream 'u' location with the fast-scanning probe (FSP) and at the outer target plate 't', all on a flux surface 1 mm outside the separatrix. Attached and detached conditions are given. Numbers on the figure refer to shot number.

These results, presented for the nominal 1 mm flux surface, are relatively insensitive to positional uncertainties (±1 mm) associated with errors in the magnetics, which can introduce a factor of ~ 2 error in absolute electron pressures. This is small compared to the very large pressure drop observed. The observed pressure loss is restricted to a 3 mm wide region (mid-plane equilvalent) close to the separatrix. This corresponds approximately to the first power-width at the divertor plate under attached conditions. Further out in the SOL, little or no pressure loss is observed. This behaviour is similar to that observed in other machines, and is often called 'partial detachment' [1].

6. Ion–neutral velocity differential

Simultaneous measurements of the parallel drift speeds in these discharges have been made using the Doppler shift obtained viewing the divertor plasma using the tangential chords indicated in Fig. 2. Fig. 4 gives the results corresponding to the detached discharges for the He II (468.6 nm) and D_α drifts, where these species are representative of the plasma and neutral drifts, respectively. In the case of the He II, arising from singly ionized helium, this ion is expected to be strongly coupled to the background plasma due to its relatively high ionization potential, as well as the low plasma temperature and high plasma density in the divertor, e.g. the momentum transfer time between He^+ and D^+ ions is estimated to be $\sim 10^{-8}$ s, compared to the parallel transit time to the plate of $\sim 10^{-4}$ s and ionization time of $> 10^{-3}$ s. The results presented are for Chord 4, which intersects the divertor fan approximately 2 cm from the plate in the poloidal direction.

Although light is potentially collected along the full length of the viewing chords, two indepedent measurements indicate that the measured signal is heavily weighted by emission near the separatrix (below the X-point). In the first, the spectroscopic drift measurements themselves provide an accurate measure of the emission location through the determination of the local magnetic field via the Zeeman/Paschen-Back splitting pattern [8,9]. In the second, two-dimensional D_γ and D_α distributions are derived by unfolding tangential TV images [7]. These also indicate that emission is close to the separatrix below the X-point.

Early in the discharge (before the H-mode period, $t \sim 0.6$ s) the divertor fan is relatively hot ($T_t \approx 25$ eV) and flows are out of the divertor, i.e. flow reversal is observed for both the He II and D_α of magnitude $\sim 4 \times 10^3$ m s^{-1}, Fig. 4. This is consistent with the FSP at the upstream location, which indicates a Mach number of $M \approx -0.2$ or reversed flow velocity of $\approx -10^4$ m s^{-1} on the 1 mm flux surface. Such reversed SOL flows are consistent with other measurements on Alcator C-Mod [11,12].

At later times, the He II flow is directed toward the plate with a velocity $v \approx 7 \times 10^3$ m s^{-1}, which corresponds to a plasma Mach number of $M \approx 0.5$ at a temperature of $T_t = 2$ eV. In contrast, the D_α velocity, while also being directed toward the plate, is substantially lower, $v_H \approx 1.5 \times 10^3$ m s^{-1}, corresponding to a neutral Mach number of $M \approx 0.1$ at a temperature of $T_H = 2$ eV.

7. Neutral flow distribution

Fig. 5 gives the parallel neutral velocity as a function of poloidal position at $t = 1.0$ s for the attached and detached cases. In general, the neutral fluid accelerates as the divertor plate is approached, with the neutrals being nearly stagnant near the X-point. In both attached and detached cases, the maximum velocity (at the plate) is considerably lower than the expected sound speed for the plasma ions, e.g. in the attached case the estimated sound speed is $c_S \approx 2 \times 10^4$ ms^{-1} based on the Langmuir probes, compared with a neutral velocity at the plate (chord 5) $v_H \approx 5 \times 10^3$ ms^{-1}. The situation is similar in the detached case, already discussed in the Section 6.

8. Discussion

The primary result of this paper is the demonstration of a significant parallel flow differential between the plasma flowing towards the plate and the neutral deuterium atoms under detached conditions, Fig. 4. While the plasma flow is roughly consistent with the ion acoustic velocity, as one would expect for a plasma in close proximity to a surface, the neutral velocity is significantly smaller, essentially stationary in comparison. Under such conditions, i.e. with local plasma densities like $n_e \sim 10^{21}$ m^{-3} (as measured) one would expect the

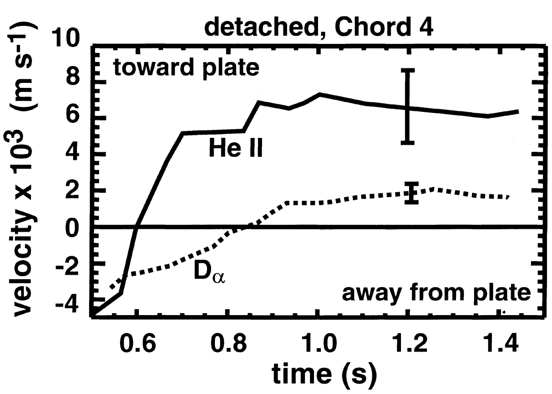

Fig. 4. Parallel drift velocity derived from the Doppler shift of He II and D_α emissions observed with the tangential viewing array in the detached discharge.

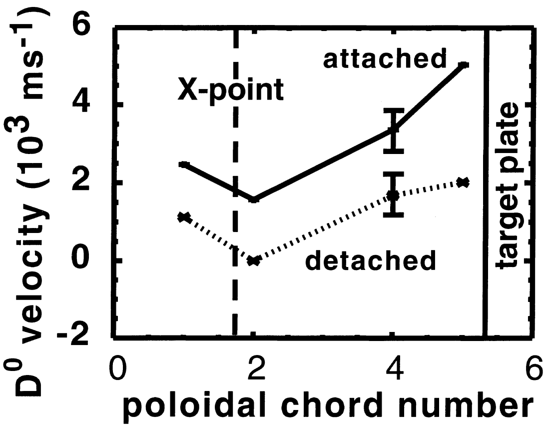

Fig. 5. Parallel drift velocity as a function of viewing chord, derived from the Doppler shift of D_α emissions observed with the tangential viewing array in the attached and detached discharges.

pressure loss observed to be dominated by friction and not volume recombination. In fact, estimates of the recombination rate based on analysis of the Balmer spectrum in these discharges confirms that ion particle loss due to the recombination sink, and thus also pressure loss Eq. (2), is small in these discharges (see the companion paper [4]).

We can estimate the rate of momentum loss in the divertor region due to ion–neutral collisions using Eq. (1) along with the experimental measurements, i.e.

$$\frac{\Delta p_{\text{tot}}}{\Delta x} \sim m\,(v - v_{\text{H}})\,n\,n_{\text{H}}\,\langle\sigma v\rangle_m, \tag{4}$$

where $\Delta p_{\text{tot}} \sim 10^3$ Pa is the observed total pressure loss (ion + electron, assuming $T_i = T_e$) in the detached case (Fig. 3), $\Delta x \sim 0.5$ m is the estimated length of the recycling region in the parallel direction, $v - v_{\text{H}} \sim 5 \times 10^3\ \text{ms}^{-1}$ from Fig. 4, $n \sim 10 n_{\text{H}} \sim 4 \times 10^{20}\ \text{m}^{-3}$ from the Langmuir probes and neutral pressure measurements and $\langle\sigma v\rangle_m \sim 10^{-14}\ \text{m}^3\text{s}^{-1}$ [5]. Putting the numbers into Eq. (4) one obtains for the left-hand side $\sim 2 \times 10^3\ \text{Pa m}^{-1}$, and $\sim 3 \times 10^3\ \text{Pa m}^{-1}$ for the right-hand side. Thus, within the errors of this rough estimation (factor ~ 4), the observed pressure loss along field lines is quite reasonably balanced by the friction the ions experience against the neutral particles on their way to the plate.

While the presence of friction is a necessary condition to produce the large pressure ratios observed under detached conditions in these discharges, a further condition required is a low electron temperature near the plate (as observed, Fig. 3), i.e. a strong reduction in the neutral particle ionization rate in comparison to the rate of ion–neutral momentum loss is required. This basic requirement was first identified in the context of divertor research by Stangeby in 1993 [13], but has also been known from the somewhat related field of gas discharge theory for decades (e.g. [14]).

Any model of plasma flow to a surface predicts that the flow should accelerate to velocities close to the ion acoustic speed near the surface. In the case of the neutral particles, the situation is less clear. Through friction with the ions, the neutrals will have a tendency to move in the same direction as the ions, but since neutrals can readily diffuse across field lines through charge-exchange they will readily be in contact with the divertor plates or baffles, as well as neutrals in the opposite fan (which should be moving in the opposite toroidal direction). All of these will tend to drag the neutral fluid to some value lower than the plasma. This is apparently observed in this experiment. One puzzling result, however, is the neutral velocity distribution, Fig. 5, which shows the neutral velocity being a maximum close to the divertor plate. So close to the divertor plate, i.e. only ~ 1 cm away compared to the charge-exchange mean free path of ~ 5 mm, one might expect to see a reduction in the neutral parallel velocity due to the presence of fully accommodated neutrals (in a momentum sense) emerging from the surface. This is not observed and at present we have no clear explanation for this.

Parallel drift measurements have also recently been made in the divertor of ASDEX-Upgrade [15,16] and DIII-D [17]. These experiments are broadly consistent with the results presented here. In general, ion flow velocities are comparable to the expected ion acoustic speed, regimes of flow reversal are observed and neutral velocities tend to be lower than ion velocities.

9. Conclusions

We have demonstrated that large plasma pressure loss along field lines can be caused by ion–neutral friction without significant volume recombination in high-powered Alcator C-Mod discharges with N_2 seeding. This may not be a general result, however, since at present few cases have been studied and there are other candidate mechanisms for loss of plasma pressure, e.g. volume recombination and cross-field drifts [18]. Clearly, more flow measurements are required, particularly in cases where volume recombination signatures are stronger, e.g. high density Ohmic discharges [4].

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