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Sub-millisecond electron density profile measurement at the JET tokamak with the fast BES system

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Abstract:

Diagnostic alkali atom beams are routinely used to diagnose magnetically confined plasmas, namely to measure plasma electron density profile in the edge and the scrape off layer (SOL) region. The beam atoms collide with plasma particles – predominantly electrons, which excite and ionize them. Spontaneous de-excitation of beam atoms results in a characteristic photon emission that can be detected through an optical system. The electron density distribution can be calculated from the light emission distribution along the beam (lightprofile).

A unique light splitting optics system was installed into the Li-BES observation system at JET tokamak in 2012, which allows simultaneous measurement of the beam light emission with a spectrometer and a fast avalanche photodiode camera (APDCAM) [1][2]. The spectrometer measurement allows density profile reconstruction with ~15 ms time resolution, absolute position calculation from the Doppler shift, spectral background subtraction as well as relative intensity calibration of the channels for each discharge. The APD system is capable of measuring light intensities on the microsecond timescale, however ~100µs integration is needed to have acceptable signal to noise ratio (SNR) due to moderate light levels. Fast modulation (~10 kHz) of the beam was implemented in 2013, and it allows us to make background subtraction on the 100us timescale, and the relative detection efficiency of the APD system can be cross calibrated with the spectrometer.

An automated routine has been developed which does the background subtraction, the relative calibration, the comprehensive error calculation and runs a Bayesian density reconstruction code. This paper will show results provided by the system, and will demonstrate its capabilities.

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[1] Speaker

***See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia**

1. Introduction

Beam emission spectroscopy (BES) is a routinely used diagnostic technique at numerous magnetically confined plasma devices for plasma edge and scrape off layer (SOL) electron density profile and fluctuation measurement. The principle of the measurement can be summarized as follows. An accelerated atomic beam penetrates the plasma where the beam atoms collide with the plasma particles, which dominantly 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 most common use of the BES is to determine the electron density profile, and to characterize its response e.g. to plasma turbulence, zonal flows, ELMs.

The diagnostic BES system (Li-BES) at JET tokamak is a tool for plasma edge and electron density profile measurement. Its capabilities have been extended through the installation of the light splitting optics [1], the avalanche photodiode camera (APDCAM) [2], the fast beam modulation system and the ion source upgrade [3]. The time resolution of the electron density profile measurement has been improved by a factor 100, and it is in the ~100μs range, depending on the condition of the system. This feature of the system enables us to resolve the evolution of fast transient events, such as ELM-s, pellet injection, L-H transition and M-mode, which are in the focus of interest at magnetically confined devices.

A brief overview of the system is given in section 2, focusing on the elements which are critical from our point of view. Section 3 describes the relevant steps of the lightprofile calculation, namely the problem of background correction, the relative calibration and the error calculation. Section 4 introduces the density reconstruction method and its validation at JET. Some relevant examples are shown in section 5 to demonstrate the capabilities of the system while the results are summarized in section 6.

2. Diagnostic setup

The Li-BES system consists of a Lithium beam gun and an observation system. The former has been recently upgraded [3], and is capable of extracting 2-3 mA ion current from the source.. This upgrade included the development of the beam modulation system which is now capable of chopping (turn on-off) the beam at 30 kHz frequency. The observation system can be divided into two parts; one is the periscope on the machine, inside the torus hall that images the beam emission on a fibre array through an optical system. The other part, which is in an optical enclosure in the diagnostic hall, has been upgraded as well in 2012 [1], and was equipped with a light splitting optical system that divides the light, coming from the torus hall through fibre optics, between a spectrometer and an avalanche photodiode camera (APDCAM) [2]. The spectrometer receives only about 10% of the light which fills its etendue.

The spectrometer is capable of measuring the light emission with 15ms time resolution, applying spectral background correction, doing relative calibration of the channels after each shot by shooting into neutral gas, and several semi automated density reconstruction codes are implemented. The APDCAM has 32 APD detectors out of which 23 measure the light from the same input fibres as the spectrometer, i.e. these channels are measured simultaneously by the two systems. The APDCAM system is optimized for the relatively low light intensities, has 250 kHz analogue bandwidth, and measures with 500 kHz sampling. The time resolution of the system is limited by the signal to noise ratio (SNR) which is in the range of 1-10 along the beam, when the ion gun is at its peak performance. This means that the relative error of the measurement can be reduced to an acceptable 5% level by 0.1–1 ms integration.

3. Lightprofile calculation

The intermediate step between the light measurement and the density profile calculation is the calculation of the lightprofile. In order to achieve the measured lightprofile, the handling of the background light, the relative calibration and the error calculation is necessary.

3.1 Background correction

The APD branch of the observation system is equipped with an interference filter with FWHM=2.4nm, however, the background light cannot be fully suppressed due to broadband radiation from the plasma. The signal-to-background ratio (SBR) of the system is in the range of 3-12, and is not homogenous along the beam, thus has to be taken into account. This can be carried out by the modulation of the beam (chopping). The timescale on which the background light is taken into account, namely the half period time of the chopping determines the maximum time resolution of the system (no faster events can be resolved if the background is high). Three chopping modes are available: slow modulation, when the beam is chopped out for each e.g. 10th camera frame synchronized with the camera frame time, fast modulation, when the beam is continuously chopped up to 30 kHz frequency and mixed modulation, which means slow modulation with fast modulation applied in the beam on phase, i.e. the beam is chopped off fully for every e.g. 10th camera frame to have sufficient background measurement for the spectrometer as well.

3.2 Relative calibration

The background corrected light intensity is proportional to the beam emission in the observed volume multiplied by the collection solid angle and the absolute transmission factor of the system, which varies from channel to channel. The absolute value of the light intensity is not relevant, only the relative light intensity distribution along the beam (lightprofile) is important in terms of density profile calculation, thus the relative calibration factors have to be determined. Two methods are implemented. The first calculates the calibration factors from a measurement in which the beam is injected into neutral gas where the beam emission can be considered homogenous, and this way the relative calibration factors are simply inversly proportional to the measured intensity. Due to the low SNR (0.1-1) in gas, this method can be used if a sufficiently long (~3s) beam into gas shot takes place after the discharge, and the beam performs well, due to low SNR (0.1-1) in gas. The second method was invented to cirumvent the uncertanities of the aforementined gas calibration and is based on the following considerations: the two branches of the detection system are measuring the same input light intensities, and thus can be cross calibrated. This is carried out by the comparison of the background corrected light level in a plasma shot in the two systems for each channel, in a carefully chosen time interval, where no events are present which modulate the background too fast (i.e. faster than the 10ms timescale of the spectrometer frame time). Both relative calibration methods were validated by the comparison of spectrometer and APDCAM lightprofiles and were found to be matching well.

3.3 Error calculation

After these considerations, one can conclude, that the reliability of the results can be quantified through a comprehensive error calculation, taking all sources into account. These are the following: electronic noise of the camera, background light and beam emission light photon noise as stochastic errors and calibration errors as systematic errors. Keeping these in mind, the error calculation was validated by comparison of the calculated and the empirical errors for a given lightprofile which were found to be matching satisfactorily.

4. Density profile reconstruction

The lightprofile and the density profile are connected through the rate equations which is a linear differential equation system. The integration of such is straightforward if one wants to calculate the lightprofile from the density profile, but becomes singular at a point along the beam in the reversed approach [4]. One solution for that is a probabilistic, Bayesian approach that searches for the most probable density profile for a given lightprofile through numerous forward calculation and marginalization. A Bayesian density profile and density profile error calculation method [5] was implemented by our group, and was validated on AUG and JET data. In Figure 1, blue line shows the density profile measured by the spectrometer, reconstructed by a non statistical method [4], while red line shows the density profile measured by the APDCAM, reconstructed by the Bayesian method [5] in the same time interval and time resolution (15ms) for an L-mode case in Figure 1 (a) and for a H-mode case in Figure 1 (b). These results show that the density profiles match between error bars for the two independent measurements and reconstruction methods, thus our measurement can be considered validated at JET.

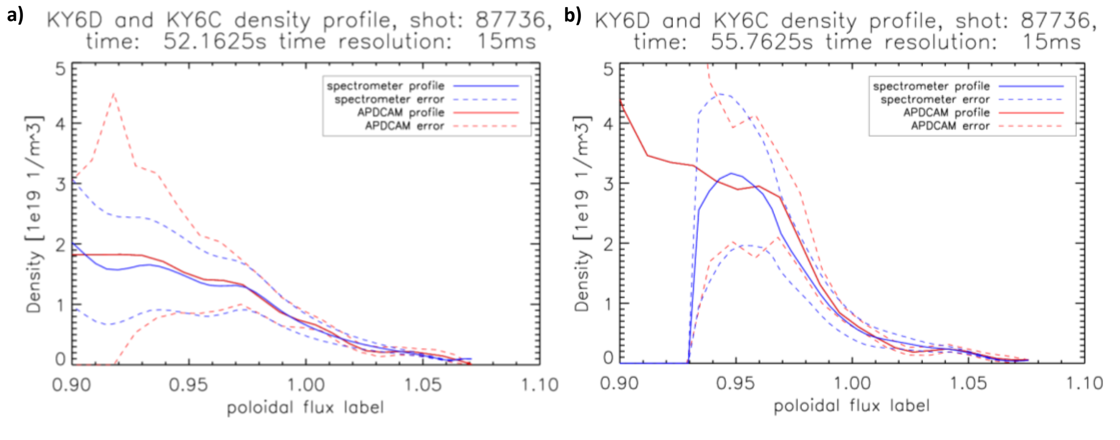

Figure 1.: JET density profile calculated from the spectrometer data (blue line) and from APDCAM data (red line) for (a) L-mode, and (b) H-mode case. Dashed lines show the errors correspondingly.

5. Density profile measurement examples

Some temporally resolved fast event are presented in this section to demonstrate the capabilities of the system.

5.1 ELM cycle

Edge Localized Modes (ELMs) are fast, periodic plasma events in H-mode, that are of interest due to their role played in impurity transport and the high particle and heat load carried by them which is hazardous in terms of machine operation and safety. Figure 2 (a) shows the time evolution of the density profile between 2 ELMs as a contour plot.

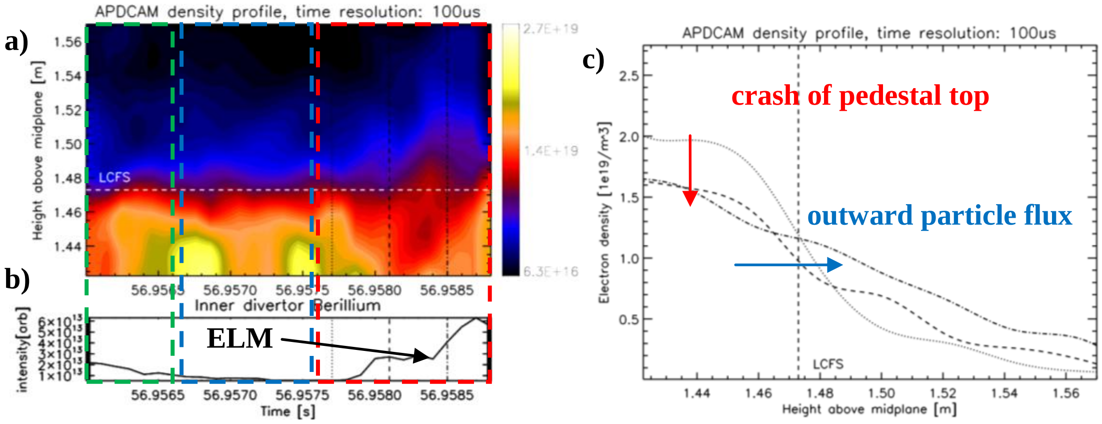

Figure 2.: Temporally resolved ELM crash: (a) contour plot of the density profile time evolution, (b) inner divertor Berillium signal, (c) density profile at the selected time slices.

The x axis is time [s], the y axis is the hight above midplane coordinate [m] along the beam which propagates downwards. The pedestal top density builds up in the time range marked with green, silent H-mode phase is marked with blue, while the pedestal top crashes and the density profile flattens in the time range marked with red. The inner divertor Berillium visible emission is shown as a reference in Figure 2 (b), where the increased load due to the ELM event is immediate on the density measurement time scale. The density profiles during the ELM crash are shown in Figure 2 (c). The line styles correspond to the vertical lines in Figure 2 (a,b). The pedestal top density is decreased by 20%, while the density in the pedestal region is increased which correspond to the ELM induced outward particle flux.

5.2 Pellet injection

Pellet injection is recognised as an important tool for plasma fuelling and ELM control. To understand the dynamics of particle deposition and distribution followed by the pellet ablation it is of interest to detect time evolution of the electron density profile on the time scale of a few tens of microseconds. The fast Li-beam diagnostics is well equipped to investigate these phenomena in the SOL and plasma edge. Pellets can trigger ELMs in H-mode plasmas therefore to disentangle the effect of fuelling and density change caused by the triggered ELMs, the dynamics of the pellet caused density profile change was investigated in L-mode discharges. As a typical example Figure 3 (a) shows the time evolution of the density profile during the ablation of a single pellet. The pellet ablation monitor (D-alpha light) is also plotted in Figure 3 (b). A pellet correlated density increase is observed the more delayed the deeper it is in the plasma as it is marked by dotted line in Figure 3 (a). The marked peak is propagating with about 100m/s speed which is in the order of the typical pellet speed. Figure 3 (c) shows the density profiles at the time slices indicated in Figure 3 (a,b) revealing also the above mentioned density increase propagating into the plasma. The time when the pellet crosses the LCFS can also be determined from this measurement with accuracy of 100 microsecond and few cm as the ablation becomes significant in the confined plasma.

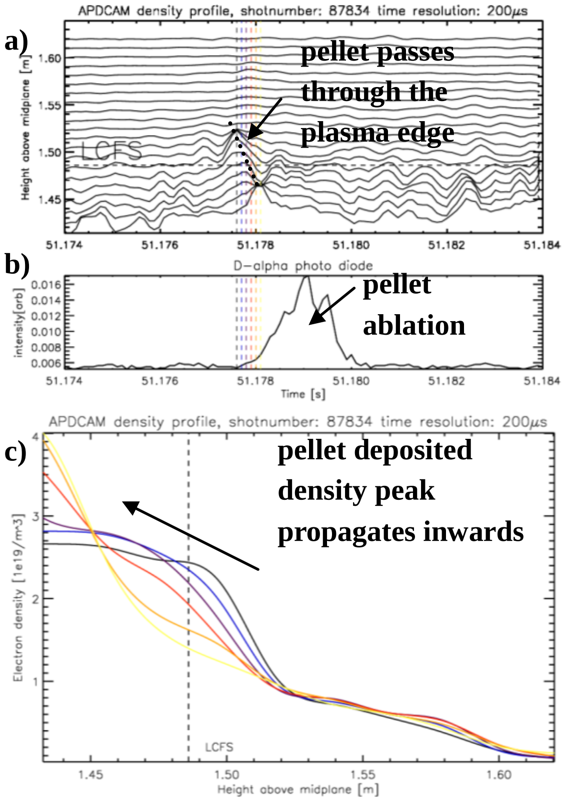

Figure 3.: Temporally resolved pellet penetration: (a) level plot of the density profile time evolution, (b) divertor D-alpha signal below, (c) density profile at the selected time slices. Level plot interpretation: each line represents the time trace of the density relative to the average density over the whole interval at a fixed radial position.

6. Conclusions

The JET LiBES system upgrade resulted in a significant increase in the performance in terms of the temporal resolution, namely the diagnostic is capable of measuring the electron density profile on the 100μs timescale. The work summarized the main properties of the diagnostic focusing at the relevant features concerning the density profile measurement. The steps of the lightprofile calculation that is the background correction, the relative calibration and the error calculation are presented as an important intermediate step towards density profile calculation. After applying a statistical density profile reconstruction method, the results were set against JET results from the parallel spectrometer measurement, and were found to be matching well, thus our method is considered validated, and can be used for further analysis. Two examples of fast events, an ELM crash in H-mode, and a pellet injection in L-mode plasma are investigated and presented in this paper. These results demonstrate the unique the capabilities of the fast JET BES system.

7. References

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