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Measurement of radiation asymmetries in MAST Upgrade double null divertor plasmas

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Introduction and motivation

The spatial distribution of all power loss channels in a tokamak plasma has important implications for the successful implementation of plasma exhaust solutions. The MAST Upgrade spherical tokamak is nominally up/down symmetric and typically utilises a connected double null magnetic configuration, but a comprehensive study of the degree of asymmetry in the power exhaust has not yet been performed. Recent diagnostic enhancements have enabled the first exploratory studies of radiated power asymmetries in these connected double null configurations. Here we investigate up/down and in/out radiation asymmetries, with the aim of informing future detailed investigations of global power balance.

Experiment description and methodology

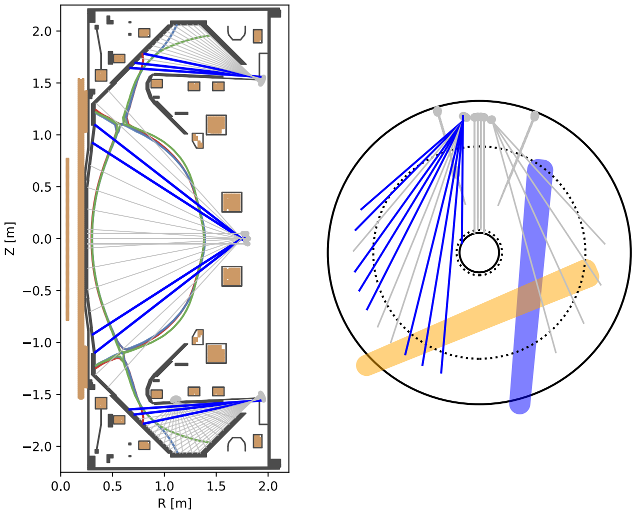

Figure 1: Lines of sight of the foil bolometers on MAST Upgrade, showing poloidal (left) and top-down (right) views with representative MAST-U equilibria for conventional (red), elongated (pale blue) and Super-X (green) divertor configurations. Channels in blue are used for asymmetry measurements.

MAST Upgrade is equipped with a suite of foil bolometers, shown in Figure 1 [1]. Poloidal and tangential arrays in the main chamber measure vertical and radial line integral brightness profiles respectively. Vertical and horizontal arrays in the lower Super-X divertor chamber are designed to enable 2D tomographic reconstructions of the emissivity profile. Recently an additional array has been installed in the upper divertor chamber. The viewing geometry matches that of the horizontal array in the lower divertor, for direct comparisons of the poloidal brightness profile and total radiated power in the the two divertor chambers.

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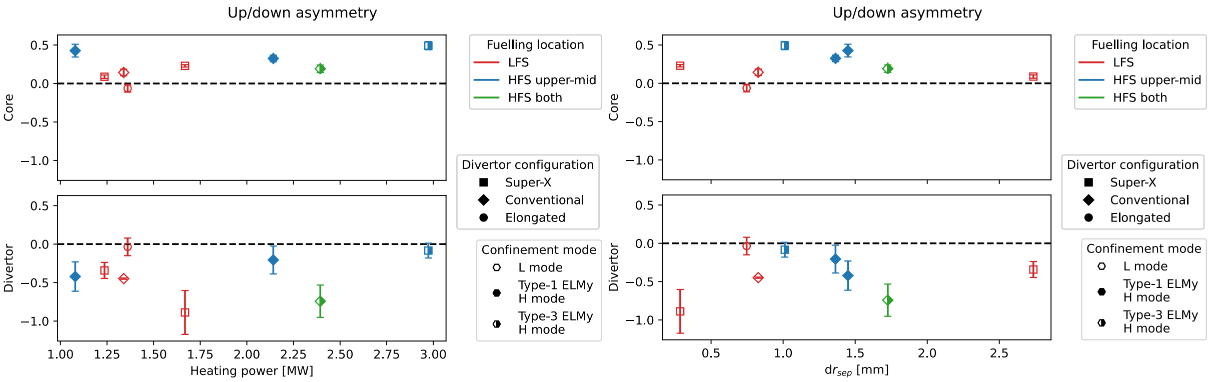

Figure 2: Measured up/down asymmetries as a function of input power (left) and distance between separatrices (right). Marker shapes and colours distinguish fuelling location and confinement mode.

The bolometers suffer from high electrical interference from MAST-U's switched mode power supplies, which greatly reduces the achievable time resolution and makes several channels unusable. As a workaround, we focus our analysis on NBI-heated discharges with higher levels of radiated power to maximise signal levels, and restrict analysis to the channels least affected by electrical pickup. These are shown in blue in Figure 1, for both main chamber ("core") and divertor channels. With B as the line-integral brightness, we define the up/down asymmetry as follows:

$$A = \frac{\langle B_{z>0} \rangle}{\langle B_{z<0} \rangle} - 1 \tag{1}$$

In/out midplane asymmetries are determined by inverting the radial brightness profiles measured by the tangential array. These channels are less contaminated by electrical interference and so most of the counter-clockwise-viewing channels are available. The clockwise channels measure a significant power flux from NBI fast ion losses and so are left out of this analysis.

An infra-red video bolometer (IRVB) provides high resolution measurements of the emissivity distribution around the lower X point and divertor legs [2]. We use tomographic reconstructions of the 2D emissivity profile to investigate inner vs outer divertor leg asymmetries.

Results and discussion

Figure 2 shows the calculated up/down asymmetry in the main chamber and divertor chambers, for plasmas with different heating powers, fuelling locations, confinement types and distance between separatrices dr_{sep} — the latter depends on the magnetic axis height. We find that there is in general a weakly positive core asymmetry, indicating more radiation emitted in the upper half of the main chamber than the lower half, and a stronger (but with larger uncertainty) negative divertor asymmetry. This trend appears to be independent of input power, confinement mode and dr_{sep}. While we might expect some dependence especially in the divertor asymmetry with dr_{sep}, previous work on MAST [3] found the target heat flux asymmetry was small for d$r_{\text{sep}} < \lambda_q$. Here the heat flux width λ_q is in the range 7 mm to 10 mm: significant radiation asymmetries are therefore likely to be observed only at larger dr_{sep} than studied here.

The strongest observed dependence is that of the core asymmetry on the fuelling location: fuelling from just above the midplane on the high field side (HFS) yields larger positive asymmetries than a mix of HFS fuelling above and below the midplane, and fuelling from the low field side (LFS) yields the smallest core asymmetries overall. We have two possible explanations for this observation: either the radiation is predominately hydrogenic and therefore dominated by regions with higher neutral hydrogen density (caused by the interaction of cold fuelling gas with the edge plasma), or the impurity radiation is increased by enhanced cooling of impurities by the fuelling gas near the puff locations.

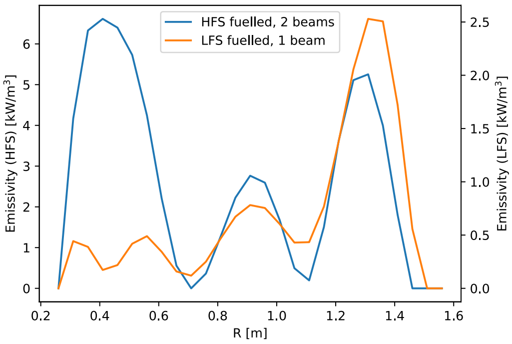

Figure 3: Radial emissivity profiles at the midplane, based on inverted brightness profiles, for plasmas fuelled from the HFS and the LFS.

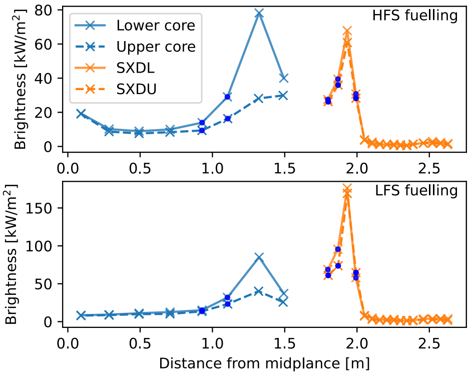

Figure 4: Synthetic brightness profiles from SOLPS simulations with HFS and LFS fuelling. Blue dots show channels used for asymmetry quantification.

The observation that the up/down radiation asymmetry is apparently most strongly dependent on fuelling location motivates comparison of radial emissivity profiles at the midplane for different fuelling locations. Figure 3 shows such a comparison. While both plasmas exhibit strong peaking of the radiation near the separatrix as might be expected (due to the increased density of partially-ionised impurities and neutral deuterium), the inboard separatrix radiates significantly more when using HFS fuelling than LFS fuelling.

We now compare these observations with predictions from SOLPS modelling of comparable MAST-U plasmas. The model cases considered have 2 MW of heating power, dr_{sep}= 0 and cross-field drifts activated. Fuelling was changed from HFS to LFS. We calculate synthetic brightness profiles using a volumetric field of view integration of the plasma emission using the Cherab framework [4], and also sample the radial profile of the emissivity at the midplane. Figure 4 shows the computed synthetic brightness profiles and Figure 5 shows the midplane emissivity profile. The in/out asymmetry variation with fuelling matches qualitatively with experiment, and a small negative up/down asymmetry factor

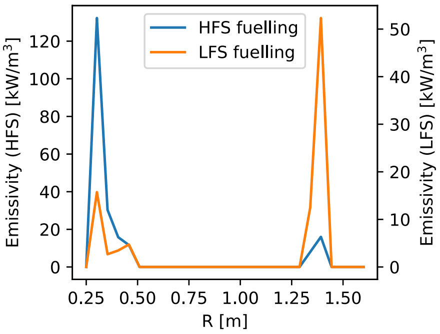

Figure 5: Radial emissivity profiles from simulations with HFS and LFS fuelling.

A is observed in the divertor channels, consistent with the measurements. The core however exhibits $A < 0$ inconsistent with experiment, which we believe is because in the simulations the fuelling is modelled by a particle source exactly at the midplane whereas in experiment the fuelling is from toroidally-localised gas valves displaced from the midplane. Since fuelling location is the strongest driver of radiation asymmetries, future modelling should consider matching the poloidal fuelling location to improve comparisons with experimental measurements.

Finally, we analyse tomographically inverted emissivity profiles from the IRVB, for a discharge with both a density and power scan. Figure 6 shows that at lower density and heating power (left) the inner leg radiates more strongly than the outer, with emission peaked at the target. As the density is increased and the power reduced (right) the inner leg radiation front detaches from the target, whereas the outer leg radiation front is still attached to the target. This illustrates different detachment onsets for the inner and outer divertor legs.

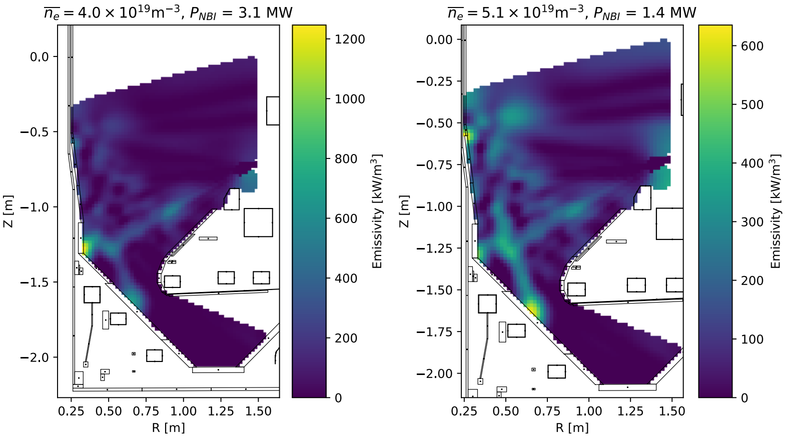

Figure 6: Experimental emissivity profile variation as the density and NBI heating is varied.

Summary and acknowlegements

Foil bolometers and an IRVB are used to measure radiation asymmetries in MAST-U. We find in the core radiation is strongest nearer to fuelling locations, while the lower divertor radiates more strongly than the upper. The up/down core asymmetry is not captured by interpretive modelling, though the in/out asymmetry is. IRVB measurements indicate differences in detachment onset between the inner and outer divertor legs.

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