Upgrade of the Lithium beam diagnostic at JET

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(Dated: 12 May 2010)

A 60kV neutral Li beam is injected into the edge plasma of JET to measure the electron density. The beam observation system has been improved by replacing a Czerny-Turner spectrometer with a high-resolution transmission-grating spectrometer and a fast back-illuminated frame-transfer camera. The larger throughput of the spectrometer, the increased sensitivity and the faster readout of the new camera allow inter-ELM measurements (frame rate of 100Hz). The calibration of the setup, as well as an improved spectral fitting technique in the presence of carbon background radiation, is discussed in detail. The density calculation is based on a statistical analysis method. Results are presented for different plasma scenarios.

I. INTRODUCTION

The Li beam diagnostic is an active spectroscopic technique for the measurement of electron density profiles in the edge plasma of tokamaks[1]. Fast Li beams with energies of 20 to 70kV can be created by extraction from thermionic emitters and collimated and accelerated to high beam velocities by a set of extraction grids. A Li beam diagnostic has been in operation at JET for more than 10 years[2], the beam emission of the Li beam atoms is detected by a spectrometer-based observation system. The upgrade of this observation system is the main subject of this paper. A transmission grating spectrometer with high throughput has replaced a Czerny-Turner spectrometer, a 15 year old Wright instruments CCD camera has been replaced by a-state-of-the-art Princeton Instrument PhotonMax camera with fast readout and high quantum efficiency. Both replacements have significantly enhanced the sensitivity of the observation system and hence allow for an improved signal-to-noise ratio and for a higher temporal resolution of the beam emission measurement.

The outline of the paper is as follows: first the experimental setup and the observation system at JET are described in some detail. A discussion of the spatial, spectral and intensity calibration is followed by an explanation of the spectral fitting technique. Finally, the resulting calibrated beam-emission data are used to derive profiles for electron density for different plasma scenarios.

II. THE LI BEAM DIAGNOSTIC AT JET

The Li beam gun is located above the transformer limbs on top of the tokamak at a radius of 3.25m and approximately 4.9m above the plasma boundary. The JET Li ion gun is similar to the ASDEX design[1,2]; details on the JET beam diagnostics are described in these proceedings[3].

At ASDEX Upgrade, DIIID and Textor, the Li beam is injected into the midplane of the tokamak. The plasma boundary at the midplane is located usually close to a poloidal limiter, hence the observation system can be designed for a fixed position. In contrast, the Li beam at JET probes the boundary on the top of the plasma. A variety of different plasma shapes is investigated at JET, the location of the seperatrix changes by more than 25cm at the Lithium beam position, hence the observation system has to be adjusted to different plasma edge positions. The optical components are installed in a periscope tube, which is located at the same radial position but seperated by a toroidal distance of d=65cm. The plasma facing side of the periscope is equipped with a tiltable mirror to adjust the measurement area to the region of interest. In closed position, the mirror doubles as a protective shutter for the plasma facing window. The spatial calibration of the observation system is performed by measuring the Doppler shift of the Li beam emission, hence, a spectrometer/CCD camera detection system is required. Spatially fixed observation systems can use a combination of narrow interference filters and fast detectors like avalanche diodes or photo multipliers. Whereas the latter systems have a larger throughput and allow for a better signal-to-noise and/or faster temporal resolution, the spectrometer setup at JET not only measures the intensity of the beam emission but also provides the spatial calibration and a spectrally-resolved detection of the background radiation.

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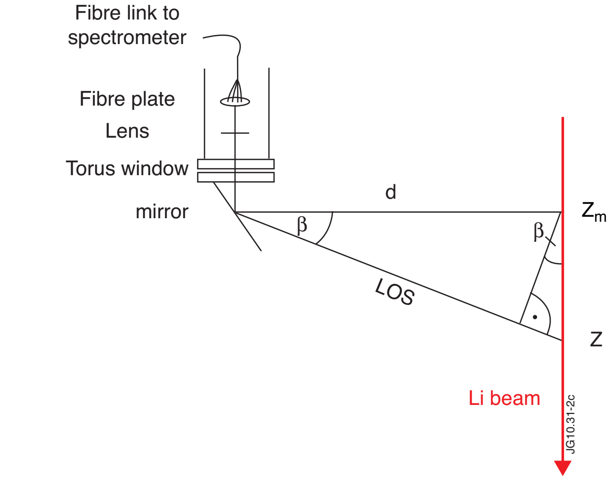

FIG. 1. Li beam periscope at JET: a mirror can be adjusted to different line of sights to observe the beam at different height above midplane z.

The old JET Czerny-Turner-spectrometer, a Chromex (now Bruker Optics) SureSpectrum 250 has an aperture of f/4.0, whereas the new high-dispersion transmission grating Kaiser Optical Systems HoloSpec spectrometer setup benefits from a f/1.8 aperture. Details on this type of transmission grating observation system are published by Bell[4]. The new Princeton Instruments PhotonMax-512 camera provides a quantum efficiency of 0.9 at the wavelength of interest $\lambda \approx$672nm, the old camera deteriorated to an efficiency of less than 0.4. Hence, by using the new spectrometer and CCD, an increased sensitivity of a factor 10 is expected.

The Li beam periscope images the beam emission on a fibre plate consisting of 31 fibres in the Li beam direction and several perpendicular fiber arrays, which are used for alignment purposes. Low numerical aperture fibres NA=0.22 with a core diameter of 1mm transmit the light over a distance of 100m to the diagnostic hall, where the spectral analysis is performed. A selection of 24 of the fibres are arranged as a linear array and imaged on the entrance slit of the spectrometer. The fibre coatings are removed to reduce the height of the fibre array to 28mm. A Nikon 1:1.8 f=85mm lens images the array on the spectrometer entrance slit, the image is demagnified to a height of 13mm. Inside the spectrometer, a second Nikon lens with 1:1.8 and f=85mm illuminates the prism and grating, finally, an Oriel Asphereab lens system (1:0.7, f=50.6mm) demagnifies the spectra to match the height of the camera detector (8.2mm*8.2mm, consisting of 512*512 square pixels of length 16μm). The spectrometer uses a straight entrance slit of 0.1mm width.

The image of each individual fibre on the CCD sensor in the direction parallel to the slit extends over ≈18 pixels. A *track* area is defined for each fibre image in the slit direction, during readout the data is integrated for each track. This procedure does not only reduce the amount of stored data but also reduces the readout noise. The full resolution in the wavelength direction is kept, however, only 180 pixels are stored in wavelength direction to reduce the amount of stored data.

Due to the short focal length of the spectrometer, the image of the entrance slit, the line of light at the same wavelength, is curved on the detector[4], see fig. 2a. This could be a problem for a charge exchange diagnostic application, where a good spectral resolution is important to determine the line width for temperature and rotation measurements. For the Li beam diagnostic, a high spectral resolution is not required. The curved image is rather an advantage because it allows a measurement of the spectral smear during the frame transfer readout (the frame transfer time is 1ms, a typical frame rate is 100/s).

The spectral calibration of the system is performed using calibration lamps with Ne I at λ_{Ne}=671.70nm and Xe I at λ_{Xe}=672.80nm . The dispersion varies from D=0.0397 nm/pixel in the centre to D=0.0413nm/pixel for tracks at the edge of the fibre array. The spectral lines have a typical width (FWHM) of 0.18nm.

III. BEAM-INTO-GAS CALIBRATION, SPATIAL CALIBRATION AND SPECTRAL FITTING

Once the instrument is spectrally calibrated, the remaining calibration information can be derived from beam-into-gas calibration pulses. In contrast to ASDEX Upgrade, where a beam into gas calibration is performed at the end of each discharge, at JET the beam-into-gas calibration is performed in offline pulses, typically one per session in between plasma pulses. D_2 is puffed into the torus and the Li beam is injected into the gas-filled torus. Collisions with the D_2 molecules excite the Li beam atoms, the Li resonance line λ_{Li}=670.78nm is observed. The signal levels are significantly lower than in the plasma case, hence a CCD integration time of 500ms is chosen.

The torus pressure during the Li beam measurement is estimated to be in the low 10^{-4}mbar. Measurements were taken at different flow rates, within the accuracy of the data no indication of an attenuation of the beam was found. The measured intensities are used for the relative intensity calibration of the observation system.

Figure 2b shows the intensities for beam into gas pulses at two different mirror position, fig. 2a shows the corresponding uncalibrated Doppler shifts. The Doppler shift increases with decreasing height above midplane, whereas, the measured, uncalibrated wavelength increases on the top and bottom of the fibre stack.

The spectral fitting of the beam emission is performed with a single Gaussian fit. A detailed analysis shows that the shape is not perfectly described by a Gaussian fit, nevertheless, the resulting errors do not exceed the percent level. Furthermore, the errors cancel out because both, the beam-emission in plasma and beam-into-gas measurement are fitted with a single Gaussian function.

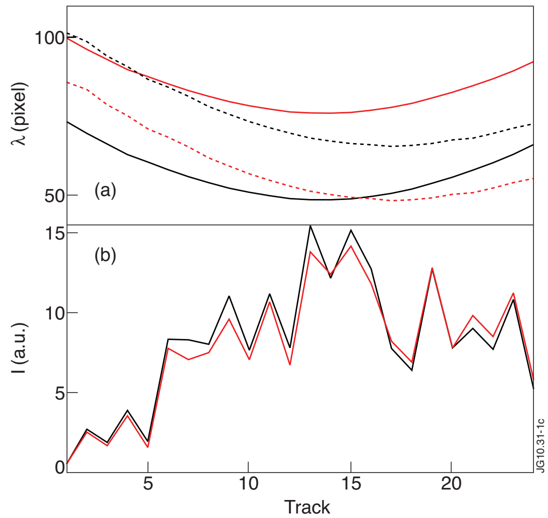

FIG. 2. Calibration of the spectrometer: (a) measured wavelength for a Neon and Xenon spectral calibration lamp $\lambda_{\rm Ne}$ (—) and $\lambda_{\rm Xe}$ (— in red/grey) and the Doppler shifted Li resonance lines from beam-into-gas pulses at two different mirror positions (- - -). (b) intensity from beam-into-gas calibration for two different mirror positions

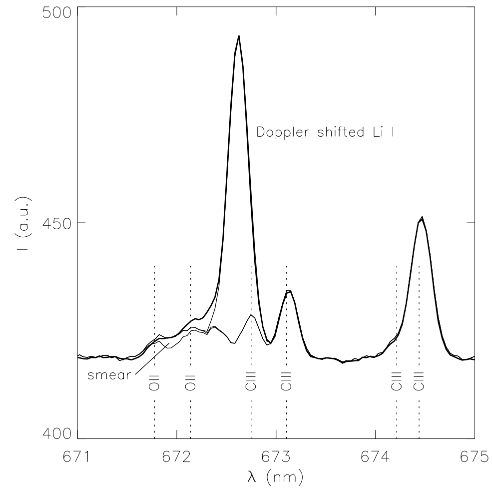

FIG. 3. Measured spectrum with beam modulation: the solid thick lines shows a spectrum including the Doppler-shifted Lithium beam-emission, the solid thin lines show the measured background, the measured background plus calculated readout smear (from beam emission only) and the fit including beam-emission. The dashed vertical lines indicate background impurities.

With some elementary geometry

$$\frac{\lambda_D - \lambda_{\rm Li}}{\lambda_{\rm Li}} = \frac{v_{\rm p}}{c}, \quad \tan\beta = \frac{z_m - z}{d} \quad \text{and} \sin\beta = \frac{v_p}{v_{\rm Li}},$$

where c is the speed of light, $v_{\rm Li}$ is the Li beam velocity, $v_{\rm p}$ is its projection on the line of sight, β is the angle between the line of sight and the horizontal direction, d is the horizontal distance between the mirror and the Li beam and z_m is the height above midplane of the mirror, the height above midplane z at the Li beam radius for each fibre can be calculated from the measured Doppler shift λ_D

$$z = z_m - d\tan\arcsin\frac{(\lambda_D - \lambda_{\rm Li})c}{\lambda_{\rm Li} v_{\rm Li}}.$$

At the edge of the beam emission profile, and at high background radiation, the measurement of λ_D can be distorted. A comparison with the Doppler-shift in beam-into-gas pulses can help. Furthermore, the angles β, as function of track position, are well fitted with a linear function. Hence distorted measurements of β can be replaced by interpolated values.

IV. TREATMENT OF THE BACKGROUND LIGHT IN PLASMA DISCHARGES

In certain plasma scenarios, significant levels of background radiation are observed at the wavelength position of the Doppler shifted Li beam emission. A modulation of the beam in synchronisation with the CCD camera timing allows a spectrally-resolved measurement of the background radiation. For this purpose, the deflection plate voltage of the Li ion gun (see sketch of the JET ion gun[3]), which are used to align the beam in the radial direction, are switched between the alignment and a deflection voltage setting.

In the past, Li beam data were taken with a beam modulation of 1:1, so a beam-on frame was followed by a beam-off frame. The average value from the adjacent beam-off frame measurements were subtracted as the background value, and a (multiple) Gaussian fit was performed to determine the Li beam emission intensity. Though the beam modulation proved to be an improvement to an analysis without background measurement, problems occur in the case of non-steady-state conditions like ELMy H-modes.

A detailed analysis of the background line radiation reveals, that in standard conditions (deuterium plasma with good vacuum conditions) the background radiation is dominated by a CIII multiplet, $1s^2 2p(^2P^0)3s$-$1s^2 2p(^2P^0)3p$ covering the wavelength range from 672.75-674.44nm. Figure 3 shows measured spectra with and without Li beam emission. The CIII multiplet is clearly visible, the individual CIII line intensities are proportional to the intensity of the lines outside the beam emission range at 674.44nm, hence by measuring this line the intensity of the CIII lines in the vicinity of the beam-emission can be predicted. For this purpose the fitting procedure first calculates for each track the shape of the spectral background for a suitable selection of background frames. The beam emission for each spectrum is then fitted with seven fitting parameters: the product

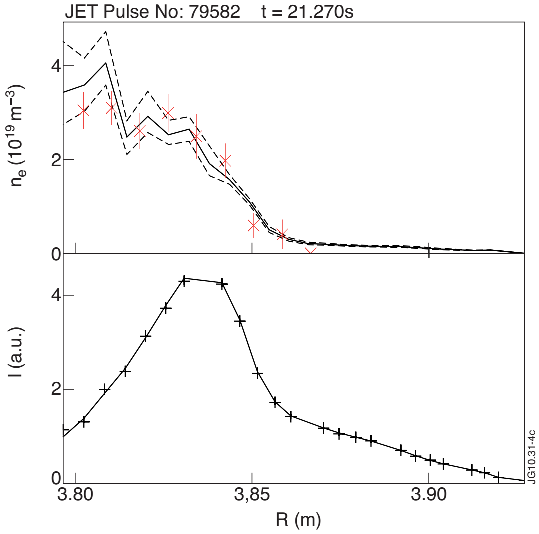

FIG. 4. (top) Comparison of the Li beam derived density profile (—) and the error bar (- - -) with the results from a high resolution Thomson scattering (×). (bottom) Corresponding Li beam intensities (+) and the fit to the data (—).

of the measured background light multiplied with a constant (one variable), a not-too-strongly-shaped quadratic background level (three variables) and the beam emission Gaussian with its width, position and intensity (three variables).

In simple cases, with low bremsstrahlung and low carbon concentration, the fitting procedure works well without constraining the fit parameters. At high background radiation as in high current experiments at high density with high levels of additional heating, some fine tuning has to be done (e.g. by carefully selecting the time range, where the CIII background data is measured and/or constraining the wavelength position and width of the beam emission Gaussian to match the results from the undistorted beam-into-gas calibration).

This improved fitting technique allows a beam modulation of typically 1:10, so one beam-off measurement is followed by 10 beam-on frames, and therefore allows a continuous measurement of the edge density which is important in the study of fast events such as ELMs.

V. RESULTS

Figure 4 shows a comparison of a Li beam derived edge density profile with the results from a high resolution Thomson scattering. The density profile has been analysed with a Monte-Carlo method, which is numerically time consuming but does a careful error analysis and provides error bars for the results. The analysis method is described in[6,7]. It is important to understand that the Li beam analysis is based on a self-calibration of the emission profile provided a sufficient range of beam attenuation is observed. As a consequence of the accumulation of the errors of the beam attenuation, the error bars for the electron density increase with increasing beam penetration into the plasma (decreasing radius R or height above midplane z).

VI. SUMMARY AND CONCLUSIONS

The Li beam diagnostic is a powerful diagnostic tool to measure profiles of electron density with high temporal and spatial resolution in the edge plasma of fusion experiments. The recent enhancements at JET, the commissioning of a new spectrometer with larger throughput and a new sensitive and fast camera, allow for a measurement with 10ms temporal resolution. An improved fitting technique for the background radiation has been developed. These improvements allow inter-ELM measurements of the edge density profile, offering new opportunities for the analysis of H-mode experiments at JET. The new detection system has been operated for 230 discharges. For the next campaigns, an optimisation of the spectrometer setup will be investigated which would make use of multiple entrance slits for the spectrometer to allow a better matching of the f-number of the spectrometer and an observation of more channels.

ACKNOWLEDGMENTS

In memory of our dear colleague Anatoly Korotkov, who passed away unexpectedly on June 22^{nd} 2009, aged 56.

This work was carried out within the framework of the European Fusion Development Agreement and was partly funded by the United Kingdom Engineering and Physical Sciences Research Council under grant EP/G003955 and by the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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