Effect of high neutral density on radiation measurements in Alcator C-Mod

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Introduction

Elevated radiation, $\sim 1\,\mathrm{MWm}^{-2}$, has been observed using foil bolometers viewing the far scrape-off layer (SOL) in high density ($n \geq 0.35n_G$) deuterium Ohmic L-mode plasmas on Alcator C-Mod. Plasmas at lower densities ($n \leq 0.2n_G$), and those at $n \sim 0.4n_G$ in He main-ion, do not exhibit such high far SOL brightness measurements, as shown in Figure 1. The increase in the brightness signal appears to track main chamber neutral pressure measurements, so it is believed that a significant heat flux from neutral particles in the far SOL and limiter shadow is contributing to the absorbed power on the bolometer measurements.

This effect is important, as it represents an additional power loss mechanism at high neutral pressures for which good diagnostic capability is currently lacking. The relevant neutral pressures, $O(10^{-1}\,\mathrm{Pa})$, are similar to those expected to be found in closed divertors such as the Super-X divertor of MAST Upgrade [1]. An understanding of how the additional neutral heat flux affects foil bolometers is therefore crucial in the successful interpretation of diagnostic measurements of high density, highly radiating plasma exhaust in long-legged divertors.

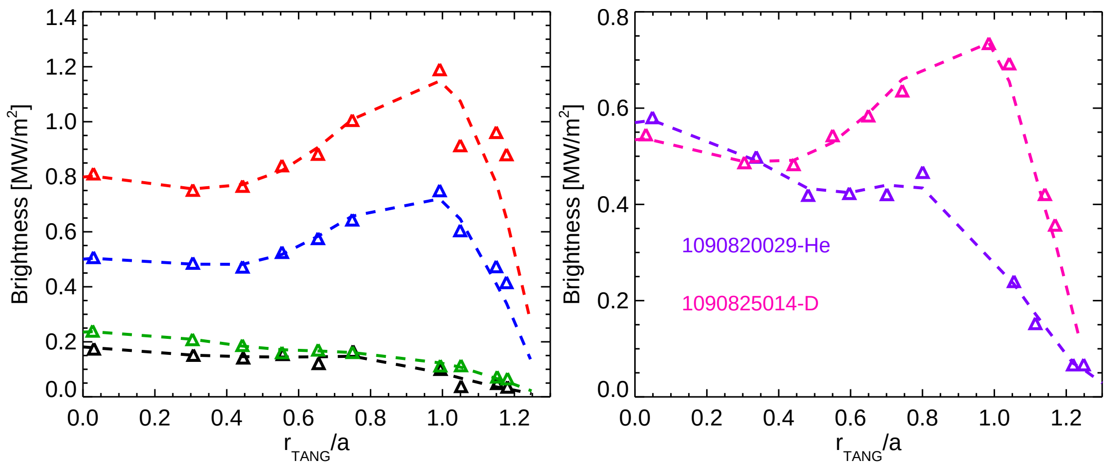

Figure 1: *Left: Foil bolometer brightness profiles for a density scan, for $n_e/n_G = 0.15$ (black), 0.23 (green), 0.35 (blue) and 0.42 (red), showing significant increase in far SOL brightness. Right: brightness profiles for D and He plasmas at $n_e/n_G = 0.47$, showing only small far SOL brightness in He.*

Methodology

We have used a 1D kinetic neutrals code, KN1D [2], to model the radial heat flux carried by the neutrals and compare this with the far SOL bolometer data. The code takes as inputs the wall pressure and n_e, T_e and T_i profiles and calculates kinetic profiles for both atomic and molecular deuterium. The input density and temperature profiles are obtained from a combination of edge Thomson scattering data and two scanning probes, a horizontal probe just above the midplane (ASP) and a vertical probe near the divertor region (FSP). We assume $T_i = T_e$. The wall pressure is taken from one of several main chamber pressure gauges distributed toroidally around the machine, all of which show similar readings ($< 20\%$ variation) for the shots we have studied. Figure 2 shows the poloidal distribution of the diagnostics inside the tokamak.

We benchmark the simulation by comparing the Ly-α emissivity profile computed by KN1D with the measured profile from a tangentially-viewing Ly-α-filtered diode array. We then compare the KN1D calculation of the neutral heat flux at the wall with the brightness measured by the outermost bolometer channel at $r/a = 1.19$, which is expected to measure almost no plasma radiation. In this simple treatment, we assume the radial neutral heat flux is equivalent to what is absorbed by the bolometer, and neglect reflections of neutrals on the bolometer sensor.

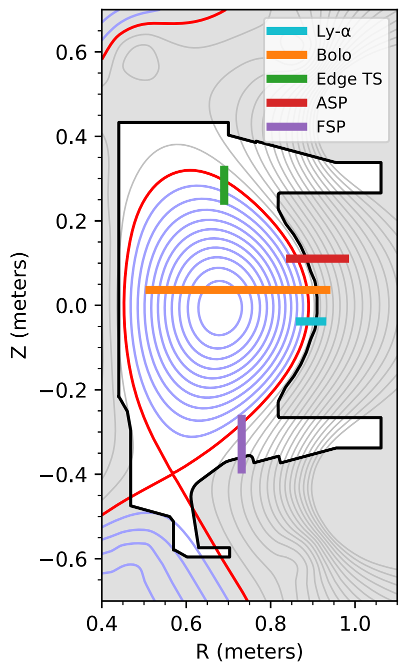

Figure 2: *Positions of the key diagnostics used in the study*

Results and discussion

We find the neutral heat flux calculated by KN1D is only 10% of the measured $r/a = 1.19$ bolometer brightness. Our assumption — that the power density on the foil bolometer due to the neutral heat flux is equal to the heat flux at the wall calculated by KN1D — therefore leaves us unable to account for the majority of the power detected by the bolometers, unless there is genuinely a significant amount of radiation in the far SOL. This under-prediction of the brightness due to neutrals is consistent across the full range of the density scan, as shown in Figure 3. That figure also shows that in Ohmic L-mode helium plasmas of comparable density the amount of radiation measured by the far SOL-viewing bolometer channel is consistently low, which suggests that impurity radiation is not the cause of the high bolometer measurements. The D_2 plasmas have Greenwald density $n_G = 7.2 \times 10^{20}\,\mathrm{m}^{-3}$.

The heat flux/brightness discrepancy can potentially be explained by considering that the

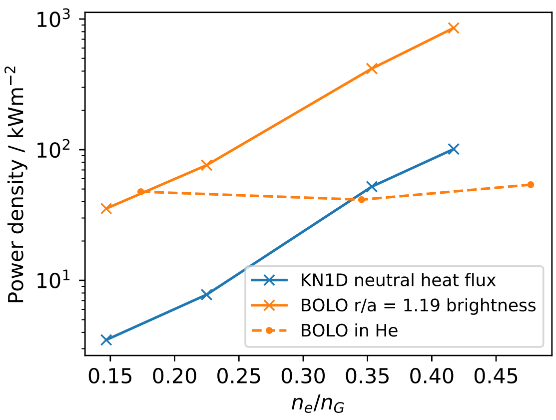

Figure 3: *Comparison of KN1D-calculated neutral heat flux and measured bolometer brightness as a function of Greenwald fraction.*

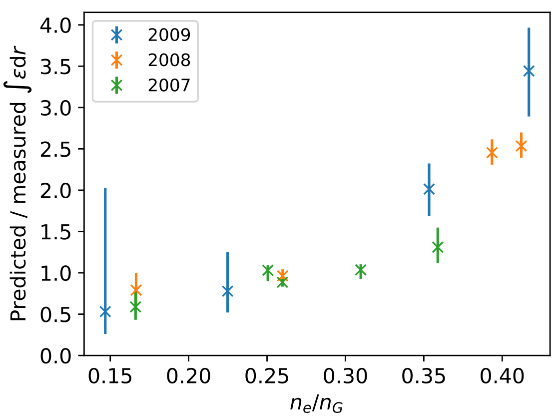

Figure 4: *Ratio of the radial integrals of the KN1D-predicted and measured Ly-α emissivity profiles vs Greenwald fraction.*

bolometer is viewing tangentially rather than radially. In fact, a suitable diagnostic to measure the radial neutral heat flux is not available: a radially-viewing bolometer would also measure all the core and edge radiation without the possibility of distinguishing this radiation from the neutral particle heat flux. The bolometer actually views a volumetric neutral heat flux profile integrated along a tangential line of sight, and we can estimate the relative size of this compared to the radial heat flux. By considering a bolometer with an tangency radius $R_T = 90\,\text{cm}$ viewing an annulus of width $\delta = 3\,\text{cm}$, we estimate that the ratio of the heat flux to a tangentially-viewing vs a radially-viewing bolometer is given by $2\sqrt{2}\left(\frac{R_T}{\delta}\right)^{1/2} \approx 15$. This assumes no net neutral absorption along the path, and is therefore an upper limit on the amount the radial output from KN1D underestimates the heat flux on the tangentially-viewing bolometer. Since the under-prediction is only a factor of 10, we cannot rule out that the neutral heat flux is truly the dominant source of the brightness measurement. However, we cannot make any more concrete conclusions about the size of the neutral contribution to the brightness with the current physical and synthetic diagnostic suite.

The second interesting result of these simulations is that the modelling significantly over-predicts the Ly-α emission for high density shots, yet the predicted and measured emission are in good agreement in lower density shots. This is illustrated in Figure 4, which plots the ratio of the radial integrals of the emissivity profiles predicted by KN1D and measured by the filtered diode array. We can see that for $0.15 \lessapprox n_e/n_G \lessapprox 0.31$ the model is able to reproduce the measured radiation, but for $n_e/n_G \gtrapprox 0.35$ the simulations predict significantly more radiation than is actually measured. It is interesting to note that $n_e/n_G \gtrapprox 0.35$ is also the boundary above which we see significant brightness in the far SOL bolometer measurements, but it is not clear yet how closely related these two phenomena are.

Whilst we cannot yet state the cause for this radiation discrepancy at high density, one possible reason is that higher-dimensional transport effects are more important in higher density regimes, and we are not able to capture these in a 1D code. Modelling with SOLPS-ITER is currently underway to search for any significant 2D effects, but it is also possible that phenomena such as limiter shadowing due to the position of the Ly-α diagnostic in C-Mod is significant. Modelling these effects may in fact require a full 3D neutrals code. At the very least a better 3D description of the boundary and an understanding of possible variations in plasma density behind limiter surfaces would need to be incorporated into the 1D model.

Conclusions

We have demonstrated that 1D modelling is unable to simultaneously predict high brightness measurements in the far SOL on foil bolometers and Ly-α-filtered photodiodes. The neutral heat flux contribution cannot definitively be neglected, but a better model and synthetic diagnostic is needed to successfully calculate the size of this contribution to the bolometer brightness measurements. We have also showed that 1D modelling using KN1D can only accurately reproduce the Ly-α emission at lower densities, whereas it significantly over-estimates the emission at higher densities. We believe that some additional 2D or 3D models of the plasma profiles and wall sources are required to reproduce measured emissivity profiles at high densities. Since even higher neutral pressures are likely to be found in highly radiative scenarios such as detachment studies, further work is most certainly required to enable successful interpretation of radiation measurements in these types of plasmas and allow for clear scientific investigation of the different heat loss channels.

Acknowledgements

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