A high-k mm-wave scattering diagnostic for measuring binormal electron scale turbulence on MAST-U

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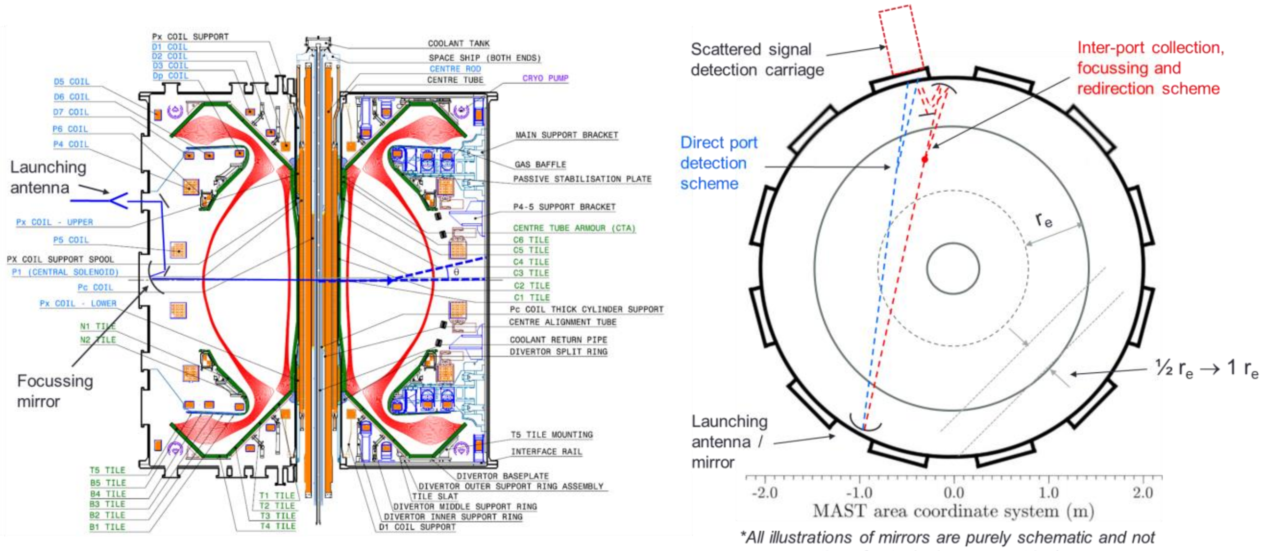
Plasma turbulence plays a key role in determining the spatial-temporal evolution of plasmas in astrophysical, geophysical and laboratory contexts. In particular, turbulence on disparate spatial and temporal scales limits the level of confinement achievable in magnetic confinement fusion experiments and therefore limits the viability of sustainable fusion power. MAST-U is a well-equipped experimental facility having instruments to measure ion-scale turbulence and electron scale turbulence at the plasma edge. However, measurement of turbulence at electron scales in the core is problematic, especially in H mode. This gap in measurement capability has provided the motivation to develop a high-k microwave scattering diagnostic for MAST-U*. The turbulence is expected to be most significant in the binormal direction with scale ranges expected of order ($k_\perp \rho_e \sim 0.1 \rightarrow 0.5$) in the confinement region of the core plasma ($0.5 < r/a < 1$). We therefore propose a binormal high-k scattering diagnostic operating with near-perpendicular incidence to the magnetic field through the scattering region.

In this paper, the results of Gaussian wave optics and beam-tracing calculations [1] are presented that demonstrate the predicted spatial and wavenumber resolution of the diagnostic along with the sensitivity of the measurement, assuming a probe beam crossing close to the diameter of the MAST-U vessel in the equatorial mid-plane. The analysis considers the variation of magnetic pitch angle ($\alpha = tan^{-1}\,(B_\theta \,/\, B_\varphi)$) as a function of plasma radius and its effect on the instrument selectivity function $F(r)$ as a function of scattering location and $k_\perp \rho_e$. An illustration of the proposed scattering geometry with respect to the MAST-U cross-sectional schematic is given in figure 1.



All illustrations of mirrors are purely schematic and not representative of actual mirror geometries

Figure 1: Proposed high-k scattering geometry on MAST-U experimental schematic.

The system we propose will operate in the collective scattering regime governed by the Bragg condition at a frequency close to 260GHz to maintain adequate $k_\perp \rho_e$ resolution over the range of interest whilst minimising beam refraction and maximising the detected signal to noise ratio. We propose the use of a compact 50mW solid-state mm-wave source (vacuum tube upgradable) coupled with a detector noise bandwidth of ~15MHz and noise temperature of ~1000K. After a detailed consideration of the MAST-U port allocation maps and the precise internal positioning of components, we here consider the option of injecting the mm-wave Gaussian beam 'optically' via a 200mm diameter upper port, and using a combination of planar and focussing mirrors to launch across the plasma from an inter-port mount on the equatorial plane (see figure 1), with scattered beams either directly incident on one of the 600mm equatorial ports or (in preference) indirectly (via a collection mirror) in an inter-port area. An example representation of the Gaussian beam-waist evolution from launch to detection is presented in figure 2. For the proposed scattering radii, there is minimal variation in the $1/e^2$ beam waist w from ~ 3 cm. For the purpose of the localisation and sensitivity calculations that follow we have therefore assumed a 3 cm $1/e^2$ beam waist.

We conducted beam-tracing calculations of the primary and scattered rays for a representative high-beta MAST-U equilibrium (results presented in figure 3). These were computed for 3 scattering coordinates of 1.0 m, 1.14 m and 1.24 m in major radius. In each case, we defined 4 equally spaced scattered beams up to a maximum scattering angle limited by the upper poloidal field coil P5.

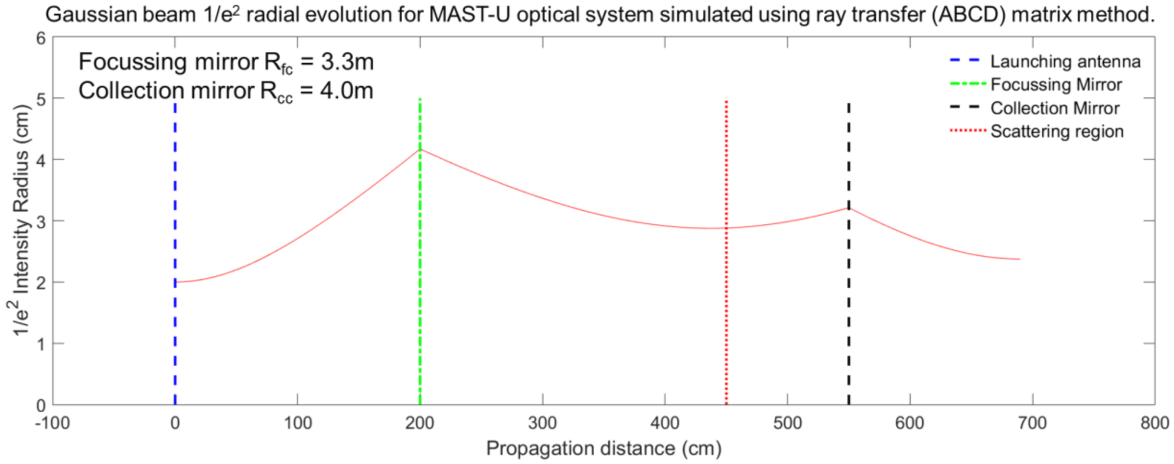


Figure 2: Example ABCD matrix calculation of Gaussian beam waist evolution for the proposed scattering geometry.

For a position mid-range between the magnetic axis and the pedestal (R_{scatt} = 1.14m) this gives a maximum measurable $k_{\perp}\rho_e$ of ~0.38. The scattered beam traces account for the variation in magnetic field pitch factor as a function of scattering radius, resulting in different angles of the scattered beamlets (with respect to the equatorial plane) for each of the three scattering coordinates.

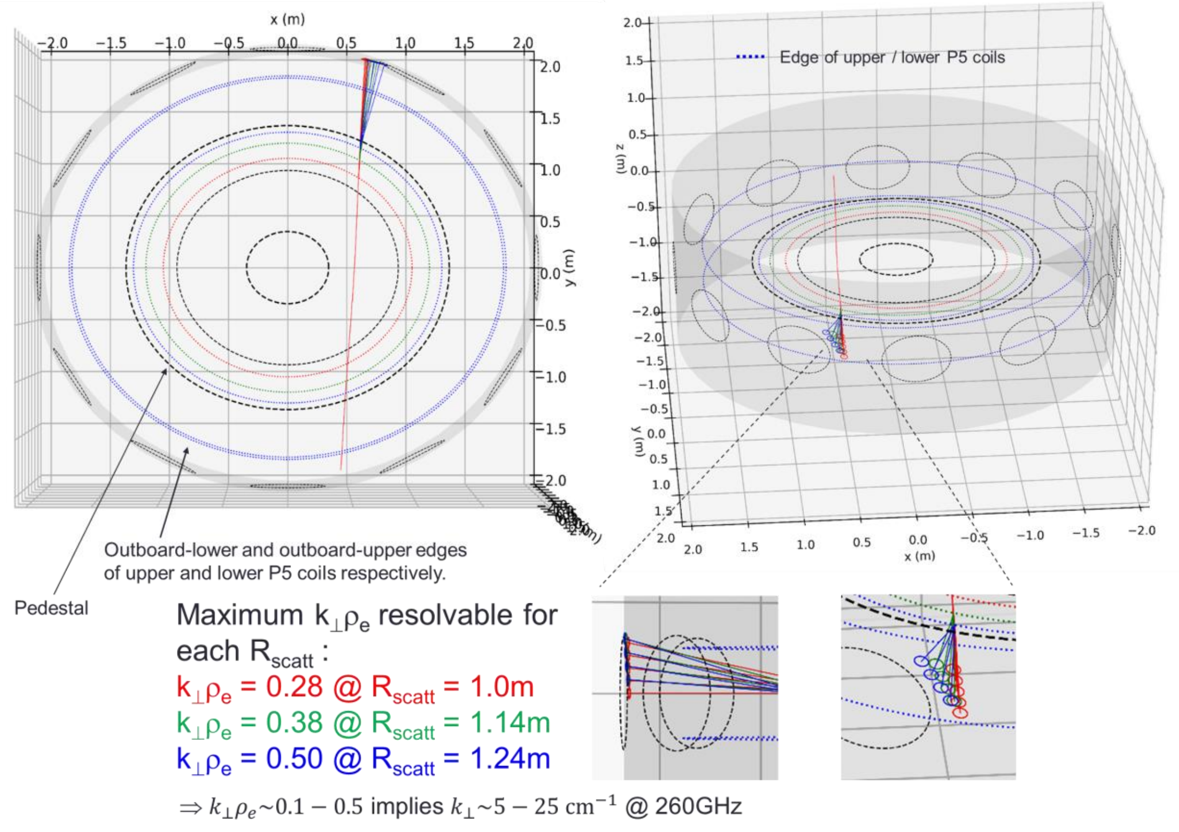


Figure 3: MAST-U high-beta beam tracing results for binormal scattering at R_{scatt} = 1.0 m, 1.14 m and 1.24 m.

Using the k⊥ data for each of the scattered components from the beam tracing simulations, we conducted an analysis of the instrument selectivity function accounting for the variation of magnetic field pitch angle α as a function of radius through the scattering coordinates. The analysis we conducted is similar to that presented by Mazzucato et al. [2, 3], and Devynck et al. [4] where it was observed that for near perpendicular incidence of the primary ray to the magnetostatic field, a strong variation in magnetic pitch factor with radius served to enhance measurement localisation.

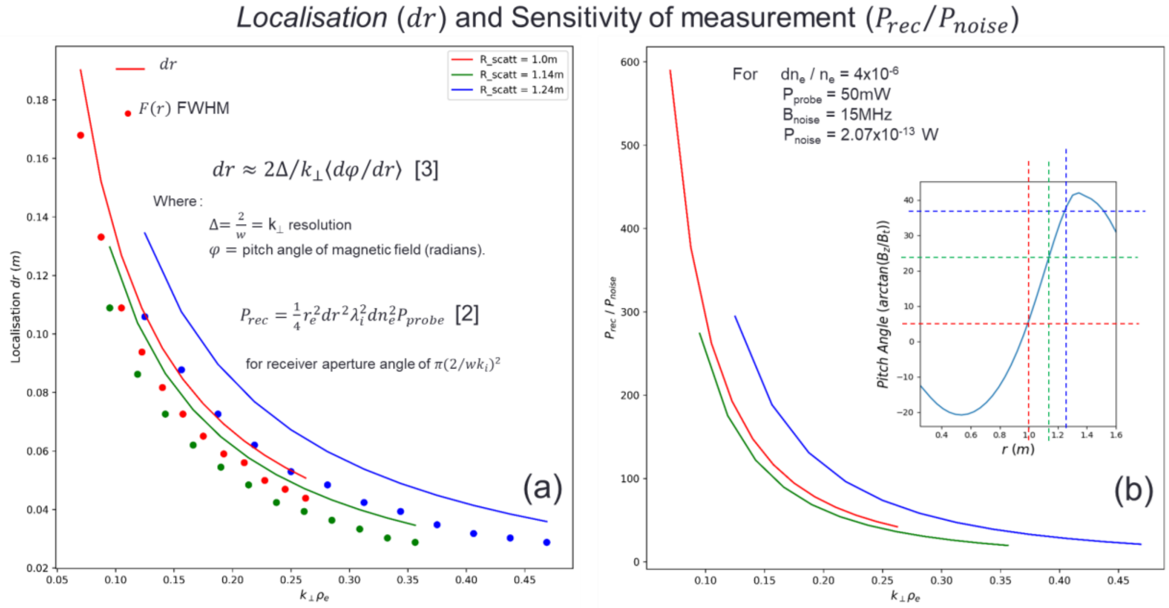

Localisation (dr) and Sensitivity of measurement (P_{rec}/P_{noise})

Figure 4: (a) Localisation dr vs $k_\perp\rho_e$ and associated sensitivity of measurement

(b) P_{rec} / P_{noise} for R_{scatt} = 1.0m, 1.14m and 1.24m.

Looking at the variation of dr with $k_\perp\rho_e$ in figure 4, there is a clear downwards trend moving towards higher $k_\perp\rho_e$ dropping to a minimum of ~0.033m for R_{scatt} = 1.14m and 1.24m ($k_\perp\rho_e$ = 0.38 and 0.50 respectively). Correspondingly, there is a drop in the signal to noise ratio SNR = P_{rec} / P_{noise} to a minimum of ~ 20 for R_{scatt} = 1.14 m and 1.24 m. This can be improved further via upgrade of the transmitted power using a vacuum tube source.

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