X RAY OBSERVATIONS OF
UP–DOWN IMPURITY DENSITY ASYMMETRIES
IN ALCATOR C-MOD PLASMAS

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ABSTRACT. A five chord, high resolution X ray spectrometer array has been used to measure vertical brightness profiles of helium-like argon emission from Alcator C-Mod plasmas, out to the last closed flux surface. During standard Alcator C-Mod operation, with the X point and the ion $B \times \nabla |B|$ drift downward, the helium-like argon brightness is a factor of $\sim 8$ larger at the top of the plasma than at the bottom, near the plasma edge. In these edge regions, where the electron temperature is low, the upper levels of observed transitions are populated by radiative recombination of hydrogen-like argon. This up-down brightness asymmetry can be explained by a factor of $\sim 8$ enhancement of hydrogen-like argon at the top of the machine at $r/a = 0.9$. This implies a vertical impurity drift from inside the plasma, since the hydrogen-like argon is born near the plasma centre. With the ion $B \times \nabla |B|$ drift upward, the enhancement switched to the bottom of the machine, but did not change when the X point was moved up. This asymmetry agrees qualitatively with the predictions of neoclassical parallel impurity transport.

1. INTRODUCTION

There have been several observations of vertical up-down impurity density asymmetries in tokamak plasmas, from Alcator A [1], the Poloidal Diverter Experiment (PDX) [2], the Texas Experimental Tokamak (TEXT) [3], the Compact Assembly C (COMPASS-C) [4] and Phaedrus [5]. Most of these are measurements [1, 2, 4, 5] of intrinsic low-Z impurities; in Alcator A, PDX and Phaedrus, asymmetric radial profiles of individual charge states have been obtained from wavelength resolving ultraviolet (UV) spectrometers. In TEXT and COMPASS-C, the observations (spectrally unresolved) were from soft X ray cameras, and the observed X ray line brightness asymmetries were assumed to be equal to the local impurity density asymmetries. Comparisons have been made between these observations and the predictions of neoclassical impurity transport theory [6, 2, 7, 8]. Only in Ref. [6] were the complete radial profiles of Alcator A compared with the predictions of the linear theory, in the collisional regime. For the PDX observations, comparison [2] with the plateau and banana regime calculations were made at the carbon V radius, to avoid complications from the edge plasma. The predictions of the non-linear theory [7, 8, 4] have been compared with the observations from TEXT and COMPASS-C, but at only one radial location, since pertinent diagnostic information, most notably the ion temperature profile, was not available. Nevertheless, in all cases the direction of the observed impurity density asymmetry, opposite to the ion $B \times \nabla |B|$ drift direction, is in agreement with the predictions of neoclassical theory.

In the case of Alcator C-Mod, up–down brightness profiles of the X ray emission from $\text{Ar}^{16+}$ have been obtained, and large up–down brightness asymmetries in the direction opposite to the ion $B \times \nabla |B|$ drift direction have been observed near the plasma edge. Here the upper levels of the lines are populated by radiative recombination of $\text{Ar}^{17+}$, which is produced at the centre of the plasma and then diffuses out to the edge before recombining, so plasma edge effects are probably not involved in producing the asymmetry. Alcator C-Mod plasmas are well diagnosed, so that complete radial profiles of relevant plasma parameters are available.

The organization of this paper is as follows: in Section 2 a brief description of the experiment is given, in Section 3 the observed impurity asymmetries are discussed, and in Section 4 modelling and comparisons with the predictions of neoclassical impurity transport are presented.

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2. EXPERIMENT DESCRIPTION

The X ray observations described here were obtained from the Alcator C-Mod [9] tokamak, a compact ($a = 22.5$ cm, $R = 67$ cm, $\kappa \leq 1.8$) high field device with all molybdenum plasma facing components. The spectra were recorded by a five chord, independently spatially scannable, high resolution X ray spectrometer array [10]. Each von Hamos type spectrometer consists of a variable entrance slit, a quartz crystal ($2d = 6.687$ Å) and a position sensitive proportional counter detector. Each spectrometer has a resolving power of 4500, a 2 cm chordal resolution and a wavelength range from 2.8 to 4.0 Å. Spectra are normally collected every 50 ms during a discharge, with 120 mA covered at any one wavelength setting. A typical value of the spectrometer luminosity function is $7 \times 10^{-9}$ cm$^2$·sr, calculated from the crystal reflectivity, spectrometer geometry and beryllium window transmission. The vertical scanning limits of the spectrometer system are ±32 cm at the plasma nominal major radius. This allows chordal views completely outside the last closed flux surface at the top and bottom of the machine for plasma elongations less than 1.8.

3. OBSERVED IMPURITY PROFILES

Figure 1 shows the time histories of several parameters of interest for an ohmically heated deuterium, $B_T = 5.3$ T, discharge. During this particular discharge there was a low density period between 0.45 and 0.55 s, and a high density steady state between 0.85 and 1.05 s. Argon ($Z = 18$) gas was injected in a 35 ms wide pulse through a piezoelectric
valve at 0.4 s. Figure 2 shows an Ar^{16+} X ray spectrum [11-17] obtained along a centrally viewing chord at 0.5 s, when the central electron density was \(1.3 \times 10^{14}\) cm\(^{-3}\) and the central electron temperature was 2.35 keV. This spectrum is dominated by the resonance line \(w\) (\(1s^2 1P_1 - 1s^2 1S_0, 3949.28\) mA), and the forbidden line \(z\) (\(1s^2 3P_1 - 1s^2 1S_0, 3994.28\) mA) and the intercombination lines \(x\) and \(y\) (\(1s^2 3P_2 - 1s^2 1S_0, 3965.99\) mA and \(1s^2 3P_1 - 1s^2 1S_0, 3969.40\) mA, respectively) are prominent. Also visible are several weaker satellite lines. The thin line in the figure shows a synthetic spectrum whose line intensities are equal to the calculated central chord brightnesses, whose line widths are given by the appropriate Doppler broadening for the ion temperature and whose line wavelengths are taken from Refs [18, 19]. The chordal brightnesses of \(w\), \(x\), \(y\) and \(z\) are determined from emissivity profiles calculated from the collisional-radiative model of Refs [20, 21], which includes population of the upper levels via collisional excitation of helium-like Ar^{16+}, radiative recombination of hydrogen-like Ar^{17+} and inner shell ionization of lithium-like Ar^{15+}. The measured electron density profiles are obtained from the laser interferometer [22], Thomson scattering and reflectometer diagnostics, while the electron temperature profiles are obtained from the electron cyclotron emission [23] and Thomson scattering diagnostics. The argon charge state density profiles are calculated from the MIST code [24], using impurity transport coefficients [25], appropriate for this portion of the discharge, of \(D = 5000\) cm\(^2\)/s and \(V = -222(r/a)\) cm/s. The agreement between the measured and simulated spectra is very good. The only free parameter in this comparison is the normalization, which is used to measure the argon density in the plasma. The total argon density time history determined in this way is shown in Fig. 1. The central argon density peaks at a value just under \(4 \times 10^{14}\) cm\(^{-3}\) during the low density plateau, and then settles to \(\sim 1 \times 10^{16}\) cm\(^{-3}\). The total number of injected argon atoms was \(1.7 \times 10^{14}\), and given a plasma volume of \(\sim 10^6\) cm\(^3\), the argon penetration (defined as the ratio between the number of atoms in the plasma to the number injected) was around 2.5% [25, 26].

Spectra may be obtained along five separate chords during one discharge by the spectrometer system.

FIG. 2. Central chord Ar^{16+} spectrum showing the resonance line, \(w\), the intercombination lines, \(x\) and \(y\), and the forbidden line, \(z\), as well as several satellites. A synthetic spectrum is shown by the thin line.

FIG. 3. Spectra from a top viewing chord (solid curve) and from a bottom viewing chord (dotted curve) from \(r/a \sim 0.6\). A synthetic spectrum is shown by the thin line. The chordal views are shown in the inset.
Figure 3 shows X ray spectra of Ar$^{16+}$ taken from two chords tangent to the same flux surface (from the EFIT code [27]), which crosses the plasma midplane at a major radius of 81.2 cm, after 0.5 s of a discharge similar to that shown in Fig. 1. The plasma centre, denoted in the figure by the '+' sign, was located at $R = 68.1$ cm and $Z = -0.7$ cm, so these spectra are both characterized by $r = 13.1$ cm (81.2 cm - 68.1 cm). The vacuum vessel centre is shown by the 'x' sign. The individual lines of sight are shown in the inset in the figure, and the spectrum shown by the solid curve was from a view that crosses the vertical plane at $R = 67$ cm at $Z = +16.5$ cm (solid line), while the dotted spectrum was from $Z = -18.0$ cm (dotted line). The two spectra are nearly identical in intensity, indicating that the argon X ray emission along this flux surface is constant. (The mappings of the two lines of sight back to the plasma midplane are shown by the dot and the asterisk.) These spectra are quite different from the central chord spectrum of Fig. 2, in that the overall intensity is greatly reduced, and all the line intensities have grown relative to the resonance line.

Spectra obtained from near the last closed flux surface are presented in Fig. 4. The solid curve shows a spectrum from along the line of sight, indicated by the solid line, viewing the top of the plasma, characterized by $R = 89.4$ cm, $r = 21.1$ cm and $Z = +28.9$ cm. This spectrum is dominated by the forbidden line $z$, as the resonance line has fallen in intensity compared with Fig. 3, the satellites have all disappeared and the lines are all very narrow. This is indicative of a recombining plasma [12, 16], where the line population is overwhelmingly dominated by radiative recombination of hydrogen-like Ar$^{17+}$. The reason that Ar$^{17+}$ exists at this radius, where the electron temperature is ~200 eV, is because of the fast radial (outward) impurity transport, described by $D = 5000$ cm$^2$/s. The dotted curve shows a spectrum from along the line of sight, indicated by the dotted line, viewing the bottom of the plasma but near the same flux surface, characterized by $R = 88.5$ cm, $r = 20.2$ cm and $Z = -30.9$ cm. The brightness of this spectrum is

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**Figure 4.** Spectra from a top viewing chord (solid curve) and from a bottom viewing chord (dotted curve) from $r/a \sim 0.9$. In this case, the ion $B \times \nabla |B|$ drift was downward. A synthetic spectrum is shown by the thin line, normalized to the top spectrum.

**Figure 5.** Spectra from a top viewing chord (solid curve) and from a bottom viewing chord (dotted curve) from $r/a \sim 0.9$. In this case, the ion $B \times \nabla |B|$ drift was upward. The lines are narrower than in Fig. 2 because of the lower ion temperature at this radius. Also shown in the figure, by the thin line, is a synthetic spectrum for these viewing chords, again in good agreement with the observed spectra.
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FIG. 6. Vertical brightness profiles for the forbidden line with the ion $B \times \nabla |B|$ drift downward (asterisks) and upward (boxes).

a factor of 8 brighter. (The X point was located at the bottom of the machine for these spectra.) Figures 4 and 5 demonstrate that impurity X ray emission is not constant on flux surfaces near the edge, and that this large up–down impurity asymmetry is in the direction opposite to that of the ion $B \times \nabla |B|$ drift direction. These results are summarized in Fig. 6, where the brightness of the forbidden line is plotted as a function of the vertical distance from the line of sight to the vacuum vessel centre at $R = 67$ cm. The asterisks were obtained during the low density plateau of a sequence of identical discharges similar to that shown in Fig. 1, with the ion $B \times \nabla |B|$ drift direction downward. The asymmetry begins at the top of the plasma around $+20$ cm, and extends out to the last closed flux surface, with a maximum brightness ratio (from the top to the bottom) of about a factor of 10. The points shown as boxes were obtained from a series of discharges with similar conditions, except with the ion $B \times \nabla |B|$ drift direction upward, and in this case the asymmetry (enhancement) is at the bottom of the plasma. Similar observations have been made from Alcator C [28] plasmas. Figure 7 shows the resonance and forbidden line brightness profiles for a series of identical 8 T, 350 kA hydrogen discharges at Alcator C with $T_e = 1400$ eV, $n_e = 1.8 \times 10^{14}$ cm$^{-3}$, a limiter radius of 16.5 cm and the ion $B \times \nabla |B|$
FIG. 8. Electron and ion temperature profiles at 0.5 s for a series of discharges identical to that shown in Fig. 1. The thin solid line is an analytic fit to the ion temperature data.

FIG. 9. Measured electron density profile (thick solid curve) at 0.5 s for a shot similar to that shown in Fig. 1, and an analytical approximation (thin curve). The calculated total argon density profile ($\times 1000$) is shown by the chain curve.

FIG. 10. Calculated argon density profiles for helium-like Ar$^{16+}$ and hydrogen-like Ar$^{17+}$ charge states. The dotted bump at $\sim 21$ cm is a modelled perturbation.

drift direction upward. In this case, there is also a large enhancement at the bottom of the plasma. This may explain the underestimate of the calculated brightnesses compared with the observed profiles in the modelling of Ref. [16].

4. MODELLING AND COMPARISON WITH NEOCLASSICAL THEORY

In order to calculate the brightness profiles of the forbidden line for comparison with the profiles of Fig. 6, the electron temperature and density profiles, and the individual argon charge state density profiles must be known. The electron temperature profile is shown in Fig. 8, obtained during the low density plateau of the discharge shown in Fig. 1. Also shown in the figure, by asterisks, is the ion temperature profile, obtained in a sequence of identical discharges, from the Doppler broadening of the argon X ray lines, along with an analytic fit to the data. For this low density portion of the discharge, the electron temperature is nearly 75% higher than the ion temperature, although the profile shapes are similar. The electron density profile at 0.5 s is shown in Fig. 9, along with an analytic fit. Also shown in the figure is the total argon density ($\times 1000$), calculated from MIST, using $D(r) = 5000$ cm$^2$/s and $V(r) = -222(r/a)$ cm/s. The calculated individual charge state density profiles for hydrogen-like Ar$^{17+}$ and helium-like Ar$^{16+}$ are shown.
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in Fig. 10 by the solid curves. The density of Ar\textsuperscript{17+} in the outer regions of the plasma is several orders of magnitude higher than would be the case for coronal equilibrium [16], allowing radiative recombination to dominate the population of the upper levels of the Ar\textsuperscript{18+} lines in the very cold regions.

As a point of reference, consider the resonance and forbidden line brightness profiles from the bottom of the plasma, with the drift down. The measured and calculated brightness profiles are shown in Fig. 11, and the agreement is very good. This agreement is taken as support for the collisional–radiative model, the measured electron temperature and density profiles, the calculated argon charge state density profiles and the modelled impurity transport. The calculated brightness profiles are not extremely sensitive to the exact form of the impurity transport coefficients. Figure 12 shows the brightness profiles from the top of the plasma with the drift down, where the perturbed Ar\textsuperscript{17+} density profile from Fig. 10 has been used; the large bumps between 18 and 22 cm are well fitted by the perturbation in the Ar\textsuperscript{17+} density profile. In fact, the perturbation to the charge state density profile was determined by adjusting the calculated brightness profiles to match the observed profiles. This density perturbation is about a factor of 8, near the last closed flux surface. It would be very difficult to account for this brightness asymmetry with an asymmetry in the electron temperature, because the radiative recombination rate [20] is a weak function of temperature. From Thomson scattering measurements at +19.4 cm (r = 16 cm) and -22.6 cm (r = 19 cm), there is no indication of an up–down electron temperature or density asymmetry, although in principle there could be an electron density asymmetry outside of 19 cm. However, the most reasonable explanation of the observed brightness asymmetry is an up–down impurity density asymmetry, since there are aspects of the measurements in qualitative agreement with the predictions of neoclassical impurity transport theory [6, 2, 7, 8]. The up–down impurity enhancement is in the opposite direction from the ion $B \times \nabla |B|$ drift direction, and switches direction when the magnetic field is reversed. This impurity asymmetry is independent of the location of the X point; the asymmetry did not change with the X point located at either the top or the bottom of the machine.

A quantitative comparison with the predictions of neoclassical impurity transport will now be given. In all treatments, the impurity density is taken
to be of the form \( n_1 + \tilde{n}_I \sin \theta \), where \( \theta \) is the poloidal angle measured from the midplane. In the discussions of Refs [6] and [2], it is assumed that the impurities are only present in trace quantities (\( \alpha \equiv n_1 Z^2/n_i \ll 1 \)) and are in the Pfirsch–Schlüter regime (\( \nu_{\ast 1} \equiv \nu_{\ast 1}/(e^{3/2} \omega_{\ast 1}) \gg 1 \)), that the plasma has a large aspect ratio (\( R/a \gg 1 \)) and is circular, and that the perturbation is relatively small (\( \tilde{n}_I/n_1 \leq 0.3 \)). (For perturbations with a \( \sin \theta \) dependence, \( \tilde{n}_I/n_1 \approx 1 \), or the impurity density will become negative.) For the discharge of Fig. 1 at 0.5 s, \( \alpha \approx 0.06 \) (\( n_{Ar} = 2.7 \times 10^{19} \, \text{cm}^{-3} \)) and \( \nu_{\ast 1} \) is everywhere \( \geq 50 \), so that the first two conditions are satisfied. The aspect ratio of Alcator C-Mod is \( \approx 3 \), and for the discharge of Fig. 1 the elongation was 1.6, so that the other conditions are marginally met. From Eq. (2) of Ref. [2], the impurity density perturbation is found to be, for the Pfirsch–Schlüter regime,

\[
\frac{\tilde{n}_I}{n_1} \approx 1.76 \times 10^{-7} \frac{n_i q^2}{T_i^{3/2}} \left( \frac{-n_i}{n_1} + \frac{T_i}{17T_1} \right)
\]

with \( n_i \), the background deuteron density, in \( \text{cm}^{-3} \), \( T_i \) in electronvolts, \( Z_i = 17 \) for argon, \( B_T = 5.3 \, \text{T} \), \( q \) is the safety factor and primes indicate spatial derivatives. (This expression differs from Eq. (13) of Ref. [6] by a factor of \( \sqrt{2} \).) The \( q \) profile for the discharge of Fig. 1 at 0.5 s, determined from EFIT, may be approximated by

\[
q(r) \approx \exp\left(\frac{r}{17.3 \, \text{cm}}\right)^{2.65} - 0.075.
\]

The spatial profile of the neoclassical impurity perturbation of Eq. (1) may be calculated from the profiles of Figs 8 and 9 and the \( q \) profile, assuming \( n_i = n_e \), and is shown in Fig. 13 by the solid curve. The calculated perturbation grows very rapidly past 10 cm, and continues to values beyond the validity of the treatment. A non-linear extension of the calculation leading to Eq. (1), intended to be self-consistently valid for large impurity density perturbations (\( \sim O(\epsilon) \)), is presented in Refs [7] and [8]. The ratio \( \tilde{n}_I/n_1 \), calculated from Eq. (2.17c) in Ref. [8], is also shown in Fig. 13, by the dotted curve. These two curves are identical for radii smaller than 13 cm; the non-linear perturbation peaks at a value of 0.22 at 15 cm, and then decreases back to zero. The maximum allowable perturbation in the non-linear treatment has the value of \( \epsilon \). Also shown in Fig. 13 is the density perturbation from Fig. 10, determined from the best fit to the brightness profile of Fig. 12. While the qualitative agreement between the inferred impurity density perturbation and those calculated from neoclassical theory is good (the direction of the asymmetry, and the increase with minor radius), there are quantitative differences, in that the inferred asymmetry is larger in magnitude, and occurs closer to the last closed flux surface, compared to the calculated profiles. Observed cross-field transport [29] is known to be much larger than the neoclassical predictions, but this has not been taken into account in the above theoretical comparisons. There may also be some anomalous mechanisms at work for parallel transport. A self-consistent two dimensional (2-D) impurity transport calculation (as in Ref. [2]) has not been performed. The calculated asymmetry is sensitive to the details of the electron density profile. The large observed asymmetry is certainly not due to the influence of neutral particles, since it was not affected by changing the X point from the bottom to the top of the machine. Operating in the divertor configuration is not relevant for this effect since it has been observed in Alcator C and other limited devices [1, 3, 4]. Edge impurity source asymmetries are not relevant in the Alcator C-Mod and Alcator C cases since the observed asymmetry is due to \( \text{Ar}^{17+} \), which must come from the plasma centre.
5. CONCLUSIONS

Large up-down asymmetries in Ar\textsuperscript{16+} X ray brightnesses have been observed from the edge of Alcator C-Mod plasmas, where the upper levels of the transitions are populated by radiative recombination of Ar\textsuperscript{17+}, which has come from the plasma centre. Modelling of the observed brightness profiles indicates that the brightness asymmetries can be explained by an asymmetry in the Ar\textsuperscript{17+} density of a factor of \( \approx 8 \), just inside the last closed flux surface. This asymmetry is in the opposite direction from the ion \( B \times \nabla |B| \) drift direction, and changes direction when the direction of the toroidal magnetic field is reversed. These observations are in qualitative agreement with the predictions of neoclassical parallel impurity transport theory (in the collisional regime) in the direction of the impurity asymmetry with respect to the toroidal magnetic field direction, and in the increase of the asymmetry towards the plasma edge. The observed asymmetry, however, is larger in magnitude than the predictions, and peaks at a larger radius.

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