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

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***Abstract*—We describe a high-k mm-wave scattering diagnostic for measuring binormal wavenumber electron scale turbulence on the MAST-U spherical tokamak. Gaussian wave optics and beam-tracing calculations are presented that show the predicted spatial and wavenumber resolution of the diagnostic along with the sensitivity of measurement. The proposed system will operate at a frequency of 376GHz and will facilitate adjustable localization of the turbulence measurement from the magnetic axis out to the plasma edge.**

Keywords—turbulence, plasma, microwaves, scattering, tokamak.

I. INTRODUCTION

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 [1]. MAST-U is a well-equipped experimental facility having instruments to measure ion-scale turbulence throughout the plasma 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 mm-wave scattering diagnostic for MAST-U. The turbulence is expected to be most significant in the binormal direction with scale ranges expected of order $k_\perp \rho_e \sim 0.1$ -> 0.4 (where $k_\perp$ is the binormal turbulence wavenumber and ρ_e the electron gyroradius) in the confinement region of the core plasma.

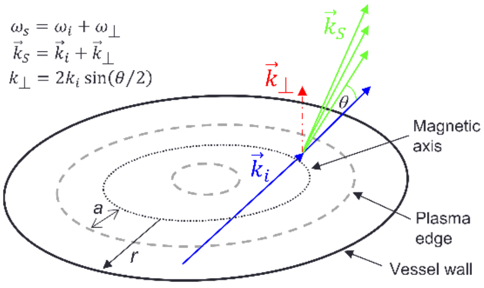

Fig. 1. Proposed binormal high-k scattering geometry across MAST-U plasma

A radial scattering diagnostic operating at 280GHz tangential to the magnetic field was previously installed on the NSTX facility with great success [2]. In satisfaction of the required measurement specifications on MAST-U, we propose a binormal high-k scattering diagnostic operating with near-perpendicular incidence to the magnetic field through the scattering region. The illustration in fig. 1 shows the geometry of scattering with reference to an equatorial midplane slice illustrating the plasma edge (pedestal), magnetic axis and plasma minor radius a. The primary ray in blue is subject to scattering due to the turbulence wavevector $k_\perp$ in red, resulting in the scattered wavevectors k_s. The scattering is in a "coherent" regime, where the scattering parameter $\alpha = 1/k_\perp \lambda_{D_e} \geq 1$ with λ_{D_e} the Debye length. The incident, turbulent and scattered waves satisfy the three wave matching conditions in terms of frequency and wavenumber, and the scattering angle is related to the incident and turbulent wavevectors by the Bragg condition.

II. THEORY AND RESULTS

In this paper, Gaussian wave optics and beam-tracing calculations [3] are presented that show the predicted spatial and wavenumber resolution of the proposed diagnostic for sample MAST-U operating conditions, along with computations of the localisation and sensitivity of measurement. The analysis considers the variation of magnetic pitch angle $\alpha = \tan^{-1}(B_p/B_t)$ as a function of plasma radius (where B_p and B_t are the poloidal and toroidal magnetic field components respectively) and its effect on the instrument selectivity function $F(r)$ as a function of scattering location and $k_\perp \rho_e$ [4]. The proposed system will operate at a frequency of 376GHz to maintain adequate $k_\perp \rho_e$ resolution whilst minimising beam refraction and maximising the detected signal to noise ratio.

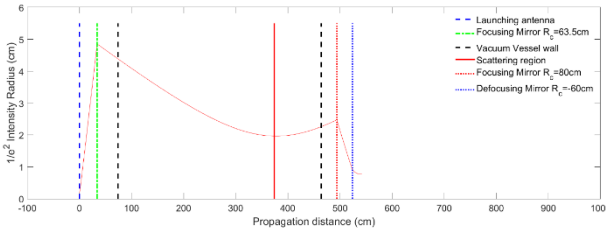

Fig. 2. ABCD matrix calculation of Gaussian beam waist evolution for the proposed scattering geometry.

The results of ABCD matrix computations of the Gaussian beam waist evolution through the launching optics, plasma volume and receiving optics are presented in fig. 2. The beam is launched from a custom smooth profiled horn developed at Strathclyde [5]. This produces a highly divergent beam that intercepts a focussing mirror with a $1/e^2$ radius of 4.9cm. The beam then traverses the MAST-U vessel wall and converges on a waist of 2cm within the scattering region. The waist is relatively flat and extends over 50cm with minimum variation. The beam then traverses the vessel wall and is intercepted by a focussing / de-focussing mirror pair prior to the receiving horns and linear detector array.

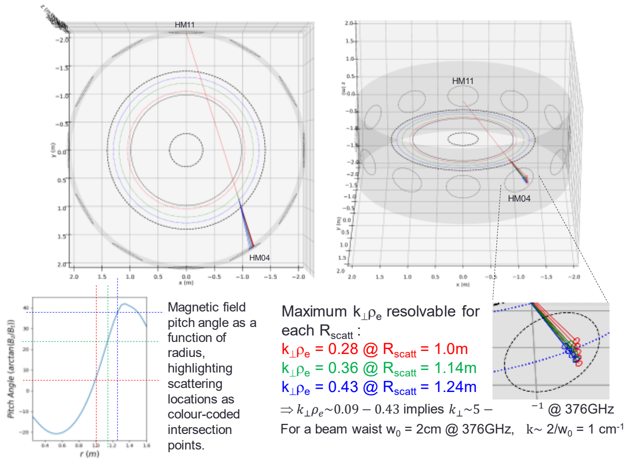

Fig. 3. MAST-U beam tracing results for binormal scattering using a representative sample equilibrium.

Beam-tracing calculations [3] of the primary and scattered rays are presented for a representative MAST-U equilibrium (fig. 3) corresponding to 3 scattering coordinates along the primary ray path. For a position midway between the magnetic axis and the pedestal (R_{scatt} = 1.14m) this translates to a maximum measurable $k_\perp\, \rho_e$ of ~0.36. It is evident from the beam tracing calculations that the binormal direction varies with the pitch factor of the magnetic field (which itself varies with scattering radius). This results in a rotation in alignment of the scattered wave spectrum as indicated in fig. 3 for different scattering radii. In order to maintain alignment of the receiving optics and detector channels for different scattering radii (and different operating equilibria on MAST-U), the entire detection carriage will translate and rotate via rotational and linear drive stages. The linear (radial) translation will facilitate changing the focus of the receiving optics (and therefore the effective scattering radius) along the primary ray path by up to 20cm displacement. Simultaneously, the rotational drive shall maintain binormal alignment of the optics and detector channels with respect to the magnetic field pitch orientation for a given scattering radius.

Using the $k_\perp$ data for the scattered beam spectrum from the beam tracing simulations, we conducted an analysis of the instrument selectivity function accounting for the variation of magnetic field pitch angle $\alpha = \tan^{-1}(B_p/B_t)$ as a function of radius through the scattering coordinates. The analysis we conducted is similar to that of Mazzucato et al. [4], and Devynck et al. [6] 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 serves to enhance measurement localisation.

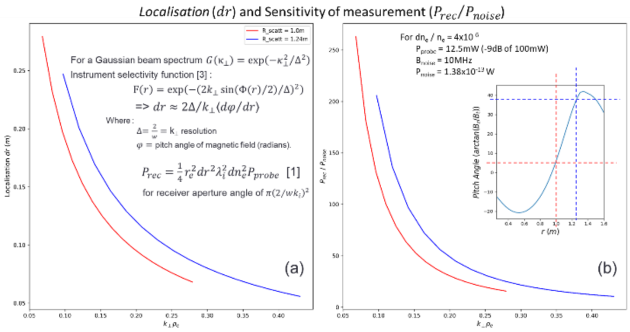

Fig. 4. (a) Localisation dr vs $k_\perp\rho_e$ and associated sensitivity of measurement (b) P_{rec}/P_{noise} for R_{scatt} = 1.0m, 1.14m and 1.24m.

With reference to fig. 4a, it is evident that the localisation length is maximised for lowest $k_\perp\rho_e$ (smallest scattering angle), with a dr of ~25cm for $k_\perp\rho_e$~0.1 at R_{scatt}=1.0m, dropping to ~7cm for a $k_\perp\rho_e$ of ~0.28. At R_{scatt} = 1.24m, a minimum dr of ~6cm is calculated for $k_\perp\rho_e$~0.43. Assuming a solid-state source power of 100mW with detection losses of $-9dB$, detector noise of 1.38×10^{-13} W (this is larger than Bremsstrahlung noise from the plasma) and a low density modulation amplitude of $dn_e/n_e = 4 \times 10^{-6}$, the corresponding signal to noise ratio P_{rec}/P_{noise} has been plotted in fig. 4b. Broadly, this shows a range in P_{rec}/P_{noise} from 265 $\rightarrow$ 16 for $k_\perp\rho_e$ of 0.07 $\rightarrow$ 0.43 respectively. This is very reasonable considering the minimum density modulation amplitude required resolvable in experiments would typically be an order of magnitude greater than 4×10^{-6}, and there is flexibility to further improve sensitivity by compressing the bandwidth of detection (currently 10MHz), thereby reducing detector noise. The proposed mm-wave source for the diagnostic is a 376GHz frequency-multiplied solid state source, which has the advantage of being resiliant to magnetic field variations and can therefore be mounted relatively close to the MAST-U vessel, minimising transmission losses. The proposed detection electronics comprise low-noise heterodyning receivers, with the scattered signals entering discrete feedhorns for each detection channel and down converted in mixers to an intermediate frequency. This is then amplified, bandpass filtered and downconverted to baseband using a commercial IQ mixer to provide the in-phase and quadrature components of the scattered signals, prior to digitisation using a multichannel, high-bandwidth DAQ for analysis.

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