A new diagnostic to measure edge ion temperatures on MAST

T.W. Morgan[1], H. Meyer[2], D. Temple[3], G.J. Tallents[1]

[1]*Department of Physics, University of York, Heslington, York, UK*
[2]*EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, UK*
[3]*Department of Physics, Imperial College, University of London, UK*

Introduction

Understanding the pedestal region of tokamak plasmas remains an important problem as this boundary region determines the confinement of the plasma as a whole. Ion temperatures in the pedestal region are a vital component of the pedestal pressure but on MAST the core charge exchange recombination spectroscopy (CXRS) system does not necessarily have the spatial resolution (~1cm) to reliably identify any variations in T_i of similar scale length to T_e in the pedestal region, as the electron temperature pedestal width Δ_{T_e} can be as low as 0.5cm [1]. MAST charge-exchange measurements at the edge in H-mode using the heating beams are complicated by high background and show a response to deuterium gas puffing through a corresponding increase in signal intensity. Using this response to changes in the neutral density a novel technique to measure ion temperatures at high spatial resolution in the pedestal region has been developed.

Diagnostic system

MAST has a flexible active edge Doppler spectroscopy diagnostic. This provides 30 or 60 toroidal chords covering a 10cm radial extent of the plasma edge with a maximum spatial resolution of 4.5mm or 3.0mm. The charge exchange (CX) emission line used was the C^{6+} $n = 8-7$ line at 5290.5Å. A perturbation in the background charge exchange emission was provided by injecting a burst of cold neutral deuterium radially into the plasma at the viewing position and subtracting the increased signal from the background line-integrated emission measured between bursts. This provides measurements every 25-50ms (due to the response of the gas valve) with a time resolution of 5ms or 10ms.

Modelling using ADAS atomic data [3] shows that a significant boost to local emission due to charge exchange (predominantly CX from the $n = 2$ state of the deuterium rather than the ground state) is obtained rather than other processes such as electron excitation of C^{5+}. The measured data are likely to be from ions in thermal equilibrium with the bulk deuterium ions as C^{6+} is long lived in the plasma. Modelling using GTNEUT (a 2D neutral transport code) [4] also indicates that the burst will remain coherent and penetrate the plasma 7-10cm, far enough for background subtraction to give a localized measurement at all measured radii. However, curvature broadening due to the finite width of the gas puff will decrease the spatial resolution by ~1mm.

Using this model a given T_i profile can be shown to be accurately measured without inversion. Comparison with measured data shows that the signal density is typically boosted by around 50% in the pedestal region, but that the signal increase falls significantly within 5-10cm of the plasma edge. However, this penetration depth is adequate on MAST for accurate measurements of the pedestal and edge region.

Measurements

A series of measurements in a variety of plasma scenarios were made. Complications arise from the presence in the edge region of an impurity line lying in close proximity to the measured charge-exchange line. This necessitated a two-Gaussian fit to the signal and the background. In L-mode this impurity line dominates near the plasma edge, making accurate fitting to the CX-line difficult, while in H-mode the charge exchange signal remains dominant at all measured positions. This can be explained by the large increase in C^{6+} density in H-mode [5] which generally results in a hollow profile and an increase in edge C^{6+} density. Therefore the H-mode measurements tend to be of higher quality due to the better signal to noise ratio.

Under conditions in L-mode where core CXRS measurements are possible up to the edge, measurements agree closely with the CXRS ion temperatures. Good agreement between the measured temperatures and electron temperatures measured via Thomson scattering are also observed in the core inside of the pedestal region. Within the pedestal region profiles often show a much shallower gradient than that of the electron temperatures, generally maintaining a similar or shallower gradient to that inside the pedestal, while the electron temperatures follow a much steeper gradient which is closely correlated to the large electron density gradient which characterises the pedestal (figure 1d). This can lead to a large difference between T_i and T_e at the plasma edge. Similar observations have been made on a number of other machines, for example at DIII-D [6] and ASDEX Upgrade [7]. However, this is not always the case as some plasmas show a larger ion temperature gradient and a closer correlation of the ion and electron temperature (figure 1c).

Analysis

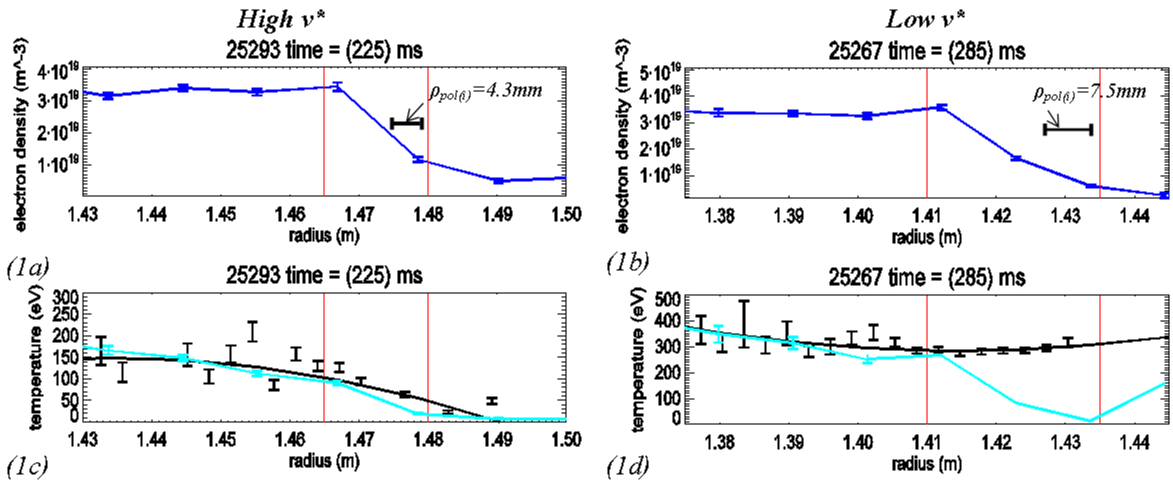

Figure (1): Pedestal position n_e T_e T_i (a) electron density across edge region for typical large T_i gradient pedestal (b) electron density across edge region for typical small T_i gradient pedestal (c) electron and ion temperature profiles across edge region for typical large T_i gradient pedestal (d) electron and ion temperature profiles across edge region for typical small T_i gradient pedestal

A possible explanation for the small ion temperature gradient can be obtained following Kagan and Catto [8]. Using a modified gyrokinetic formalism they show that generally to first order any flux surface is a closed system such that the flux surface will equilibrate with itself. However, in the pedestal in the banana regime the radial gradient scale for the ions can be of the order $\rho_{pol(i)}$ and thus all flux surfaces in the pedestal are coupled to each other such that departures from one flux surface will affect the surrounding region, leading to the entire pedestal becoming a closed system. Therefore across the pedestal region only small temperature gradients of the order $\rho_{pol(i)}\nabla \ln T_i$ well below 1 are permitted in the banana regime. In the Pfirsch-Schlüter regime this would not necessarily be expected as the departures from a given flux surface are smaller, while the plateau regime would be transitional. Furthermore, as $\rho_{pol(e)}$ is much smaller than $\rho_{pol(i)}$ this analysis does not hold for electrons, permitting larger electron temperature gradients to exist than are permitted for ions, as observed. Although this formalism has been done for large aspect ratio tokamaks the argument is general enough to also apply in the spherical tokamak case.

An analysis of the collisionality $\nu^* \equiv \left(\tau_{\text{bounce}} / \tau_{\text{detrap}}\right)$ of the measured profiles indicates that the pedestal regions cross the plateau regime, defined as $1 < \nu^* < \varepsilon^{-3/2}$ ($1 < \nu^* < 4$ where $\varepsilon = r / R \sim 0.4$ on MAST), as the banana regime applies when $\nu^* < 1$ and the Pfirsch-Schlüter regime applies when $\nu^* > \varepsilon^{-3/2}$ while the collisionalities measured lie in the range $0.1 < \nu^* < 30.0$. Therefore one would expect a positive correlation between ν^* and the inverse

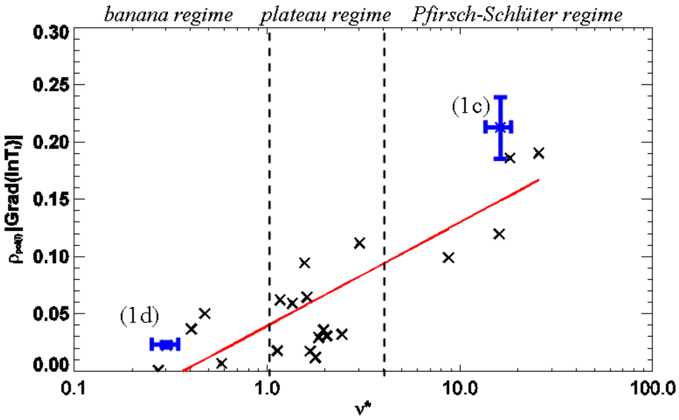

Figure (2): correlation between ν^* and $\rho_{pol(i)}\nabla \ln T_i$ at base of pedestal. Marked points are those in figure 1.

temperature-gradient scale length, (defined as $\rho_{pol(i)}\nabla \ln T_i$), as the coupling between flux surfaces will decrease with ν^* in this transitional case. Analysis of the measured profiles indeed shows a correlation between these indicating that T_i / T_e decreases and the T_i gradient increases as the collisionality approaches the Pfirsch-Schlüter regime (figure 2). As the deuterium ions have a collisionality which is smaller by a factor $(Z_D / Z_C)^2$~1/36 we would therefore expect that the observed profiles would be replicated in the bulk deuterium for the flattened gradient case. As the heat exchange time for D^+ and C^{6+} (~0.01ms) is much smaller than the heat exchange time for D^+ and e^- (~5ms) it seems likely that the observed profiles are similar for the two ion species.

Conclusion

A new edge ion temperature measurement diagnostic system has been successfully implemented on the MAST tokamak. The profiles measured often show a much shallower ion temperature gradient than is observed for the electron temperature, the scale length of which appears to be correlated with the collisionality of the C^{6+} ions. As it is likely that the carbon and deuterium ions are in equilibrium the bulk temperatures should follow a similar profile.

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