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M.Brix, A.Korotkov, M.Lehnen, P.Morgan, K.McCormick, J.Schweinzer, D.Summers, J.Vince and JET EFDA Contributors

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M.Brix[1], A.Korotkov[2], M.Lehnen[1], P.Morgan[2], K. McCormick[3], J.Schweinzer[4,3], D.Summers[2], J.Vince[2] and JET EFDA Contributors*

[1]Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Trilateral Euregio Cluster, Euratom Association, D-52425 Jülich, Germany
[2]UKAEA Fusion, Euratom Association , Culham Science Centre, Abingdon, OX14 3EA,UK
[3]Max Planck Institut für Plasmaphysik, Euratom Association ,D-85148 Garching, Germany
[4]EFDA Close Support Unit, Culham Science Centre, Abingdon, OX14 3DB, UK
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ABSTRACT

An accurate determination of the density profile at the plasma edge is of great importance for the understanding of H-mode transport barrier physics, as well as for the general characterisation of edge properties under plasma scenarios ranging from ELM-free H-modes to advanced tokamak concepts. Lithium beams have been successfully applied to this end on AS-DEX Upgrade, W7-AS, TEXTOR and JET, whereby the deconvolution of the Li(2p) light profile along the beam yields density profiles with high spatial and temporal resolution. Recent modifications of the Li-ion gun and neutralization cell on JET have lead to an increased reliability and performance. Furthermore, calibration procedures for the transmission and radial calibration of the observation system have been developed. The diagnostic has been operated at JET successfully for more than 700 pulses.

PRINCIPLE OF THE DIAGNOSTIC:

The principle of the lithium beam diagnostic is based on the analysis of the shape of the line emission profile of the lithium resonance line (λ =670.8nm). Whilst penetrating the plasma, the beam is excited and attenuated by collisions with electrons and plasma ions. Both the line emission from excited states and the beam attenuation increase with density. As a consequence, a peaked beam emission profile is found (see Figs.3 and 4). The atomic physics of the interaction of the beam atoms with the plasma is described in [1] and [2], the latest and most accurate collection of cross-sections is compiled in [3]. For a self-consistent density deconvolution, it is crucial that the whole emission profile is observed and that the relative calibration of the observation system is known.

DIAGNOSTIC SETUP:

The principle of the lithium beam generation is illustrated in Fig.1. Li^+ ions are extracted from a Li-β-eucryptite coated tungsten disc, which is heated to a temperature of ~1300°C. By means of ion optics a beam with a diameter of ~20mm is formed. The ion beam is neutralized in an alkaline metal vapour neutralization cell with an efficiency of up to 80% (for more details see [4]).

The HV stability of the ion gun has been improved by slight modifications to the ion optics and by rounding off sharp edges. The neutralization element has been changed from Li to Na because comparable neutralization efficiencies could be achieved with Na at a significantly lower operation temperature (250°C for Na instead of 500°C for Li). As a consequence, the reliability of the heating elements and the sealing of the poppet valve have been increased.

OBSERVATION SYSTEM:

The Li beam source is installed on top of JET at ~4m distance from the last closed flux surface. The beam is observed by a periscope which is installed at a similar poloidal but different toroidal location. The alignment of the observation system on the beam can be optimised by rotation of the periscope and by rotation of the fibre plate. The fibre plate supports optical fibres which relay the beam emission to the diagnostic hall (the overall length of the fibres is ~100m). In addition, a mirror allows observation at different heights above midplane to accommodate different plasma shapes. The diameter of the image points at the beam location increases with decreasing heights above midplane from 6mm to 12mm.

In the diagnostic hall, the line emission profile is imaged on the entrance slit of a 0.25m Czerny-Turner-spectrometer. The spectra are recorded using a CCD camera and the data acquired by means of a PC-based system. The spectrometer settings and the binning of the CCD data is set to allow a resolution of 24 radial and 50 spectral points, typical spectral resolution is $\Delta\lambda = 0.3$nm. The temporal resolution of the observation system is determined by the fastest frame rate of the CCD data acquisition $\Delta t \geq 50$ms.

RELATIVE CALIBRATION OF THE OBSERVATION SYSTEM:

A calibration procedure has been developed to monitor the quality of the alignment of the observation system to the beam. The procedure is applied on an inter-shot basis and controls i) the injection of deuterium into the torus to build up a constant pressure of $\sim 10^{-4}$ mbar, ii) the injection of the Li beam into the gas filled torus and iii) the triggering of the data acquisition.

The Li atoms are excited by collisions with the deuterium molecules without significant ionisation, the resulting uniform beam emission profile is recorded by the observation system. The reciprocal of the recorded intensity profile corresponds to the relative radial transmission of the observation system. After successive applications of the calibration procedure followed by remote controlled optimisation of the periscope and fibreplate, the observation system was found to be well aligned with respect to the beam.

RADIAL CALIBRATION OF THE OBSERVATION SYSTEM:

The radial calibration of the observation system can change with the JET vessel temperature (e.g. in campaign C4 the vessel temperature has been reduced from 300°C to 200°C), with the mirror position and after events like major disruptions. Fortunately, due to the inclination between the line of sight and the beam axis, a change in the radial calibration can be detected by the Doppler shift of the observed line emission. A fit of the theoretically expected Doppler shift to the measured shift finalises the radial calibration.

ANALYSIS PROCEDURE:

The interaction of the Li atoms with the plasma electrons and ions can be described by a collisional-radiative model (CR model, see [1,2]). The equation for the first excited state of the CR model can be written as

$$n_e = \left(\frac{dn_2}{n_2\, dx} - \sum_{i=1}^{n} \left(\frac{n_i}{n_2}\, k_{2i} \right) \right) \Big/ \sum_{i=1}^{n} \left(\frac{n_i}{n_2}\, a_{2i} \right)$$

In this equation the following symbols are used: local electron density ne, beam coordinate x, local population density of state i ni, number of all states included in the model n, local emission matrix k_{2i}, local collisional matrix a_{2i} (for more details see again [2,1]). In the first term of the numerator

n_2 can be replaced by I, the local line intensity of the lithium resonance line (as measured by the observation system). The equation can be solved directly for an absolutely calibrated system by integration (e.g. with a Runge-Kutta method).

In most experimental situations, only the relative calibration is known. Therefore the equation has to be solved by iteration of the calibration constant (which is equivalent to iteration of the initial population of the first excited state)

1) to fit a boundary condition (which may be adjusted in respect to an independent measurement of the electron density) or
2) self-consistently
   a) by making use of the fact that the beam is completely ionised at the radial point where the emission vanishes or
   b) by enforcing that both the numerator and denominator in the above equation reach zero at the same radial position. Such a singularity point is found only at high densities, further details can be found in [1,2].

The first method is standard at JET (Korotkov) whereas the latter is the standard method at ASDEX-U and W7-AS in Garching (Schweinzer). The advantage of the first method is that densities can still be deconvolved in cases with no singularity and/or a part of the emission profile missing. The latter method has the advantage that no additional density measurement has to be utilised. Figure 3 illustrates the sensitivity of the deconvoluted density profile to a slight change of the calibration constant (within 2.5% from 620 to 635). For comparison, the result of the self-consistent deconvolution method derived with the code of IPP Garching is given, too. A small change of the calibration constant has a proportional influence in the range of weak beam attenuation, whereas in the region of strong beam attenuation (shaded region) the result is very sensitive to small changes of the calibration constant. The interpretation is quite simple: the error of the calculated beam attenuation increases with increasing penetration depth. As a consequence, at a certain penetration depth the deconvolved densities become unreliable.

Overall it can be stated that both deconvolution methods agree well in the region of weak beam attenuation.

COMPARISON WITH CORE AND EDGE LIDAR:

In Fig. 4, the density profiles delivered by the core and edge LIDAR (JET Thomson scattering diagnostic) are compared with the Li beam data. The plasma scenario is a low triangularity ELMy H-mode with I_p = 2.5MA and B_t = 2.7T. The core LIDAR has inadequate spatial resolution for plasma edge measurements (~120mm). Some points from the edge LIDAR fit the edge pedestal well. However, the spatial resolution is poor (20-50)mm and density measurements are not possible at low densities $n_e<5 \cdot 10^{18}m^{-3}$ [5]. The Li beam diagnostic has good radial resolution of ~(6-9)mm (mapped on midplane) and measures densities from the plateau region to the low density plasma deep inside the scrape-off layer. The Li beam measurement has been made with a temporal resolution of Δt = 50ms continuously for an interval of 8s.

COMMENTS ON EDGE GRADIENTS

The results of the deconvolution procedure depend on the accuracy of the fitting and the smoothing of the Li line emission profile. The result discussed above for Pulse No: 53185 is basically influenced by only 8 of 24 observation channels – a higher spatial resolution might deliver more details (e.g. steeper gradients).

POSSIBLE IMPROVEMENTS

The Li gun at JET typically delivers (0.5-1.0)mA equivalent neutral current (measured on the Faraday cup at a distance of 2m from the source). Optimisation of the gun should allow an increase of the current to the values achieved in Garching (up to 2.5mA). Due to the restricted access to the torus hall, laboratory experiments are therefore required.

Further improvement of the HV stability would allow an operation at higher beam energy (increased penetration depth), increased neutral current would increase the signal-to-noise ratio.

Replacement of the camera and its data acquisition system by a fast back-illuminated camera should increase the effective signal and furthermore allow improved temporal resolution (e.g. for ELM studies).

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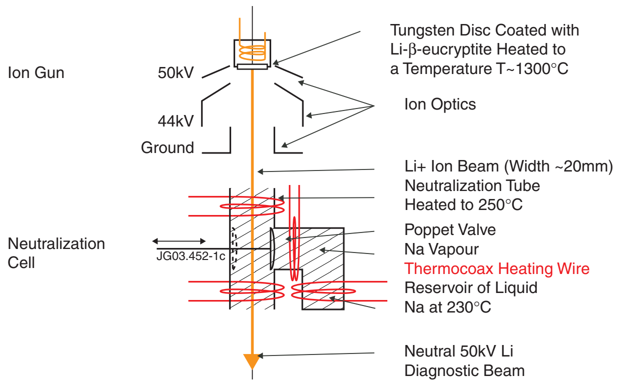

Figure 1: Principle of lithium beam generation.

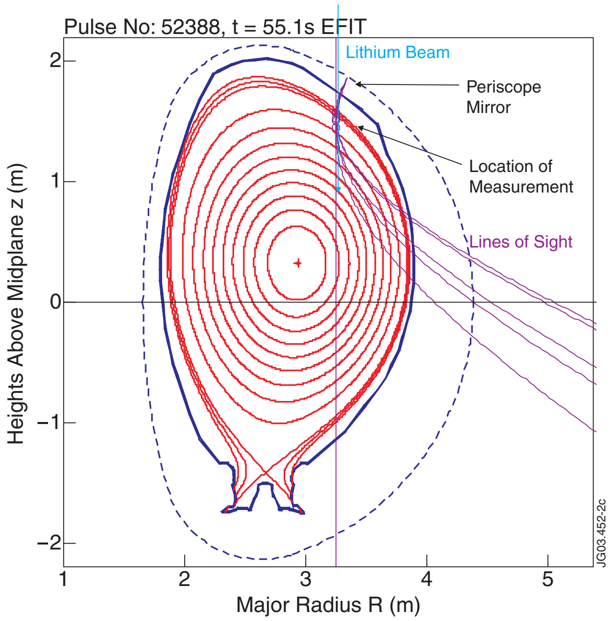

Figure 2: Lines of sight of the lithium beam diagnostic.

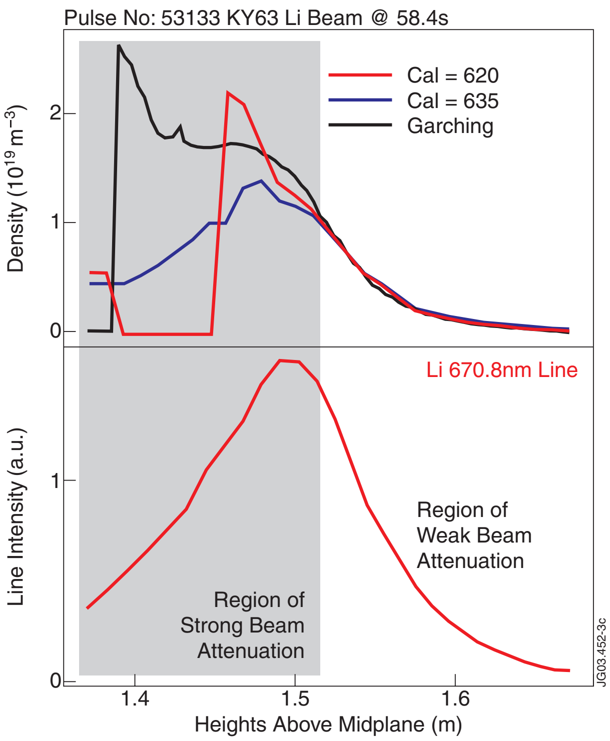

Figure 3: Influence of the calibration constant (cal) on the deconvolved densities.

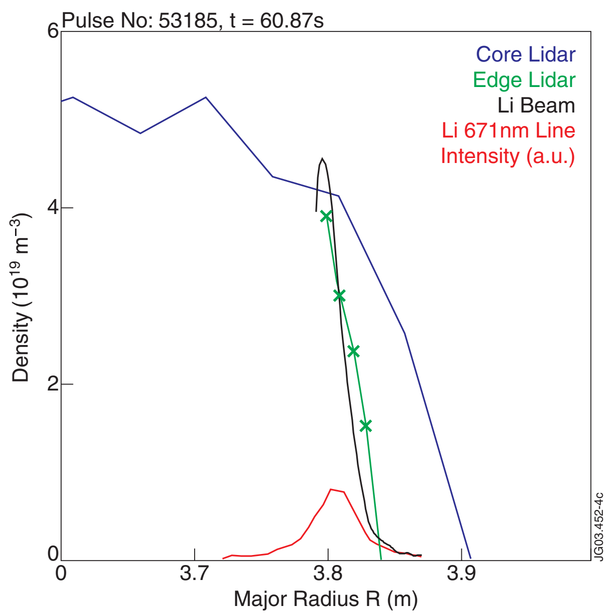

Figure 4: Comparison with core and edge LIDAR.