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Two-dimensional measurement of electron density and its fluctuation in the edge of magnetically confined plasmas by BES technique

S. Zoletnik[1], G. Petravich[1], S. Fiedler[2] and the W7-AS Team[2]

[1]*KFKI-RMKI, Association EURATOM, P.O.Box 49, H-1525 Budapest, Hungary*
[2]*Max-Planck-Institut für Plasmaphysik, Association EURATOM, Boltzmannstr. 2, D-85748 Garching, Germany*

Introduction. Beam Emission Spectroscopy (BES) has been extensively used for the measurement of various parameters of magnetically confined plasmas. The common idea in all BES measurements is that an atomic beam is injected into the plasma where the beam atoms are excited and their line radiation is observed. The observation volume is defined by the intersection of the line of sight with the beam allowing of local measurements. Using multichannel detection system – and with the help of an appropriate atomic model (and plasma parameters deduced from other diagnostics) – one-dimensional profiles of plasma parameters along the neutral beam can be determined. For Li and Na beams and for plasma temperature in the 100eV-1keV range the light emission depends predominantly on the plasma density. These beams can be used for the determination of the density profile if other plasma parameters are approximately known.

Depending on the atomic species and their velocity, the beam can access different regions of the hot thermonuclear plasma. Thermal ($v \approx 10^3 m/s$) and blow-off ($v \approx 10^4 m/s$) beams can typically penetrate only the Scrape-Off Layer (SOL), while accelerated ($v \approx 10^6 m/s$) beams provide access to at least to the edge plasma or in some cases even to the core. Penetration is limited by the ionisation of the atoms as the formed ions are deflected out of the beam.

Besides the advantageous features of the technique, BES has serious limitations as well, which originate from two sources; (1) The light emission intensity and thus the temporal resolution is limited, (2) ionisation and finite lifetime of the excited levels of beam atoms result in nonlocality, i.e. the light emission at a certain point in the plasma depends on all processes along the beam path preceeding the point in question.

This paper describes considerations and initial experiments to extend the BES technique into a quasi-two-dimensional measurement of electron density and its fluctuation. The new method has been developed and tested on the fast Li-beam diagnostic of the Wendelstein 7-AS stellarator, and constitutes an extension of the existing density profile[1] and fluctuation[2] measurements. The main motivation of the work is to obtain information on the poloidal correlation length and propagation velocity of fluctuations in the edge region. This latter would be important for finding sheared flow regions expected in the case of improved confinement modes and transport barriers.

Diagnostic set-up. On the Wendelstein 7-AS stellarator a 48keV Li-beam whith a 28-channel fast ($f_{max} > 1MHz$) observation system is used for the measurement of electron density and its fluctuation in the SOL and the plasma edge. The beam and the optical lines of sight of the observation lie in a toroidal cross-section of the machine. The basic idea of the two-dimensional extension of the diagnostic is illustrated on *Fig. 1.*

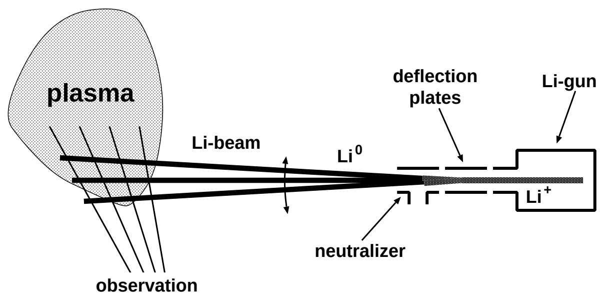

Fig. 1. Schematic of the quasi two-dimensional BES set-up. (Not to scale.)

Lithium ions are emitted by a heated lithium aluminosilicate β-eucryptite cathode and accelerated by an ion-optical system (not shown). Before neutralisation in Sodium vapour the beam goes through a pair of electrostatic deflection plates that can deflect it vertically. Using different deflections the measurement points (intersections of the observation lines of sight and the beam) define a mesh in the toroidal cross-section.

The 1D density profile along the beam can be calculated for each deflection, i.e. 'poloidal' position from the corresponding light profile and a full two-dimensional profile can be constructed from the 1D ones measured at different deflections. The time necessary for a full 2D measurement is determined by the time needed for the detection of a 1D light profile with a good enough photon statistics ($\geq 200 \mu s$) and by the poloidal resolution. As the beam width in the plasma is about 1 cm, a poloidal region of 8 - 10 cm can be scanned in 8 steps, i.e. in about 1.5 - 2 ms. This time is in most cases much shorter than the characteristic timescales involved in the evolution of the discharge but definitely longer than the correlation time τ_c of electron density fluctuations in the SOL and in the plasma edge[2]. This problem can be overcome by periodically scanning the beam over the poloidal positions at high frequency and determining the crosscorrelation functions between the light fluctuations detected at different poloidal positions. A realisation of the above idea is illustrated on *Fig. 2.*

The measurement time is divided into intervals of equal length T ($< \tau_c$) and each such interval is cut into two halves: in one (a) the beam is at the reference position, while in the other (b) it is deflected to an other poloidal position (the transition time between two positions $\delta t << T$). In the (b) subintervals the beam is periodically scanned over all poloidal positions. The correlations – as a function of time delay – between the signal from the reference position and the signals from all other poloidal positions can be calculated.

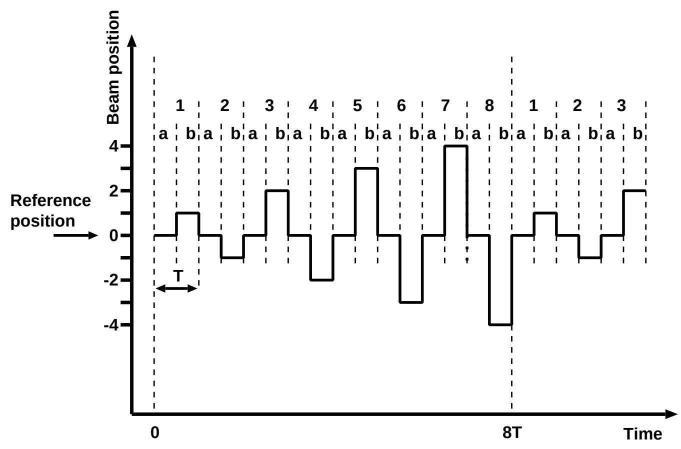

Fig. 2. Scanning scheme for a nine-virtual-beam set-up. The figure shows the idealised poloidal movement of the beam as a function of time.

To reduce the effect of noise the process is repeated over many periods and correlations belonging to the same positions and time delays are averaged. As this calculation can be done for all measurement channels, the poloidal-temporal correlation function at different radial positions can be calculated. From these correlation functions poloidal correlation length, flow velocities and correlation times can be calculated for the fluctuations. By this technique the beam is effectively split up into a set of "virtual beams".

Numerical simulations. Experimentally measured plasma parameter and fluctuation amplitude profiles, light intensities and an atomic model for the beam light emission process were used to investigate what parameters of the fluctuations can be determined by a scanning beam measurement. Random Gaussian peaks – with 1cm poloidal and radial extension, $30\mu s$ lifetime, $1km/s$ poloidal flow velocity and a realistic RMS amplitude – were added to the density profile and the poloidal spatio-temporal correlation function was determined from a total of 110ms measurement time with a simulated eleven-virtual-beam measurement. The result is shown on *Fig. 3.* The lifetime, the poloidal correlation length and the flow velocity of the perturbation can easily be read from the figure.

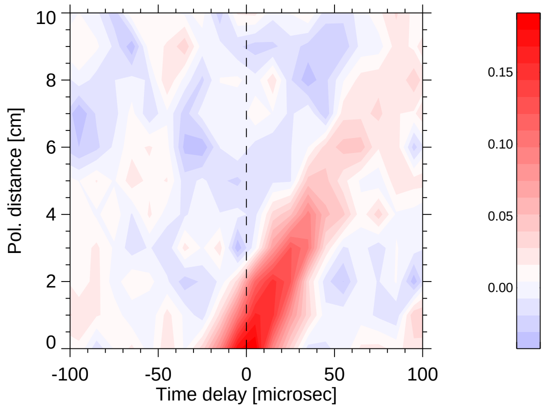

Fig. 3. Poloidal spatio-temporal correlation function in the simulated eleven-virtual-beam measurement.

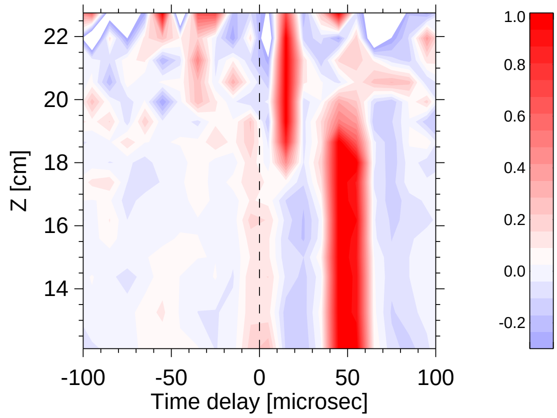

Fig. 4. Crosscorrelation as a function of distance along the beam in the simulated two-virtual-beam measurement of sheared flow.

As the flow velocity of the turbulent structures could be successfully recovered from a simulation, the question arises if one can measure the flow velocity profile along the beam with this technique. This was tested by a simulated two-virtual-beam measurement for a poloidal distance (d) of 10 cm and calculating the crosscorrelation functions of the fluctuations in the light of the two virtual beams at various positions along the beam. The flow velocity was $2km/s$ up to $Z = 17cm$ and it was changed to $6km/s$ deeper in the plasma. The result is shown on *Fig. 4*. The velocity change appears on the plot as a shift in the time delay ($= d/v_{fl}$) of the maximum of the correlation functions. However, the changeover occurs somewhat deeper in the plasma as in the simulated perturbations. This is a reflection of the finite lifetime of the excited states of atoms in the beam, which carries the information with the beam velocity for a finite distance.

Laboratory tests and proof of principle measurements. The 48keV Li beam was periodically deflected by switching 500V on and off with 100kHz frequency on one deflection plate and images of the beam in the transport tube – at about 90cm from the deflection plates – were taken with a fast digital camera.

5000 images – taken with $1\mu s$ integration time and at the same delay time, i.e. in the same phase with respect to the voltage switch – were collected into one picture from which the beam position was determined. Similar pictures were taken and processed by scanning the delay time over one full switching period. The measured positions are plotted against the delay time on *Fig. 5.* The result confirms that the beam moves between two positions within less than $1\mu s$.

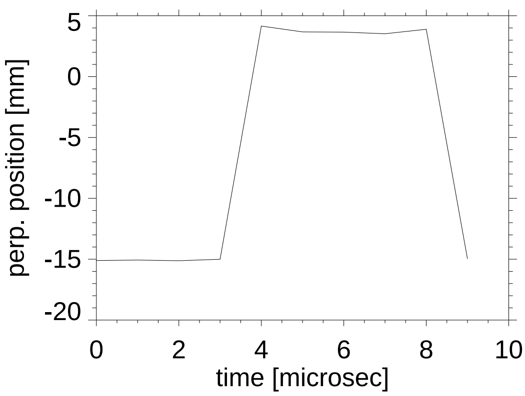

Fig. 5. Beam position vs. delay time.

The experimental arrangement on the Wendelstein 7-AS stellarator enabled a maximum poloidal beam movement of 6.5cm. Although the beam with was estimated to be 1.3cm in the plasma – due to the asymmetric voltage on the deflection plates in the described set-up, it was still considerably less than the size of the accessible poloidal region. In this experiment the original 28-channel observation system collected the light from the Li-beam that was periodically deflected with 100kHz frequency. The measurements were done in a series of identical discharges, by changing the deflection voltage from shot to shot – imitating a multiple-virtual-beam measurement.

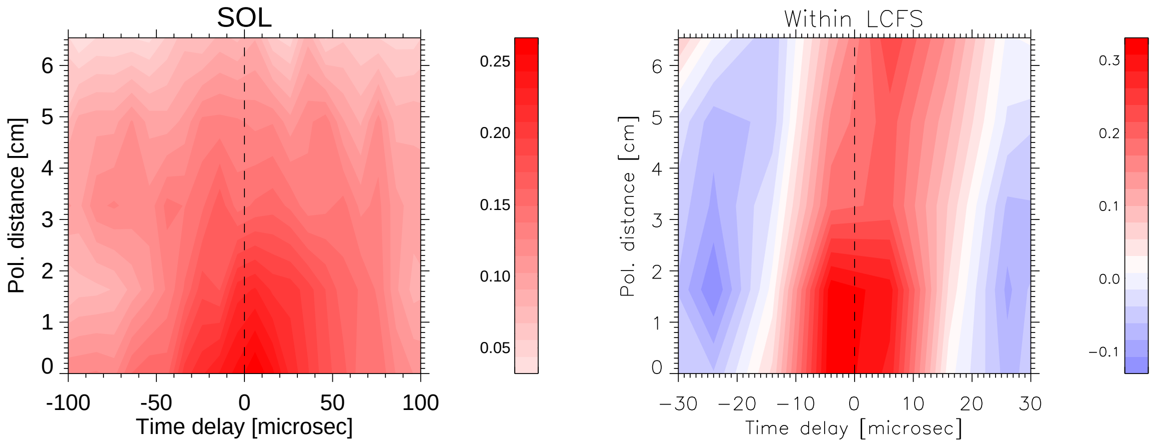

Fig. 6. Measured poloidal spatio-temporal correlation function of the fluctuations in the Li-beam light in the SOL (left) and in the edge plasma (right).

The measured correlation functions – shown in *Fig. 6* – were compiled from a series of discharges. The absolute magnitude of the correlations is reduced by the presence of photon statistical noise on the signals for which it was not corrected. The temporal behaviour of the fluctuations agrees with previous results in these regions, described in Ref. [2]. Correlation in the poloidal direction drops to half of its maximum in about 4cm in the SOL, while it stays above 60% of its maximum in the whole measurement range in the edge plasma. This is in agreement with the conclusion of Ref. [2] that the wave-like fluctuations have longer poloidal correlation length in the edge plasma than in the SOL. The correlation picture for edge plasma also reveals that the fluctuations have there a poloidal propagation velocity of about 10km/s which is also in agreement with the usual magnitudes observed in the edge plasma by spectroscopic measurements.

Conclusions. In this paper we showed that an accelerated Li-beam diagnostic – using a sophisticated beam deflection scheme and appropriate data evaluation – can be turned into a quasi two-dimensional density diagnostic, without modifying the existing system. Poloidal correlation lengths, flow velocities and lifetimes of the electron density fluctuations can be determined in the SOL and the edge plasma. Although the data evaluation technique needs further improvements to account for nonlocality, the first measurements show good agreement with expectations and other experimental results.

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