Radial impurity transport in the H mode transport barrier region in Alcator C-Mod

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Abstract. Measurements of profiles of soft X ray emissivity with 1.5 mm radial resolution are combined with high resolution electron density and temperature measurements in the edge region of the Alcator C-Mod tokamak to facilitate transport analysis of medium-Z impurities during H modes. Results from detailed modelling of the radiation and transport of fluorine are compared with experimental measurements, yielding information about the transport coefficients in the H mode transport barrier region. Evidence is found for a strong inward impurity pinch just inside the separatrix. The region of strong inward pinch agrees very well with the region of strong electron density gradient, suggesting that the inward pinch could be driven by the ion density gradient, as predicted by neo-classical theory. Simulations using the neo-classical impurity convection profile agree very well with experiments. Transport modelling shows that the X ray pedestal width is largely determined by the diffusion coefficient in the transport barrier. This allows diagnosis of changes in the edge diffusion coefficient on the basis of observations of X ray pedestal width changes. Significant differences in the edge diffusion coefficient are seen between different types of H mode. Several scalings for the edge diffusion coefficient in the enhanced Dα H mode are also identified. This may help elucidate the physical processes responsible for this attractive confinement mode.

1. Introduction

In tokamak fusion experiments, a large reduction in cross-field transport of heat and particles is seen at the transition from the low confinement mode (L mode) to the high confinement mode (H mode) [1]. The most dramatic increase in confinement occurs in a narrow region near the last closed flux surface, where turbulent transport is suppressed. This region is referred to as the edge transport barrier, or the pedestal region, because the radial profiles of various plasma quantities become pedestal-like as large gradients develop in the transport barrier region. A highly desirable feature of the standard ELM-free H mode is that the global energy confinement time is up to two times longer than that in L mode. An undesirable feature of ELM-free H mode is that the impurity ion confinement time can be as much as 50 times longer than that in L mode, resulting in a serious accumulation of impurities. It is therefore important to understand the physics of H mode and the transport of impurities in the H mode pedestal region. Several different ways to degrade the impurity confinement, without significantly degrading the energy confinement, have been found, for example, in ELMy H modes [2]. A particularly attractive type of H mode, named the enhanced Dα (EDA) H mode, has been discovered in the Alcator C-Mod tokamak [3]. This mode has much less impurity accumulation than the ELM-free H mode, while still retaining good energy confinement.

It is an important goal of the Alcator C-Mod programme to understand the physics of the H mode transport barrier in the high field, high density shaped tokamak regime unique for this device, in particular the EDA H mode. Several edge diagnostics have been installed in the last few years on Alcator C-Mod, leading to much improved measurements of the transport barrier region. This article presents an analysis of the radial impurity transport coefficients in the H mode pedestal region in Alcator C-Mod on a millimetre spatial scale. We base our analysis on highly resolved profiles of soft X ray emissivity, electron density $n_e$ and electron temperature $T_e$. In H mode, the soft X ray emissivity at the outboard plasma edge develops a distinct pedestal, located well inside the separatrix. The width of this pedestal has been observed to depend on the type of H mode and also shows clear scalings with certain plasma parameters [4, 5]. It has been speculated that the X ray pedestal width reflects the transport properties of the H mode pedestal region, and that its location well inside the separatrix shows that the impurities are confined further into the plasma because...
of the inward impurity pinch near the plasma edge [6]. The analysis presented in this article, which has been made possible by the recent addition of a high resolution electron density diagnostic covering the pedestal region, basically confirms these ideas, and provides a detailed understanding of the soft X ray measurements and the H mode edge radial transport of impurities. The diagnostics used to obtain $n_e$, $T_e$ and soft X ray emissivity profiles are described in Section 2. H mode measurements, presented in Section 3, show that the soft X ray emissivity pedestal is located further into the plasma than the electron density pedestal, which implies that the impurity density pedestal is shifted inwards compared with the electron density pedestal. We compare measured X ray emissivity profiles and profiles calculated on the basis of modelling of the fluorine transport and radiation in Section 4, and find that the inward shift of the X ray emissivity pedestal is due to an inward shift of the impurity (fluorine) pedestal. Measurements of the width and the location of the soft X ray pedestal yield information about the radial profiles of the diffusion coefficient $D$ and the impurity convection velocity $v$. We find evidence for a strong inward convection of impurities localized to the electron density pedestal region, in agreement with neoclassical theory. Modelling also shows that the X ray pedestal width can be used to estimate $D$ in the transport barrier region, allowing us to diagnose changes in the transport barrier between various types of H mode as well as identifying scaling laws for $D$ in the EDA H mode. These results are presented in Section 5. Finally, we summarize our results in Section 6.

2. Edge diagnostics

The impurity transport analysis presented in this article is based on measurements of soft X ray emissivity, electron density and electron temperature. The soft X ray emissivity is measured with 1.5 mm radial resolution at the outboard edge by an array of 38 photodiode detectors viewing the plasma edge through a 10 $\mu$m beryllium foil. During the 1997–1998 run campaign, a soft X ray array viewed the lower part of the outboard edge from above. Details of this diagnostic and the analysis methods used can be found in Ref. [4]. During the 1999 run campaign, a second array viewed the upper part of the outboard edge from below in a configuration which is essentially the mirror image of the previous configuration. All the results from the new configuration agree with previous findings from the old configuration, and the same analysis methods were employed.

The electron temperature $T_e$ is derived from ECE measurements at the plasma midplane. High resolution edge profiles of $T_e$ are obtained by sweeping the toroidal field by a small amount, moving the ECE resonance of a given frequency across the pedestal. The spatial resolution is about 9 mm when this technique is employed [7].

The electron density is derived from a newly installed visible continuum diagnostic, which measures plasma emission in a spectral band around 536 nm with FWHM of 3 nm. By using the temperature profiles from the ECE measurements, one can account for the weak temperature dependence of the radiation and derive the quantity $n_e \sqrt{Z_{\text{eff}}}$ [8, 9]. In Alcator C-Mod, $Z_{\text{eff}} \approx 1.2$ under normal operating conditions, so the variation in $\sqrt{Z_{\text{eff}}}$ is very small. Thus, the $n_e$ profile can be derived with good accuracy. The measurements are made along tangential chords which are 1 cm below the plasma midplane with about 2.5 mm radial resolution in the edge region.

A schematic diagram of the views of the three diagnostics is shown in Fig. 1. The measurements of the three diagnostics are compared by mapping the soft X ray measurements back to the plasma midplane using the EFIT flux surfaces. Because all three measurements are made very close to or at the plasma midplane, this process is very insensitive to any magnetic field line mapping uncertainties, including any uncertainty in the exact location of the separatrix (estimated to be +0 mm/−5 mm). A second soft X ray array views the top of the plasma; results from this diagnostic will be the subject of a future publication.

3. Measurements of radial profiles

Alcator C-Mod is a compact, high field tokamak [10] with all metal walls that produces high density diverted plasmas ($B_0 \leq 8$ T, $I_p \leq 2.5$ MA, $n_e = (1−5) \times 10^{20}$ m$^{-3}$, $R = 0.68$ m, $a = 0.22$ m, $\kappa \leq 1.8$). Auxiliary heating is supplied with ion cyclotron RF, and core temperatures up to $\sim$5 keV have been achieved. In Fig. 2 we show the time history of key plasma parameters for a plasma discharge with a single ELM-free ohmic H mode phase from $t = 0.87$ s to $t = 1.05$ s. The plasma current and the electron temperature remain approximately constant whereas the line averaged electron density is increasing.
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Figure 1. Schematic diagram of the locations of the three diagnostics used in the impurity transport analysis in the Alcator C-Mod vessel. A typical plasma equilibrium is shown for comparison. The ECE diagnostic views a range of radial positions along a major radius. The visible continuum array views tangentially along chords which are 1 cm below the midplane.

throughout the H mode phase. The soft X ray emission from the edge plasma increases dramatically at the transition from L mode to H mode, as is usually observed. In Fig. 3 we show measured radial profiles of electron density, temperature and soft X ray emissivity in the edge region at $t = 1.0$ s during the ELM-free H mode phase of the discharge. The soft X ray emissivity shows a distinct and narrow pedestal in the ELM-free H modes, less than 2 mm wide, as defined by the full width of the tanh-like function commonly used to characterize the H mode pedestal shapes [11],

$$A \times \frac{1}{2} \left[ \tanh \left( \frac{r_{ped} - r}{\Delta/2} \right) + 1 \right] + B(r_{ped} - \Delta/2 - r) \Theta(r_{ped} - \Delta/2 - r).$$

(1)

Here, $A$ is the amplitude of the pedestal, $B$ is the linear slope inside the pedestal, $r_{ped}$ is the location of the centre of the pedestal, $\Delta$ is the full pedestal width and $\Theta$ is the Heaviside step function. The foot of the soft X ray pedestal, which can be defined in terms of the tanh pedestal parameters as $r_{ped} + \Delta/2$, is located about 10 mm inside the separatrix. These measurements are typical of ELM-free H modes, irrespective of whether they were obtained with or without auxiliary ICRF heating.

In contrast to the soft X ray pedestal, the feet of the pedestals in electron temperature and density are located about 2 mm inside the EFIT separatrix in this case, and both of these pedestals are significantly wider (about 8 mm) than the soft X ray emissivity pedestal. The electron density pedestal can be much narrower in some H modes, but the electron temperature pedestal width measured by ECE is usually in the range 8–15 mm, barely resolvable with the 9 mm spatial resolution. The soft X ray pedestal width typically varies in the range 1–6 mm, depending on the type of H mode and on several plasma parameters, as discussed in more detail in Section 5. The narrowest pedestals, whose widths are barely resolvable at the 1.5 mm radial resolution, are seen during ELM-free H modes, and the widest are seen during type III ELMy periods and low current EDA H modes.

Regardless of the type of H mode, the soft X ray pedestal is always located well inside the pedestals...
Figure 3. High resolution profiles of $n_e$, $T_e$ and X ray emissivity shown for $t = 1.0$ s during the ELM-free H mode phase of the discharge shown in Fig. 2. Idealized profiles, closely resembling the measured profiles, are used for $n_e$ and $T_e$. In order to increase spatial resolution for the $T_e$ profile, the instrument function has been deconvolved in the idealized profile. The convolution of the idealized profile with the instrument function is also shown, resembling the measured data closely. Due to radiation from molecular deuterium, the $n_e$ values derived from the visible continuum radiation are too large near the nominal separatrix. This has been taken into account in the idealized $n_e$ profile.

of electron density and temperature. In Fig. 4 we show the location of the foot of the visible continuum emissivity pedestal plotted against the location of the foot of the soft X ray pedestal at the outboard edge, for 112 different discharges taken from a database of edge pedestal parameters. The two locations are very well correlated, but the foot of the soft X ray pedestal is on average 9 mm inside the foot of the visible continuum emissivity pedestal. The visible continuum emissivity pedestal width and location, available routinely on many discharges, are good approximations to the electron density pedestal width and location, which are only available for a relatively small number of discharges. Previous rudimentary calculations indicated that a major contribution to the soft X ray emissivity is proportional to $n_F n_e$ where $n_F$ is the density of fully ionized fluorine, and that the temperature dependence is small [4]. More detailed calculations, presented in Section 4, take the temperature effects explicitly into account. Due to strong line radiation, the temperature effects are not as small as previously thought. Fluorine is an intrinsic impurity in Alcator C-Mod, presumably originating from Teflon insulation or solvents. Recently, injections of CaF$_2$ and freon gas have confirmed that the X ray emissivity increases with the fluorine density. With the recent addition of the visible continuum emissivity diagnostic, highly resolved profiles of electron density are now available. These allow us to confirm that the steep pedestal in soft X ray emissivity is due almost entirely to a steep pedestal in fluorine density and that the density of fluorine must be very low in the region between the foot of the X ray pedestal and the foot of the electron density pedestal, since the electron density is appreciable but the soft X ray emission is very low in this region.

4. Modelling of impurity radiation and transport

4.1. Comparisons between modelling and experiments

It follows from the experimental observations presented in Section 3 that the impurities at the outboard edge are confined further inside the transport
Figure 5. Neoclassical impurity convection profile for F$^9+$ as calculated from the smoothed profiles of $n_e$ and $T_e$ in Fig. 3. The separatrix is located at $r = 0.214$ m.

Figure 6. Profile for the diffusion coefficient $D$ used in the MIST modelling.

Barrier than the bulk plasma. This strongly suggests the existence of an inward convection of impurities in the region 0–10 mm inside the separatrix. A strong inward convection of impurities localized to the edge region has previously been measured in Alcator C-Mod H modes [12] as well as in several other tokamaks, such as ASDEX [13], DIII-D [14] and JET [15]. Such an inward impurity pinch could be driven by the large ion density gradient near the edge, as predicted by neoclassical theory. The neoclassical prediction of the inward impurity pinch is, in the limit of trace impurities relevant to Alcator C-Mod [16]:

$$v_{\text{neoc}} = \nu_i q^2 \rho_i^2 \left( Z_I n_i \frac{\partial n_i}{\partial r} - \frac{1}{T_i} \frac{\partial T_i}{\partial r} \right)$$

(2)

where $\nu_i$ is the ion–ion collision frequency, $q$ is the safety factor, $\rho_i$ is the ion Larmor radius, $Z_I$ is the charge of the impurity ion, $n_i$ is the ion density and $T_i$ is the ion temperature, assumed equal to the impurity temperature. This formula is derived in a cylindrical geometry and assumes that the poloidal ion gyroradius is much smaller than the gradient scale lengths. This latter condition is usually not fulfilled in Alcator C-Mod H modes. It also assumes that the poloidal variations in plasma parameters are small. In fact, comparisons between the X ray emissivity at the top and the outboard edge of the plasma show that there are large poloidal variations in impurity density near the separatrix. In this article, we ignore these complications, which will be addressed in a future publication. We consider impurity transport to be a purely one dimensional (radial) process.

For medium- and high-$Z$ impurities, the density gradient term dominates in the transport barrier region, leading to an inward convection. On Alcator C-Mod, high resolution ion density and temperature measurements are not available in the pedestal region. However, because $Z_{\text{eff}} \approx 1$, quasi-neutrality leads to $n_i \approx n_e$. We also assume $T_i \approx T_e$, which is believed to be a good approximation because of the high electron–ion collision frequency in the high density H mode edge in Alcator C-Mod. Thus, we can use the electron measurements to estimate the neoclassical convection term. For the plasma profiles presented in Fig. 3 the neoclassical convection profile for fully ionized fluorine (F$^9+$) is shown in Fig. 5. There is a large inward pinch confined to a narrow region close to the separatrix. The MIST code [17] is used to calculate the steady state density profiles for all the charge states of fluorine. As inputs to the code we use the measured $n_e$ and $T_e$ profiles, the neoclassical convection velocity and a simple profile for the diffusion coefficient $D$, the latter being shown in Fig. 6. This profile, which has values of 0.01 m$^2$/s in the edge transport barrier region and 0.2 m$^2$/s in the core region, is similar to previous experimentally derived $D$ profiles for ELM-free H modes [12]. The steady state profiles of the various charge states of fluorine calculated by the MIST code are then used together with the electron density and temperature profiles to calculate profiles of emission from fluorine line radiation and recombination radiation, as well as bulk plasma bremsstrahlung. The spectral distributions of these processes are convolved with the transmission function for the 10 $\mu$m beryllium foil and added up, yielding a profile of soft X ray emissivity which can be directly compared with the measured profile. This method directly incorporates the effects of $T_e$ and $n_e$. Although the temperature dependence is somewhat stronger than was concluded on the basis...
of less detailed calculations [4], it remains relatively weak over the region where the soft X ray pedestal is located.

In Fig. 7(a) we show the radial profiles of the three highest charge states of fluorine, as calculated by MIST, and in Fig. 7(b) we show the calculated soft X ray emissivity, compared with the measured profile, showing excellent agreement. It is confirmed that the soft X ray emissivity profile closely resembles the profiles of the densities of the high charge states of fluorine. The central fluorine density is treated as a free variable, chosen in this case to be 0.14% of the central electron density in order to match the absolute value of the measured X ray emissivity profile. Thus, we can derive absolutely calibrated profiles of the fluorine density. As illustrated in Fig. 7(b), most of the soft X ray emission comes from line radiation, with a smaller but significant contribution from recombination of fully ionized fluorine. The dominant line is that of Lyman $\alpha$ (the $n = 2$ to $n = 1$ transition of hydrogen-like fluorine at $\lambda = 14.98$ Å). Originally, line radiation was thought to be less important, but these new detailed simulations show that line radiation accounts for more than half of the soft X ray emission from fluorine, and therefore the profile of hydrogen-like fluorine is at least as important to the soft X ray emissivity profile as the profile of fully ionized fluorine. The bremsstrahlung radiation from the main plasma is unimportant because most of the bremsstrahlung photons are not energetic enough to penetrate the beryllium filter at the rather low temperatures characteristic of the edge region. We conclude that modelling of fluorine transport and radiation, using a neoclassical inward pinch combined with a simple empirical profile for $D$, and the measured profiles for $T_e$ and $n_e$, yields profiles of soft X ray emissivity which are remarkably similar to the measured profiles. An inward pinch profile consistent with neoclassical theory has been reported in H mode discharges on several other tokamaks, including DIII-D [14] and ASDEX [13]. Modelling of the fluorine transport with no inward pinch results in profiles of soft X ray emissivity which are much wider (about 10 mm) and closer to the separatrix than the measured soft X ray emissivity profiles.

4.2. Modelling of other impurities

A variety of different impurities has been injected into H mode discharges in Alcator C-Mod, and with the exceptions of neon and fluorine, none of these leads to appreciable increases in the measured edge soft X ray emissivity [4]. Oxygen, which is an intrinsic impurity, may contribute somewhat to the X ray emissivity, but since Alcator C-Mod is regularly boronized, the oxygen levels are generally too low to contribute significantly to the soft X ray emissivity. We have performed modelling of the oxygen and neon transport and radiation processes, and have confirmed that the soft X ray emissivity profiles originating from oxygen and neon are very similar in shape to those from fluorine, when the same profiles of $n_e$, $T_e$, $D$ and $v = v_{neoc}$ are used in the modelling. We find that when the beryllium filter function has been taken into account, X ray emissivity levels from a given density of oxygen would be about one third of the X ray emissivity levels from the same density of fluorine. For oxygen, the dominant contribution of X ray emission comes from recombination of the fully stripped ion.

Modelling of neon transport and radiation processes shows that the soft X ray emissivity transmitted through the beryllium filter leads to levels three times larger than the same amount of fluorine. For neon, the dominant source of X ray emissivity through the beryllium filter is line radiation, mostly from the Lyman $\alpha$ line of hydrogen-like neon at $\lambda = 12.13$ Å. The neon Lyman $\alpha$ line is much stronger than the fluorine Lyman $\alpha$ line because a larger fraction of the neon is in the hydrogen-like state, and because the Lyman $\alpha$ line for neon is at a higher photon energy than the fluorine Lyman $\alpha$ line,
so that a larger fraction of it is transmitted through the beryllium filter. These results agree well with the experimental observation that even rather modest injections of neon can increase the soft X ray emissivity by factors of 2–5. After such an injection, the X ray emissivity profile shape remains the same as before the neon injection with respect to the width and location of the soft X ray emissivity pedestal, which is also in agreement with the modelling. Neon is not an intrinsic impurity, so it contributes to the X ray emissivity only during discharges where it is actively injected. No oxygen injections were performed during the operation of the edge soft X ray arrays, so their sensitivity to the oxygen content has not been directly confirmed in experiments.

4.3. Modelling of X ray pedestal dependence on $D$ and $v$

A sensitivity study has been performed to investigate the effects of $D$ and $v$ on the X ray pedestal, calculated on the basis of the MIST simulations. In this study, a narrow, triangular shape for $v$ was used, peaking at $-100$ m/s, similar in shape to the neoclassical inward pinch, as seen in Fig. 8. The location of this pinch, as defined on the figure, was then varied. For $D$, the core value was kept constant, but several different values for the edge region were used, as shown in Fig. 9. The edge values were chosen to span the range measured previously in injection experiments for the three types of H mode seen on Alcator C-Mod (ELM-free, enhanced $D_\alpha$, and type III ELMy H modes). These simulations show that when the inward pinch is located 10–20 mm inside the EFIT separatrix, regardless of the value of $D$, the location of the inward pinch coincides with the following location:

$$R_{\text{stop}} = R_{\text{ped}} - 0.4\Delta_X.$$  \hspace{1cm} (3)

Here, $R_{\text{ped}}$ is the centre position and $\Delta_X$ is the full width of the computed soft X ray pedestal, as defined by the tanh-like fit in Eq. (1). $R_{\text{stop}}$ is located just below the top of the X ray pedestal, regardless of the width. $R_{\text{stop}}$, as defined above, is typically 11–16 mm inside the EFIT separatrix in actual experiments, so we infer that the innermost point of inward pinch should be located at the innermost point of large electron density gradient, i.e. at the top of the electron density pedestal. We have investigated if this is generally the case for measured profiles, using the database of pedestal parameters, which includes both the soft X ray pedestal measurements and the visible continuum emissivity pedestal measurements for a large number of discharges. As mentioned, the visible continuum emissivity pedestal provides a reasonable approximation to the electron density pedestal. We define the top of the visible continuum emissivity pedestal, $R_{\text{vctop}}$, as

$$R_{\text{vctop}} = R_{\text{vcped}} - \Delta_{vc}.$$  \hspace{1cm} (4)

Here, $R_{\text{vcped}}$ and $\Delta_{vc}$ are the fitted central position and width of the visible continuum emissivity pedestal. In Fig. 10 we plot $R_{\text{stop}}$ versus
Figure 10. Correlation between $R_{vctop}$ and $R_{cltop}$ for 1463 pedestal measurements from 112 different discharges. Binned averages of $R_{vctop}$ are also shown, each with a vertical bar indicating the standard deviation in each bin.

$R_{vctop}$ for a large number of plasma discharges from the database. This figure shows a clear correlation between the two locations, with a systematic shift of about 2 mm. This supports our conclusion that the X ray pedestal location is determined by the location of the inward pinch, which in turn is determined by the location of the plasma density pedestal.

The width of the calculated X ray pedestal is determined by the edge value of $D$. Edge values of $D$ around 0.01 m$^2$/s, corresponding to previous measurements in ELM-free H mode, yield X ray pedestal widths of 1.5–2 mm, whereas edge values of $D$ around 0.05 m$^2$/s, corresponding to type III ELMy H mode values, yield X ray pedestal widths around 4.2 mm. These predictions are in good agreement with measurements of the soft X ray pedestal width during ELM-free and type III ELMy H modes, as discussed in Section 5. In Fig. 11 we plot the simulated soft X ray emissivity pedestal width as a function of the transport barrier diffusion coefficient, as derived from the sensitivity study just described. We also performed a similar parameter scan with a triangular pinch of the same width, but peaking at $-300$ m/s instead of $-100$ m/s. The results were similar, except that the calculated X ray pedestal widths were somewhat smaller than those quoted here, because of the steeper slope of the pinch profile. They still showed a clear tendency for the X ray pedestal width to increase with increasing edge $D$. It should also be noted that if a different shape is chosen for the pinch profile, this will also affect the details of the correlation between $D$ and the X ray pedestal width. However, the tendency for the X ray pedestal to be wider at higher edge $D$ values is robust. The peak value of the inward pinch cannot be determined from the steady state profiles of X ray emissivity, since the inward pinch peaks in a region where there is essentially no highly ionized fluorine, and thus where there is very low X ray emissivity. Impurity injection experiments should be able to address this question.

5. Interpretation of X ray pedestal width measurements

5.1. Dependence of X ray pedestal width on H mode type

In previous publications, it was noted that the soft X ray emissivity pedestal width at the outboard edge is significantly larger in the EDA H mode (3–7 mm, depending on the plasma current) than in ELM-free H mode (1.5–3 mm) [4]. We have also consistently seen that during type III ELMy H modes with relatively poor confinement, the X ray pedestal becomes wide (5 mm or more). The sensitivity analysis allows us to interpret these measurements and conclude that the diffusion coefficient in the transport barrier is significantly larger in the EDA H mode than in ELM-free H mode, and even larger in type III ELMy H mode. This agrees well with previous independent
measurements of the edge diffusion coefficient, as well as with the general observation that the distinguishing characteristic of the EDA H mode is that it has a much lower particle confinement time than the ELM-free H mode [3]. Type III ELMy H modes, which on Alcator C-Mod occur only in H modes near the H–L threshold, are frequently observed to have only marginally better energy and particle confinement than L modes. Typical values of impurity confinement times (τ_{imp}), obtained from laser blow-off injection measurements, are: 20 ms in L mode, 30–50 ms in type III ELMy H mode, 50–200 ms in EDA H mode and >0.5 s in ELM-free H mode.

5.2. Scalings of the X ray pedestal width in EDA H mode

Several empirical scaling laws for the soft X ray pedestal width have been found in EDA H mode. The soft X ray pedestal width is an increasing function of the inverse of the plasma current, 1/I_p. The observed scaling with 1/I_p, which is stronger than linear, could also be a scaling with the safety factor at the 95% flux surface, q_{95}, since the two are strongly correlated when the toroidal magnetic field is kept constant. The toroidal field is usually kept near 5.2 T in Alcator C-Mod to allow for efficient on-axis RF heating, and most of the EDA H modes have been obtained at toroidal fields very close to this value. A few ohmically heated EDA H modes were obtained at lower toroidal fields but the measured X ray pedestal widths did not conclusively show if I_p or q_{95} is the relevant scaling parameter. A limited sweep of toroidal field from 5.0 to 6.0 T during a single discharge with constant I_p showed no measurable change in the X ray pedestal width. This suggests that 1/I_p is more important than q_{95}, but it is not conclusive evidence because the toroidal field was changed by only 20%. Future upgrades of the RF system will enable efficient heating at a variety of toroidal fields, which may allow us to address this question better. An approximately linear scaling of the soft X ray pedestal width with plasma triangularity (0.18 ≤ δ ≤ 0.45) has also been observed. On the basis of these results, we conclude that the edge diffusivity is an increasing function of triangularity and of 1/I_p (or q_{95}). This suggests that the quasi-coherent fluctuations observed in EDA H mode, which are believed to be caused by the increased diffusion in the transport barrier, are more unstable at low plasma current (high q_{95}) and high triangularity. This is consistent with previous results showing that high q_{95} and moderate to high triangularity tend to favour the EDA H mode over the ELM-free H mode [3]. We also note that previous laser blow-off injection experiments in L mode in Alcator C-Mod showed that D is an increasing function of q at the plasma edge, rather than 1/I_p [18].

The pedestal database has also been used to identify a third parameter affecting the X ray pedestal width, and therefore the diffusion coefficient in the transport barrier region, namely dI_p/dt. Ramping the current up tends to increase the X ray pedestal width, whereas ramping the current down tends to decrease it, as compared with pedestal widths at the same constant plasma current. We illustrate this in Fig. 12. This result has yet to be confirmed in a dedicated series of experiments. It is not caused by a time lag in the response of the soft X ray pedestal width to the change in I_p. It implies that the diffusion coefficient in the transport barrier is larger when the current is being ramped up than when the current is being ramped down. One should therefore expect that the impurity confinement time is lower when the current is being ramped up. It also suggests that the fluctuations in EDA are sensitive to relatively small changes in the edge current density profile, which presumably may be affected by the direction of the ramp. We also speculate that it may be easier to obtain EDA H modes when ramping the current up than when the current is kept steady or is
being ramped down, since we have generally observed
that parameters favouring wide X ray pedestals also
favour the EDA H mode over the ELM-free H mode.
Experiments to test this are planned.

6. Summary

By combining highly resolved measurements of
the soft X ray emissivity, electron density and elec-
tron temperature in the region just inside the sepa-
ratrxi, it is possible to make detailed measurements
of impurity transport coefficients in the H mode
transport barrier. Our results show the existence of
an inward pinch, whose location coincides with the
region of large plasma density gradients, as predicted
from neoclassical theory. Simulations using the neo-
classical pinch profile yield results which are in excel-
 lent agreement with the measured soft X ray emissiv-
ity profiles. The diffusion coefficient in the transport
barrier region, which is much reduced compared with
that in the core region, determines the soft X ray
pedestal width, although the inward pinch profile
also affects the width to some degree. Measurements
of the soft X ray pedestal width can therefore be
used to estimate the transport barrier diffusion coef-
ficient. In this way, we confirm previous findings that
the transport barrier diffusion coefficient is very low
in ELM-free H mode, of the order of 0.01 m²/s (lower
than the neoclassical diffusion coefficient), somewhat
larger in EDA H modes, and largest, near 0.10 m²/s,
in type III ELMy H modes. We also find that in
EDA H mode, the transport barrier diffusion coeffi-
cient increases with triangularity and 1/I_p (or q95).
D is also affected by the direction of the current
ramp. This latter finding suggests that the quasi-
coherent fluctuations, which presumably are driving
the enhanced diffusivity in EDA H mode, are sen-
tive to the edge profile of the current density or to
the magnetic shear.

Acknowledgements

The authors would like to thank S. Wolfe for
magnetic surface reconstructions, B. LaBombard and
S. Gangadahra for freon injections, D. Mossessian

and J. Hughes for Thomson scattering measure-
ments, S. Wukitch for ICRF heating, J. Goetz for
impurity injections and impurity transport mod-
eling, and M. Greenwald for fruitful discussions
about EDA H mode. The work at the Alca-
tor C-Mod facility at the Massachusetts Institute of
Technology was supported by USDOE Coop.
Agreement No. DE-FC02-99ER54512.

References

[1] Wagner, F., et al., Phys. Rev. Lett. 49 (1982) 1408.
[2] Zohm, H., Plasma Phys. Control. Fusion 38 (1996)
1213.
[3] Greenwald, M., et al., Phys. Plasmas 6 (1999) 1943.
[4] Pedersen, T. Sunn, Granetz, R.S., Rev. Sci.
Instrum. 70 (1999) 586.
[5] Granetz, R.S., et al., paper presented at 17th IAEA
Conf. on Fusion Energy, Yokohama, 1998.
[6] Hutchinson, I.H., et al., Plasma Phys. Control.
Fusion 41 (1999) A609.
[7] Hubbard, A.E., et al., Phys. Plasmas 5 (1998) 1744.
[8] Foord, M.E., Marmar, E.S., Terry, J.L., Rev. Sci.
Instrum. 53 (1982) 1407.
[9] Foord, M.E., Marmar, E.S., Nucl. Fusion 25 (1985)
197.
[10] Hutchinson, I.H., et al., Phys. Plasmas 1 (1994)
1511.
[11] Groebner, R.J., Carlstrom, T.N., Plasma Phys.
Control. Fusion 40 (1998) 673.
[12] Rice, J.E., et al., Phys. Plasmas 4 (1997) 1605.
[13] ASDEX Team, Nucl. Fusion 29 (1989) 1959.
[14] Perry, M.E., et al., Nucl. Fusion 31 (1991) 1859.
[15] Pasini, D., et al., Plasma Phys. Control. Fusion 34
(1992) 677.
[16] Rutherford, P.H., Phys. Fluids 17 (1974) 1782.
[17] Hulse, R.A., Nucl. Technol./Fusion 3 (1983) 259.
[18] Marmar, E.S., Rice, J.E., Terry, J.L., Seguin, F.H.,
Nucl. Fusion 22 (1982) 1567.

(Manuscript received 20 March 2000
Final manuscript accepted 21 July 2000)

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Subject classification: F1, Te; F2, Te; I1, Te; J1, Te;
K0, Te

1804 Nuclear Fusion, Vol. 40, No. 10 (2000)