Fluctuation response analysis of plasma turbulence with BES diagnostics

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Introduction Beam emission spectroscopy (BES) is an active plasma diagnostic that relies on the light response emitted by neutral atoms injected into the plasma in form of a high energy neutral beam. The diagnostic is employed for the study of the plasma density profile and its fluctuations caused by various plasma transport phenomena and turbulent processes [1]. The spatial scale of the detectable turbulent structures is limited by the spatial resolution of the diagnostics system. RENATE (Rate Equations for Neutral Alkali-beam TEchniqe) is a BES synthetic diagnostic [2], which is based on a collisional radiative model [3] . It has the capacity of modelling a 3D neutral beam of alkali or hydrogenic species within arbitrary magnetic geometry. In conjunction with an independently modelled observation system, it deliveres the expected photon count on each detector of the observation system. Detailed beam and observation modelling allows the assessment of various aspects of beam evolution, spatial resolution and response to density fluctuation.

Current paper introduces the Fluctuation Response Function (FRF) as means to study the light response caused by various types of plasma turbulence [4]. The paper focuses on the spatial resolution aspect of the FRF, applied to BES diagnostics on the EAST tokamak as well as the study of individual aspects to spatial resolution. Hints are made regarding further applicability.

Definition of the fluctuation response calculation In order to perform fluctuation response calculations, the following timescale assumptions are made: $\tau_{\overline{n}} \gg \tau_{\delta n} \gg \tau_{\text{beam}}$, where $\tau_{\overline{n}}$, $\tau_{\delta n}$, are the timescales of the density profile ($\overline{n}$), density fluctuations (δn) respectively, while τ_{beam} is the time of flight of beam atoms in the observed region. It is also assumed that the electron density $n_e(\mathbf{r},t)$ can be decomposed as: $n_e(\mathbf{r},t) = \overline{n}(\psi) + \delta n(\mathbf{r},t)$, where the average density is $\overline{n}(\psi)$ and the spatially and temporally rapidly varying part is $\delta n(\mathbf{r},t)$, which has zero mean value. Furthermore, it is assumed that the fluctuations are small compared to the average profiles $|\delta n| \ll \overline{n}$. For simplicity the average density is taken to be a flux function (the flux coordinate is denoted as ψ), however the only requirement for the following formalism to be valid is that $\overline{n}$ is approximately constant on a flux surface in the region shined through by the atomic beam. Similar approximations are made regarding the measured photon current on detector i, denoted as $\Phi_i(t)$, can be decomposed to an average $\overline{\Phi}_i$ and a fluctuating part $\delta\Phi_i(t)$, which is the response to the density perturbation. A functional is defined as $\Phi_i(t) = \mathscr{S}_i[n_e(\mathbf{r},t')]$ that calculates the photon current corresponding to a given plasma density along the injected beam, resulting in:

$$\delta\Phi_i \equiv \mathscr{S}_i[n_e(\mathbf{r})] - \mathscr{S}_i[\overline{n}(\psi)] \approx \int \delta n(\mathbf{r}) R[i,\mathbf{r}|\overline{n}(\psi)] dV. \tag{1}$$

where the independent variables of the FRF are the detector number i and the spatial position $\mathbf{r}$, while it also depends on the average density profile. The response function at $\mathbf{r}_0$ can be calculated by setting the fluctuation as a localized elementary perturbation $\delta n(\mathbf{r}) = \delta(\mathbf{r}-\mathbf{r}_0)$.

The FRF is determined for a fluctuation BES system by the use of RENATE. First, a poloidal plane is chosen, centred at the observed region of the beam. Hann function shaped density perturbations are placed on the plane in the order of $10^{18}\ m^{-3}$, where the SOL density is of similar magnitude and edge density is one magnitude higher, extended along the magnetic field lines throughout the beam geometry. The photon current variation is determined in accordance with E. (1). The resulting FRF holds information regarding the light response to localized density perturbations, which allows for density perturbation reconstruction given a stationary averaged photon profile. Localization of perturbations and their subsequent light response on each detector also determines the fluctuation sensitive areas for each detector, resulting in a measure of the effective spatial resolution of the system, as well as the crosstalk between channels. Overlapping of perturbations is required to overcome spatial anti-aliasing.

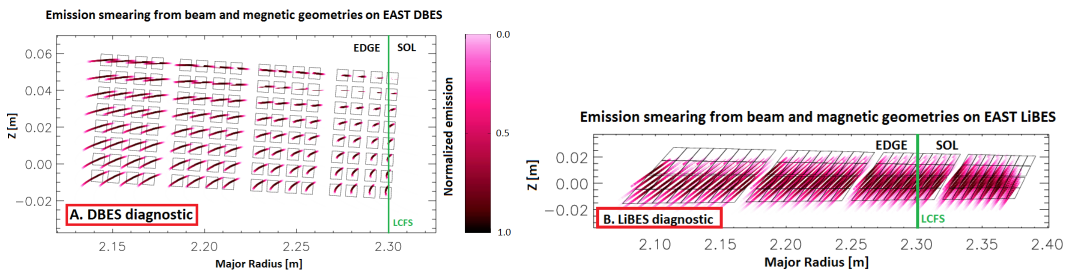

Figure 1: Emission smearing from beam and magnetic geometry. A: EAST DBES observation system for plasma edge observation on tangential beam. B: EAST LiBES observation system.

Spatial resolution For an adequate understanding and interpretation of detected turbulence on a BES system, knowledge of its spatial resolution and response function is required [5]. The EAST tokamak is equipped with a LiBES and DBES diagnostics with an observation system of 4×32 and 8×16 APDCam detector matrices, respectively. The spatial resolution of a BES diagnostic system is effected by the beam and magnetic geometry, the optical projection of detector grid and the emission smearing caused atomic physics processes. Study of the various aspects of spatial resolution are presented, as well as the fluctuation response calculation.

BEAM AND MAGNETIC GEOMETRY are crucial aspect to BES spatial resolution, especially for 2D observations. Rapid particle transport along magnetic field lines results in field line elongated turbulent structures in fusion plasmas. Localization of these structures is strongly dependent on the alignment of field lines with the lines of sight (LOS) of the observation system. Fig. 1 visualizes the emission smearing for all detectors caused by the alignment of field lines with LOS within the beam geometry. The emission along a LOS, scaled with shades of purple, is projected onto a central poloidal plane by following field lines resulting in a point spread function (PSF) for each detector pixel. The area of the PSF is indicative of the misalignment of field lines to LOS. The DBES system shows extremely good spatial resolution on the plasma edge, the radial aspect is slightly degrading towards the core, indicated by the radial elongation of the PSF. The LiBES system show tilted PSF-s indicating a significant crosstalk between vertically separated detector channels.

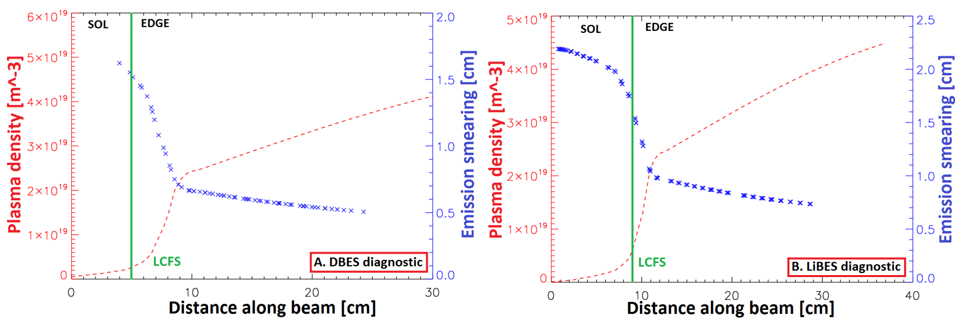

Figure 2: Emission smearing from atomic physics processes. A: EAST DBES observation system for plasma edge observation on tangential beam. B: EAST LiBES observation system.

ATOMIC PHYSICS processes impact the spatial resolution by smearing the emission in beam direction caused by the finite lifetime of excited atomic levels. The amount of smearing is dependent on the velocity of beam atoms and depletion time of the observed atomic level, subsequently by the atomic species of the beam. Fig. 2 shows the amount of smearing along the beam. The smearing has only a radial contribution, as both beams are injected in the equatorial plane of the device. Impact of beam species is considerable, a 50 keV lithium beam smear considerably more than a 80 keV heating beam. Impact of plasma density is also considerable: in low collisionality areas on the plasma edge and SOL region this has a greater impact on the spatial resolution.

FLUCTUATION RESPONSE FUNCTION holds information regarding the fluctuation sensitive areas for each detector pixel (Fig. 3) The area of positive response, marked by red, indicates strong, well localised responses caused by perturbations located closely in front of the observed region. Perturbations located further away from the observed region produce negative responses due to beam attenuation. The positive response area gives a measure of the effective spatial

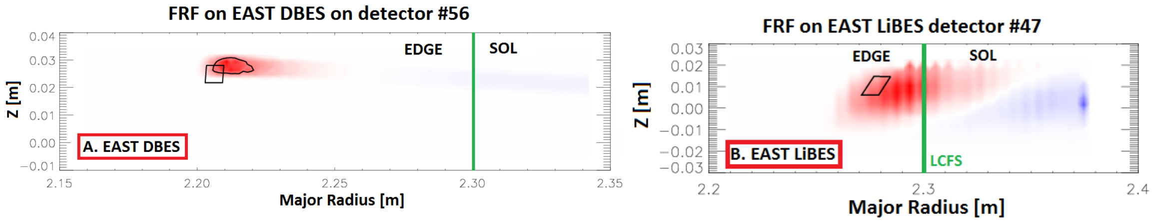

Figure 3: Fluctuation response function. A: EAST DBES observation for plasma edge observation on tangential beam on detector #56. B: EAST LiBES observation on detector #47.

resolution of the observation system, which incorporates the smearing from the atomic physics in beam direction, the tilted smearing caused by beam and magnetic geometry and the projection of the detector pixels. The areal extent of the FRF presents a considerable elongation in beam direction, indicative of the effect of atomic physics processes, typically strong for a LiBES system with observation on the pedestal top, as well as a generally tilted structures indicative of emission smearing arising from the alignment of the LOS with magnetic field lines (Fig. 3B). Fig. 3A shows the response for a DBES observation pixel well within the LCFS, the radial extent is small, due to minimal effect of deuterium smearing in high densities, vertical extent of the sensitive area is very small as well, in coincidence with Fig. 1A, showing extremely good localization of density perturbations.

Conclusions The fluctuation response function (FRF) was shown to be a powerful tool to characterize the response of the light detected by a BES system to field aligned density perturbations. Mapping the positive response to each detector, provides good measure of the spatial localization of the corresponding fluctuation sensitive area, which in turn determines the total spatial resolution of the system. The complex information provided by the FRF was decomposed, and features effecting the spatial resolution were identified and analysed separately. A suit of these methods provides comprehensive understanding of the spatial resolution issues of BES systems.

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