

Edge density profile and turbulence measurements with an alkali beam diagnostic on Wendelstein 7-X

M. Vécsei¹, G. Anda¹, O. Asztalos², S. Bozhenkov³, G. Cseh¹, D. Dunai¹, S. Hegedűs¹, R. König³, D. Nagy¹, M. Otte³, G. I. Pokol², B. Tál¹, S. Zoletnik¹ and the W7-X team³

¹ *Department of Plasma Physics, Wigner Research Centre for Physics, Hungary*

² *Institute of Nuclear Techniques, Budapest University of Technology and Economics, Hungary*

³ *Max-Planck-Institute for Plasma Physics, Germany*

Introduction: Beam Emission Spectroscopy is a plasma diagnostic utilized for turbulence analysis and the reconstruction of electron density profiles in the plasma edge [1]: The light emitted through the excitation and subsequent deexcitation of a neutral alkali atomic beam entering the plasma at high energy is detected by the diagnostic system. From the light profile the electron density profile can be reconstructed using Bayesian statistics. The Alkali Beam Emission Spectroscopy (A-BES) system has been installed recently at the Wendelstein 7-X stellarator. In comparison to the conventional Lithium-based BES systems, the shorter lifetime of the relevant excited state of the Na atoms facilitates a more localized analysis of the density profiles. This is a considerable advantage for the analysis of transport processes at the plasma edge, especially at the steep gradients expected at the banana-shaped cross section of the W7-X plasma. In the following an overview of the diagnostic system and early results of the experiments are presented.

The diagnostic system: The diagnostic consists of a 60 keV Sodium atomic beam injector [2] which can provide about 1 mA ion equivalent neutral current for a 2 cm FWHM beam. The beam emission is observed from the poloidal direction with a high-etendue ($\Omega/4\pi = 3 \times 10^{-4}$) 40 channel optical system, where each channel collects light from a 4×0.5 cm (toroidal \times radial) area of the beam. The 588.9 nm 3p-3s radiation line of the sodium atoms is led through a fibre bundle array to Avalanche Photodiode (APD) detectors measuring with 2 MHz sampling rate. For overview and spatial calibration, a few percent of the light is directed to a 1280 \times 1024 resolution CMOS camera. Despite the 500 kHz analogue bandwidth, the data detected by the APD has a peak signal-to-noise ratio up to 50, enabling the study of fast transients and turbulence.

The geometric configuration of the diagnostic system is shown in Figure 1a: The atomic beam enters the vessel from port AEA21 and crosses the plasma at a constant toroidal angle of $\phi = 72$ at the torus midplane. The observation optics is located vertically above the beam, at port AEB20. An example for the image detected by the CMOS camera is shown in Figure 1b. In addition to the CII background radiation, a considerable amount of light is generated by Sodium gas originating from the beam neutraliser. The latter has a significant contribution to the detected light profiles in the SOL.

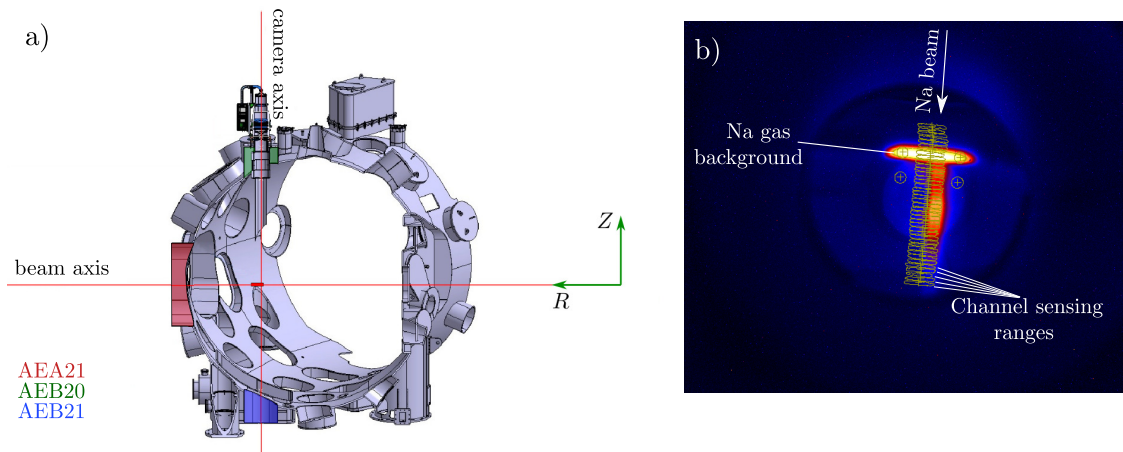


Figure 1: a) CAD drawing of the diagnostic configuration. b) The image detected by the CMOS camera. The prominent elliptical shape at the start of the beam corresponds to the Sodium gas signal. The sensing range of the APD channels are superimposed to the picture. Port AEB21 can be observed in the background.

Data processing: The spatial calibration of the system is done with the CMOS camera. The camera system has a view on port AEB21. Utilizing the engineering data of the port, one may calculate the location of the beam image in stellarator R and Z coordinates. The APD observation channels were back-illuminated to a screen in the laboratory and their sensitivity areas were imaged with the CMOS camera. This way the sensitivity areas of the APD channels can be mapped to the stellarator coordinates. The relative amplitude calibration of the channels is performed after every shot as the light profile is expected to be constant when the beam is injected into neutral gas. Thus, continuing the measurements for a short time period (0.5-1s) after each plasma discharge, the signal in the recombined gas is sufficient for the relative calibration of the channels. In order to remove the considerable background signal in the SOL, the beam has been modulated at high frequencies (≈ 50 kHz). For every half period the beam is diverted, so that it does not enter the plasma. A demodulation algorithm [3] is used to separate the background and beam signals.

The electron density is reconstructed with the Bayesian method [4]. The reaction rates for the Sodium excitation and de-excitation through plasma collisions can be obtained from Ref. [5]. Hence, by measuring the light profile, one may reconstruct the electron density profile utilizing the differential equation governing the occupancy of the energy levels of the Sodium atoms. It is noted that the Bayesian reconstruction does not require the absolute calibration of the channel signal amplitudes. The results of various measurements, such as density profiles obtained from Thomson scattering or reflectometers can be optionally incorporated to the reconstruction as well. Currently, these are not utilized and there are only two prior assumptions of the reconstruction: Firstly, it is assumed that the density profile is approximately linear in the core. Secondly, the density profile is assumed to be reasonably monotonous. The strength of these assumptions can be set by two free parameters.

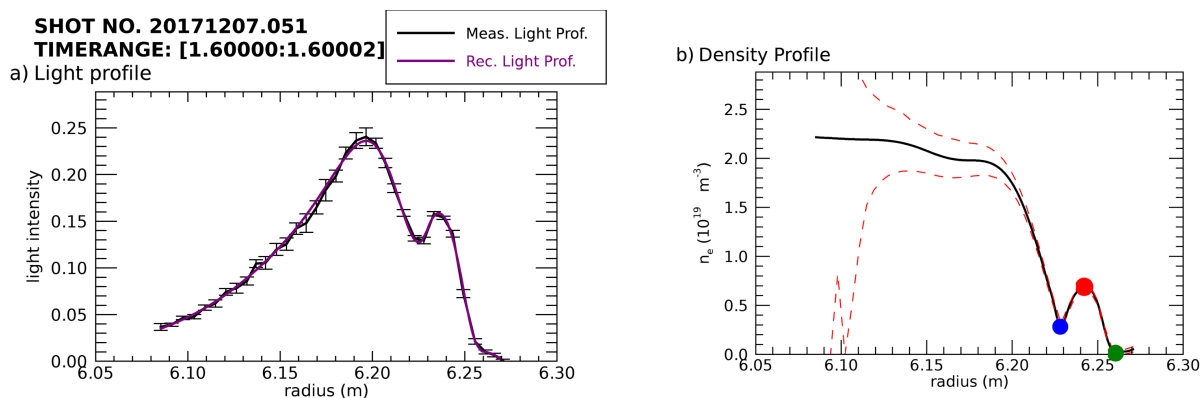


Figure 2: a) The detected light profile (black) and the reconstructed light profile (purple) corresponding to the density of Figure 2b. b) The reconstructed density profile and the approximation of the corresponding error.

Results: The diagnostic has been installed to Wendelstein 7-X on December 2017. A number of successful measurements has been performed on 7th December. Preliminary results from the diagnostic are presented in the following.

Shot No. 20171207.051 was performed with hydrogen fueled plasma with pellet injection. The detected light profile along the beam after background subtraction is shown in Figure 2a. The estimated error of the detected light profile is approximated from the sum of the squared variance of the detected signal during beam-on and beam-off time intervals. In general, during the shots the uncertainty of the reconstructed density profile in the core has been found to increase substantially. Hence, the reconstructed data only give an order of magnitude approximation for the electron density in this regime.

An initial peak in the density profile has been found for shot No. 20171207.051. To investigate the source of the phenomenon, the structure of the magnetic surfaces along the beam has been calculated, which are shown in Figure 3. The colored points on the Figure 2 and 3, correspond to each other, implying a reasonably good spatial calibration of the diagnostic. The results thus imply a local maximum of the electron density in the magnetic island for this shot.

The time evolution of the density profile along the beam has been reconstructed for shot No. 20171207.006 with 50 μ s time resolution. The result is shown in Figure 4. The increase of the core density due to the pellet injection can be observed.

Finally, the correlation function of the light profile fluctuations in the [166Hz, 50kHz] frequency band is shown in Figure 5. for the same shot. Here, the spatial and temporal cross-correlation of the light profile is plotted. The reference channel is the one located at $R \approx 6.25$ m and the correlation has been calculated for the 0.6 – 1 s time interval. The magnetic island is located approximately in the $R \in [6.20, 6.25]$ interval. Figure 5. implies outward propagating fluctuations of the light profile. Remarkably, before the fluctuations in the magnetic island reach its center, positively correlated fluctuations appear on the opposite side of the island.

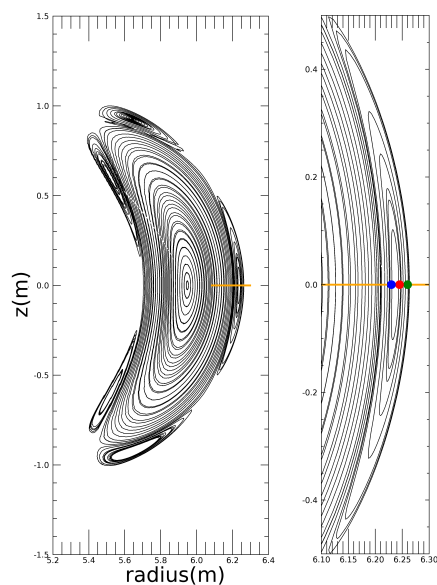


Figure 3: The magnetic surfaces for shots No. 20171207.006 and 20171207.051.

Summary: The A-BES system allows the analysis of the density profile at the banana-shaped cross section of Wendelstein 7-X. From the currently available data, density profiles may be reconstructed with an at most $50\mu\text{s}$ temporal resolution near the plasma edge over an 8 – 10cm long region. Moreover, the diagnostic is capable of analysing the density profiles and fluctuations in the magnetic island.

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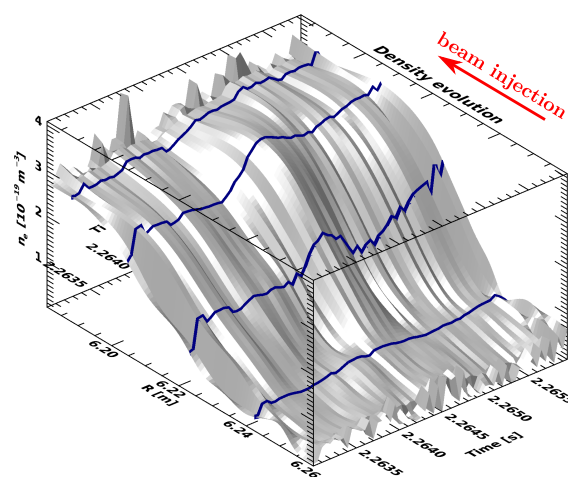


Figure 4: The time evolution of the detected density profile for shot 20171207.006.

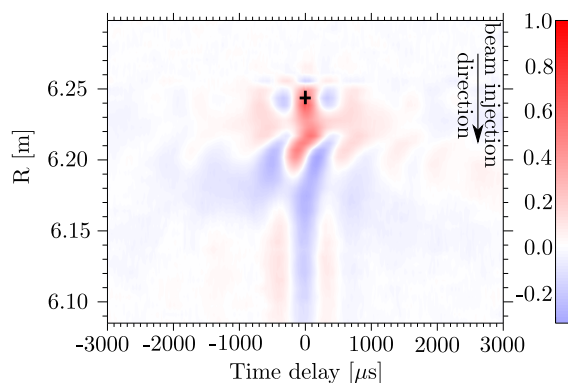


Figure 5: The spatial and temporal cross correlation of the light profile for shot No. 20171207.006 for the channel located at $R \approx 6.25\text{m}$, marked with a cross.