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Capabilities of alkali Beam Emission Spectroscopy for density profile and fluctuation measurements

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A comprehensive, IDL language BES [1] simulation program has been developed, the primary objective of which is to support the design and development of atomic beam diagnostic measurements. The simulation models the beam-plasma interaction, considering the atomic physical processes according to a Collisional-Radiative model [2]. The atomic physics kernel performing this calculation is suitable for calculations with any alkali beam but only Li cross sections have been implemented so far.

The simulation calculates the light profile, using a magnetic geometry and measured or simulated one dimensional plasma parameter profiles – n_e, T_e, Z_{eff}, average impurity charge – as a function of flux coordinates. In addition it takes the observation process into account, including the geometrical factors of the set-up, the efficiency of the whole optical system, the characteristics of the filter, the Doppler-shift of the detected light and the covering of the observed region by detector segments. There is also the possibility to calculate with “extended beam”, that considers the beam profile (i.e the radial current distribution within the beam), allowing different evolution of the different beam slices. Simulating the observation, the detected photon number per detector per unit time can be obtained, that determines the photon statistics which gives the upper limit of temporal resolution of a fluctuation measurement. As a further support of fluctuation measurement design, the simulation can calculate the light response of the beam to the density fluctuations. Quasi-2D (“virtual beam”) measurements [3] - when the beam is deflected between two or more positions - can also be simulated by the code.

The effect of observation

It can be concluded from the extended beam calculations that the evolution of the populations of excited atomic states – thus the intensity of the spontaneous emission – follows well the flux surfaces. As a consequence if the lines of sight are not tangential to the flux surfaces (like in Fig. 2), then the measured light profile, $I(x)$ will be smoothed in comparison

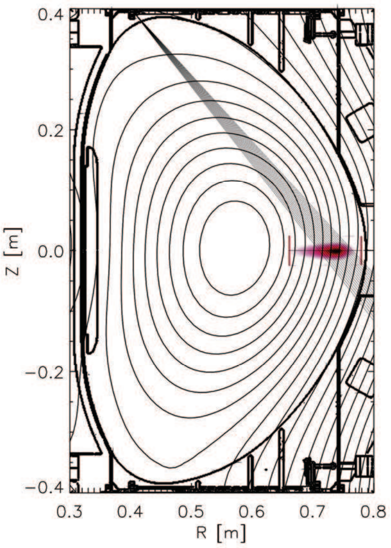

Fig. 1. Extended beam calculation, set-up: flux surfaces, poloidal projection of beam emission intensity, lines of sight, vacuum chamber (Compass-D #30866 H-mode discharge, n_e=1,1·10^{20} m^{-1})

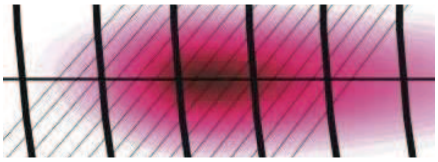

Fig. 2. enlargement of the of the beam of Fig. 1. (mirrored horizontally)

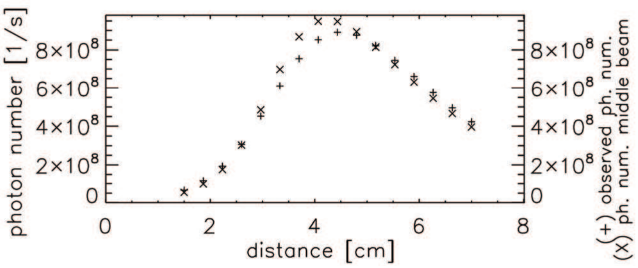

Fig. 3. detected photon numbers per second, per detectors, using a real, extended beam (+) and a hypothetical, 1D beam on the beam axis (×) (measurement of Fig. 1.)

with an ideal, hypothetical case of a 1D beam measurement (see Fig. 3). The $1/I(x)\cdot dI(x)/dx$ logarithmic derivative playing important role in the density reconstruction calculation [4] will be decreased because of the effect of such a distortion, which leads to the underestimation of n_e, in a static density profie measurement. The systematic error of the recontructed n_e distribution is about 30%, in the example represented on Fig. 1- 3, showing a calculation with typical plasma (COMPASS-D #30866) and beam parameters (40 keV, width: 2 cm). Distorsion can be even more severe in case of: 1. wider beam, 2. lines of sight less tangential to the flux surfaces, 3. higher electron density gradient along the beamline.

Light profile correction

A new algorithm has been developed, which can reconstruct the emitted intensity distribution on the beam axis, assuming that the beam evolution folows the flux surfaces. This can eliminate the light profile distorting effects of the observation, – the smoothing effect ensuing from the integration over the lines of sight through beam slices of different evolution status, and the changing geometrical optical efficiency of detection along the beam.

The measurement of the emitted light can be formalized in the following way:

$$S(x)=\int I(x')T(x,x')dx'\approx\int I(x')p(x')\tau(x-x')dx'\approx p(x)\int I(x')\tau(x-x')dx',$$

where $I(x')$ is the emission distribution along the beam axis, $S(x)$ is the measured light profile, $T(x,x')$ is the transfer function of the measurement, the effect of which can be approximated by the combination of a $\tau(x-x')$ convolution kernel, and a $p(x')$ slowly varying amplitude modulation part. $\tau(x-x')$ and $p(x')$ are calculated by simulating the observation of light emitted from each flux surface intersecting the beam axis at x'. Introducing the $S'(x) = S(x)/p(x)$ quantity, and applying the convolution theorem, the above expression transformed into $\tilde{S}'(k) \approx \tilde{I}(k) \cdot \tilde{\tau}(k)$, where we take the conversion to the k wave number space by Fourier transformation (denoted by ~). We can utilize the facts, that $\tilde{\tau}(k)$ is broad band, because the width of $\tau(x - x')$ is limited by the width of the beam, while $\tilde{S}'(k)$ and $\tilde{I}(k)$ are localized to low wave numbers, which is concluded from the lifetime of the initial atomic state of the observed transition. $\tilde{I}(k)$ can be evaluated approximately: $\tilde{I}(k) \approx \tilde{S}'(k)\tilde{\chi}(k)/\tilde{\tau}(k)$, where $\tilde{\chi}(k)$ is a low-pass filter {$\tilde{\chi}(k) = 1$ *if* $\tilde{S}'(k) \geq \max_k \left[\tilde{S}'(k)\right] \cdot \delta$, $\tilde{\chi}(k) = 0$ *elsewhere*; with a small factor, δ}, which is necessary because otherwise division by $\tilde{\tau}(k)$ would amplify the high wave number noise present in $\tilde{S}'(k)$ producing a wavy emission profile.

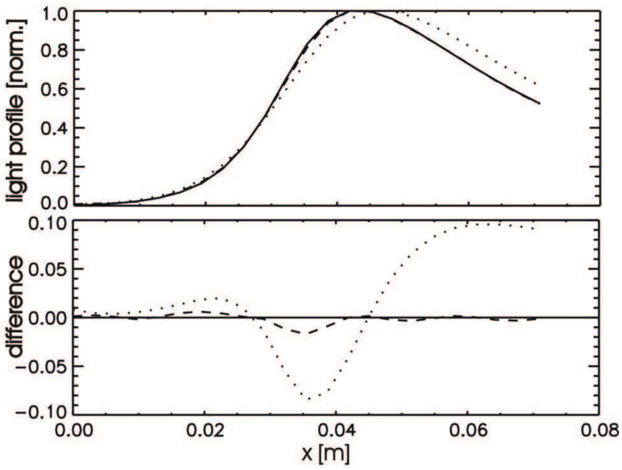

Fig. 4. *Upper graph*: Light profiles of an emission reconstruction (normalized to 1); *solid*: emission distribution on the beam axis $I(x')$, *dotted*: measured light profile $S(x)$, *dashed*: reconstructed emission distribution $\approx I(x')$; *Lower graph*: difference from $I(x')$ (the measurement of Fig. 1)

Demonstrating the operability and efficiency of the method, the emission reconstruction light profiles (normalized to 1) of the measurement of Fig. 1 are plotted on Fig. 4: the emission distribution on the beam axis $I(x')$, which represents an ideal measurement, the measured light profile $S(x)$, and the reconstructed light profile, as an estimation of $I(x')$. Application of the algorithm results in significant improvement even on those light profiles which are the most disadvantageous from the view-point of the locality of the measurement (wider beams, sharper angles between beam and lines of sight).

First successful application

Extensive Li BES calculations have been performed for the Compass-D tokamak (to be reinstalled at Prague). All possible configurations of the beam and the observation on the four available ports shown on Fig. 5 have been investigated using 20, 40, 60 and 80 keV beam energies, considering plasma parameter profiles and magnetic geometry based on measured ones during the prior operation of the device. The optimal set-ups have been determined for different measurement purposes.

For radial density profile measurement, the port 1 is recommended (see Fig. 5), were the deepest effective radial regions can be probed with the same plasma and beam parameters. The pedestal of a $1{\cdot}10^{20}$ m^{-3} H-mode plasma is coverable by a 40 keV beam and the optimal observation direction is **I** from port 2. The deeper laying outer core can only be measured in a $3{\cdot}10^{19}$ m^{-3} L-mode plasma by a 60 keV beam. However, in this case, from the direction I we should have to look into the divertor, and to avoid this, the direction **III** is preferred for observation.

The spatial resolution of a fluctuation measurement is changing along the beam and can be evaluated by examining the response matrix of the measurement, but estimation can be given by the distance covered by beam atoms in the lifetime of the initial atomic state of the observed transition, which is 2.8 cm for 40 keV and 4.0 cm for 80 keV. For both 1D and quasi-2D fluctuation measurements the most appropriate arrangements are: 1. beam injection from port 1, observed from direction **I** or **III**; 2. beam injection from port 3 observed from direction **II** which can be followed out from direction **I** inserted a mirror onto the optical axis.

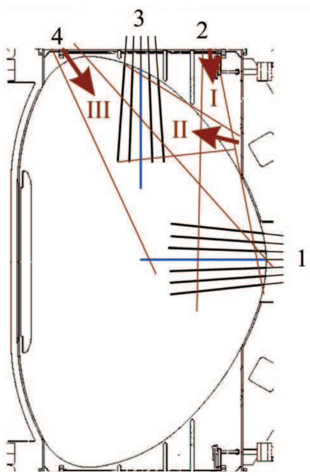

Fig. 5. Optimal measurement arrangements; available ports: 1-4. observation: I-III.

Conclusions

A comprehensive BES simulation program has been developed, which supports design of alkali BES measurements and aids the interpretation of the results of the measurement. The effect of the observation geometry on light profiles has been investigated, which cannot be neglected in some set-ups. An algorithm has been developed for the elimination of the light profile distorting effect of the observation, based on de-convolution filtering and corrections by geometrical factors, which can reconstruct the emitted intensity distribution on the beam axis. Extensive calculations have been performed for the Compass-D tokamak. Optimal arrangements and beam parameters have been determined for density profile and fluctuation measurement purposes.

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