Spatial resolution modelling of various beam emission spectroscopy experiments

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Introduction

Beam Emission Spectroscopy (BES) is a diagnostic technique of magnetically confined plasmas, routinely used on numerous experimental devices. The principle of the measurement can be summarized as follows. An accelerated atomic beam - either heating (HBES) or diagnostic (LiBES) beam – penetrates the plasma where the beam atoms collide with the plasma particles, which, among others, excites the valence electrons of the beam atoms. The de-excitation of these electrons results in a characteristic photon emission, which intensity distribution and fluctuation can be detected through an optical system. As the atomic physics processes are primarily density dependent, the main purpose of the BES is to determine the electron density profile, and to characterize its response e.g. to plasma turbulence, zonal flows, ELMs.

One of the main parameters of a BES system is the spatial resolution, namely the radial and the poloidal resolution. This defines a lower limit for the detectable fluctuation wave number, and affects the density profile reconstruction as well, thus this parameter is essential for both the heating and the diagnostic beam emission spectroscopy systems.

After the short description of the applied comprehensive RENATE BES simulator this paper will show spatial resolution calculation results for proposed and existing experiments, and comparisons with measurements.

The RENATE simulation code

Comprehensive simulation of the beam, the magnetic, the machine and the observation geometry, and the modeling of the observation are needed in order to obtain the spatial resolution of such a system. The RENATE beam emission simulator [1] is a tool for BES system modeling, and fulfils the above mentioned conditions: the program calculates the beam evolution for given magnetic, plasma and beam parameters through the evaluation of the rate equations within the confines of the collisional-radiative model [2][3]; as well as the detected photon flux on each individual detector segments. The spatial resolution for small perturbations can be obtained from the so called fluctuation response calculation, which evaluates the response of the photon flux for each detector caused by infinitesimally small density perturbation at various locations. The spatial resolution can be obtained by the projection and the integration of the fluctuation response along the field lines to a poloidal plane. The dimension of the positive fluctuation response distribution is considered as the spatial resolution.

Also a lower level simulation, the so called geometrical point spread function calculation is available, where the beam emissivity is interpolated along magnetic field lines and projected onto a chosen poloidal plane along the line of sight from the observation point.

KSTAR and EAST application

Both KSTAR and EAST tokamak devices are equipped with diagnostic beam and heating beam emission spectroscopy systems. On KSTAR a single optical system is viewing approximately along field lines onto crossed Lithium and heating beams. The HBES system on EAST has similar geometry while the LiBES looks approximately 45° relative to field lines. The size of a heating beam cross section is typically in the range of 20x60cm, while it is in a 3x3cm range in case of a diagnostic beam, thus the latter measurements are less affected by the distortion of the observation. Plasma parameters are considered to be elongated along the field lines, thus good spatial resolution can be obtained if the lines of sights are aligned along field lines. This cannot be fulfilled in all locations, thus a detailed characterization study is necessary.

The design of these four systems (KSTAR HBES, KSTAR LiBES, EAST HBES, EAST LiBES) was supported by RENATE simulations those results corresponding spatial resolution are to be summarized here, focusing on the KSTAR HBES system, since measurement results are available only there yet.

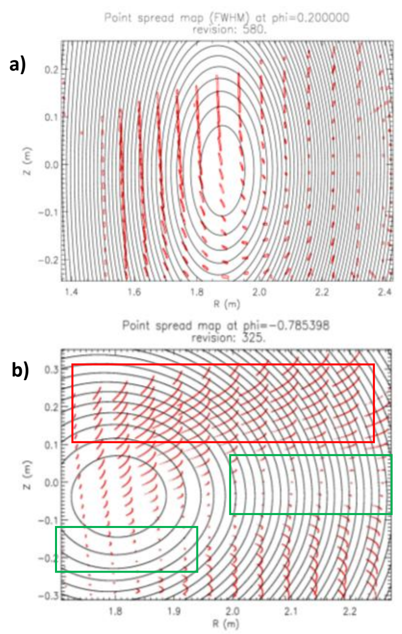

Figure 1.: Results of point spread function calculations for EAST HBES (a), KSTAR HBES (b) and detection sensitivity areas for EAST Li-BES (c)

One can see in Figure 1 a) and b), which shows point spread function calculations for the two HBES systems that the pure geometrical effects can cause such smearing that would prevent a spatially resolvable measurement in case of inappropriate observation. (e.g. the region indicated with red square in case of the KSTAR HBES system) It is also clear that the geometrical effects are negligible compared to the spatial resolution of the detection system, which is approximately 1x1cm set by the detector pixel pitch and the magnification of the optics. (e.g. the region indicated with green square in case of the KSTAR HBES system).

The Li-BES system case is different: the size of the point spread functions can be kept small even if the observation is not along the field lines.

Another effect which has to be considered is the finite lifetime of the observed transition. The smearing due to the ~27ns decay time of the 2p-2s transition in case of a 50keV Lithium beam is approximately 2cm.

A precise picture can be drawn if one uses the aforementioned fluctuation response calculation results those take the effect of the beam evolution into consideration. Figure 2 a) shows the response of one detector segment (2x2cm) for Dirac delta fluctuations along the beam (beam direction left to the right), the response is negative from higher distances mainly due to ionization processes, and positive near the detector (obviously no response thereafter due to causality). Figure 2 b) and c) show the contours of 50% and 75% of the maximum response for a detector array, projected along the field lines on a poloidal plane for KSTAR HBES and the EAST LiBES, while d) and e) show the maximum extent of the 50% maximum response in the radial and the poloidal direction respectively. The latter two plots give the radial and the poloidal resolution of the system directly, in the 2-3cm range in the simulated area.

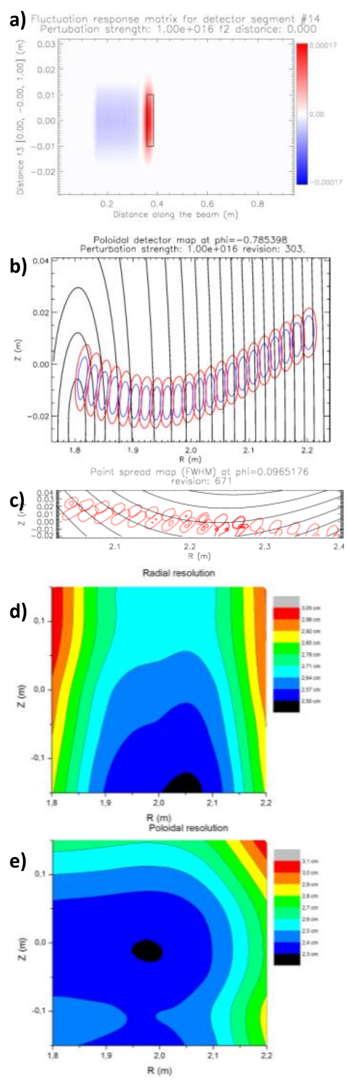

Figure 2.: KSTAR HBES fluctuation response calculation results: one detector segment (a), detector array, only positive response (b) for EAST Li-BES (c), and maximum extent of 50% positive response for a poloidal plane in radial (d) and poloidal (e) direction.

Comparison with measurement

The spatial resolution calculation was compared with KSTAR HBES measurement [4] data. Spatial resolution is estimated from the cross-correlation calculation between one reference BES channel and the other 31 channels. A 100ms long stable L-mode discharge part was chosen (#9212, [2.0s,2.1s]). The reference BES channel was BES-2-5, which is located around the middle of the detector array, about 2cm inside the separatrix. The cross correlation functions were calculated and the photon peak was subtracted from it, thus the result is not affected by the photon statistics. By plotting the 0ms time lag cross-correlation amplitude, one can calculate an upper limit for the spatial resolution since it is the convolution of the fluctuation correlation function and the measurement system transfer function. Figure 3 shows the contour plot of the 0 time lag amplitude of the normalized cross correlation functions. As it can be seen the radial spatial FWHM (the resolution) is approximately 33mm, while the vertical resolution is 20mm, indicating that the resolution is close to the detector image pitch.

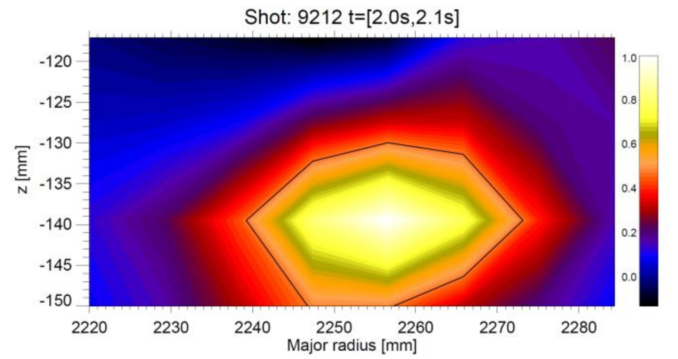

Figure 3. - Cross-correlation map of the 0s time lag amplitudes: the 50% maximum (autocorrelation) amplitude is encircled with dark line.

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