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Measurement of edge plasma parameters at W7-X using Alkali Beam Emission Spectroscopy

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A 60 keV neutral Alkali beam system was designed, built and installed for beam emission spectroscopy measurement of edge plasma on W7-X.

As the decay length of the first excited state of sodium is much shorter than lithium it was selected as beam species. This way the steep density gradient at the bean shaped cross section of the Wendelstein 7-X plasma can be resolved.

Unexpectedly a thermal sodium beam was also observed in the far Scrape Off Layer of W7-X plasma during the first measurements in 2017. It was found to originate from the recirculating neutralizer which uses sodium vapour. To resolve this issue the neutralizer material was changed to Potassium.

The observation system consists of two parts: a 40 channel avalanche photo diode (APD) camera unit and a CMOS camera which run in parallel: 95 % of the collected light goes to the APD unit which is digitized with 2MHz sampling rate while the CCD camera is operated in the 100 Hz range. Chopping the beam up to 250 kHz is also possible for precise background measurement on the time scale of the turbulence.

In this paper the main improvements of the sodium beam system using potassium for ion beam neutralization and the first measurement results are described.

Keywords: alkali beam emission spectroscopy, ion source

1. Introduction

Spatially and temporally well resolved electron density measurements at the plasma edge are of great importance in the study of magnetic fusion devices. There are only a limited number of non-perturbative diagnostic techniques for this task, most notably thermal He beam and reflectometry. The alkali beam based beam emission spectroscopy (BES) diagnostic has excellent time (μs) and very good spatial (<0.5cm) resolution at the same time.

Capabilities of accelerated lithium beam based BES diagnostics were demonstrated at almost every present tokamak and stellarator experiments (ASDEX[1], ASDEX Upgrade[2], JET[3], TEXTOR[4], DIII-D[5], W7-AS[6], LHD[7] and COMPASS-D[8]) and was designed and installed also at W7-X in year 2017. The working principle of the alkali beam based BES can be summarized as follows: alkali ions (lithium or sodium) are extracted from a thermionic ion source and accelerated by an ion optic. Neutralization of the ion beam is done in sodium vapour. The neutral beam penetrates the plasma and is excited by plasma particles. The excited state decays with photon emission at a characteristic wavelength. As the excitation is mainly determined by the plasma electron density, the alkali BES diagnostic measures the plasma electron density and its fluctuations [11]. For accurate background light correction the beam can be chopped out from the plasma with up to 250 kHz.

Limitations of the diagnostic are the restricted penetration depth (10-20 cm) and the light intensity measured by the observation system. The latter depends on the neutral beam current and diameter, the optical observation system etendue and the efficiency of the detector system. Tuning of the interference filter by changing its temperature could also be very important.

Using Sodium alkali neutral beam a new limitation emerged. The sodium vapour used for ion beam neutralization appears as a thermal beam in the far Scrape Off Layer (SOL). As the sodium loss of the neutralizer can not be decreased a new material had to be chosen for ion beam neutralization (see in Section 2.3).

The article is organized as follows. Section 2.1 gives an overview of the injector hardware. In Section 2.2 the latest improvements of the system are summarized and in 2.3 the recirculating neutralizer is discussed. In Section 3 the test measurement with potassium filled neutralizer is shown. Section 4 shows the integration of the complete system at W7-X while in Section 4.1 and in 4.2 the observation system and the interference temperature tuner are described. In Section 5 the first measurements results are presented.

2. Injector hardware

2.1 Overview of the system

The alkali beam hardware is discussed in detail in Ref. [10] and only shortly summarized here. The arrangement of the W7-X alkali beam injector can be seen at Figure 1. The thermionic ion source is placed in a Pierce electrode and followed by a two-step ion optic, based on the original design used first at ASDEX [1]. The last element of the ion optic called puller is on -500V potential, i.e. it works as an electron suppression ring, as well. The ion beam

enters into the deflection plates area where a pneumatic controlled miniature shutter is mounted between the electron suppression ring (puller) and the first deflection plate pair. The beam can be moved both poloidally and toroidally in this region by applying an electric field between the deflection plate pairs. A moveable Faraday cup is placed to measure the beam parameters.

The deflection area is followed by the recirculating neutralizer where the ion beam is neutralized – usually in sodium vapour. Because of place restriction the diagnostic chamber could not have been mounted directly on the entrance port of the torus but only about half a meter further. This way the system consists of two flight tubes (each of them with a length of about 0.5m). At the diagnostic chamber a moveable Faraday cup and two observation cameras (with observation windows) are placed to measure the neutral beam parameters and the beam displacement from the beam axis, if there is any.

The injector is designed to produce a max. 60kV neutral alkali beam with about 1 mA neutral current and 2 cm FWHM. Additionally, the beam can either be chopped out completely (up to 250 kHz) or it is able to hop between two parallel beam positions in the plasma with about 400 kHz frequency and a few cm from each other for poloidal flow velocity measurement [11]

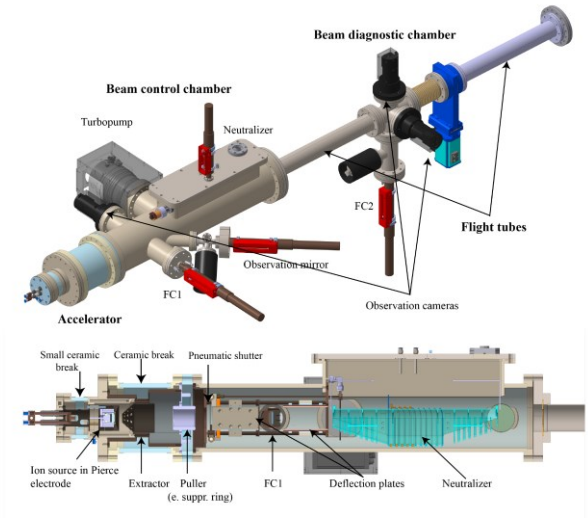

Fig. 1. Overview of the W7-X alkali beam injector.

2.2 Latest improvements of the beam hardware

As mentioned before, one of the key parameters of the diagnostic is the measured light level, which highly depends on the beam focusing. The starting surface of the beam is critical, both its angle and its distance from the extractor. At earlier versions the main and the extractor voltage was insulated by two ceramic discs placed inside the vacuum chamber, as part of the holding structure of the Pierce electrode. In the present system the insulation became part of the chamber, see Figure 1 (called small ceramic break). The holder structure of the Pierce electrode is stainless steel and is matched both on the flange and on the back side of the Pierce electrode, this way its position is fixed.

The high voltage system consists of two 60kV power supplies (Glassman, EJ60P10-F22-ETH) which are placed in a cabinet outside the torus hall. The HV system at the injector can be seen at Figure 2. There are load resistors (100MOhm at the ion source, 45MOhm at the extractor), serial resistors (90 kOhm in both HV line to protect the system in case of HV sparks and discharges) and HV filter capacitors (55nF) to filter the ripple of the HV power supplies (only to each other). A new improvement is the HV transformer (made by Adimtech Ltd.). A toroidal iron core with primary windings (n=520) is placed in a torus shaped UHMW polyethylene housing. The primary cables are let out from the HV area via a so called chimney (goes under the table on Fig. 2). The insulation does not break between the torus and the chimney. This way the secondary winding (n=16, not shown on Fig. 2) which is on the main voltage does not have to be insulated from the surrounding elements.

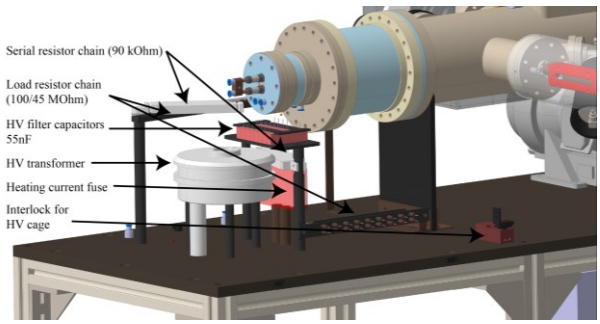

Fig. 2. HV system of W7-X alkali beam injector.

2.3 Recirculating neutralizer

Alkali ions extracted from the ion source and accelerated by an ion optic need to be neutralized in a sodium vapour cell via the charge exchange process. The concept of this kind of neutralizer is to heat up sodium, produce sodium vapour pressure in a cell, and minimize the loss of sodium by condensing and reflowing the sodium vapour (outside the neutralization volume) [10].

The loss of the neutralization can be calculated as follows:

$$\varphi = n_v v \frac{r^4 \pi}{2L^2}. \qquad (1)$$

where n_v is the density and v is the thermal velocity of Sodium atoms, r is the diameter of the hole on the central cell and L is the length of the neutralizer middle cell [10]. This equation results about 7.5e17 particle flux (1/s) at both ends of the neutralizer. As a first attempt one can assume that the thermal beam leaves the neutralizer with an angle which is defined by the opening of the neutralizer (25mm), the opening of the middle cell (25mm) and their distance (0.1m). The distance between the neutralizer and the plasma edge is about 3m and the entrance port diameter is about 63 mm. It means that a thermal beam with about 1.3e16 particle flux reaches the plasma. 1mA neutral beam means about 6e15 particle flux. The measured light level of the thermal beam is about one magnitude higher than the beam light. As it does not explain the light intensity difference, there are two

possibilities: either the temperature of the neutralizer is under or the neutral beam current is over estimated. 10% higher neutralizer temperature would result about 3.7e16 thermal particle flux at the plasma and 0.5 mA neutral beam current would mean about 3e15 particle flux. As the measured extracted beam current was about 1.6-1.8 mA during OP1.2a and taking into account the about 40% focusing and about 80% neutralization efficiency the real neutral beam current could have been about 0.5mA. These assumptions would explain precisely the one magnitude difference in the light level.

Although additional investigations are necessary to describe accurately the light level measurement the consequence is clear: sodium vapour can not be used for neutralization of accelerated sodium beam. Instead of sodium two other alkali might be used, either lithium or potassium. Assuming the same cross section for the charge exchange interaction, to reach the same vapour pressure with lithium would require about 560 °C degrees while with potassium that would take about 210 °C degrees. This way potassium was chosen as an alternative for sodium beam neutralization.

3. Neutralization test with potassium

The clone of the W7-X alkali beam have been built up in Wigner RCP. Its neutralizer was filled up with about 6.7g potassium (98% purity). The beam diagnostic chamber was placed directly after the neutralizer chamber, without any flight tube. Beam energy and HV ratio (Umain/Uext) were fixed at 40kV and at 9, where the sodium beam current had a maximum in the Faraday cup. The results can be seen at Figure 3.

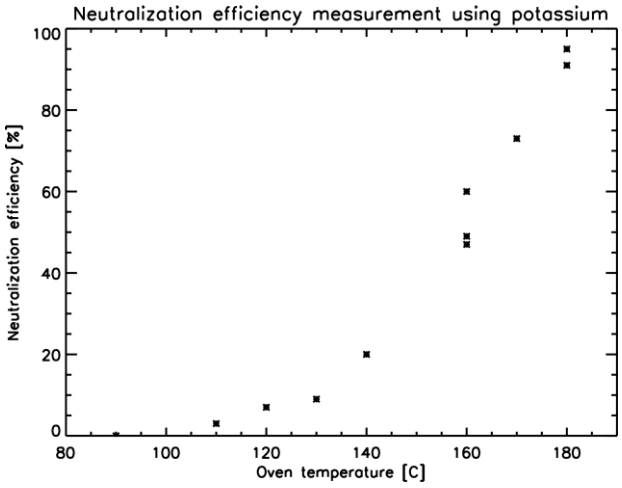

Fig. 3. Neutralization efficiency of a 40keV energy sodium beam using potassium vapour.

At above 180 °C degrees the neutralization efficiency reached almost 100% which shows very good agreement with the calculated vapour pressure of potassium in Section 2.3.

4. Integration of the system

The injector is placed between the two NBI systems at section 5. The entrance port of the neutrali beam is AEA21 while the observation system located in the same cross section using port AEB20, see Figure 4.

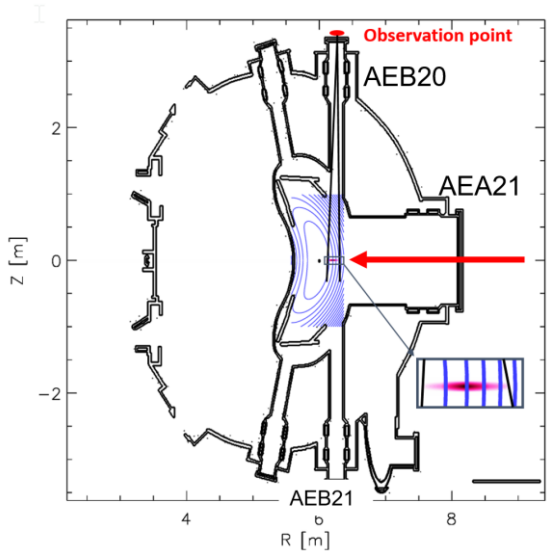

Fig. 4. Integration of the alkali BES at W7-X.

4.1 Observation system

The beam emission is observed from the poloidal direction with a high-etendue ($\Omega/4\pi = 3x10^{-4}$) 40 channel optical system, where each channel collects light from a 4 x 0.5 cm (toroidal x radial) area of the beam to an avalanche photodiode system (APDCAM, Fusion Instruments Ltd.). To achieve sufficiently high photon flux the optics contains relatively big lenses (up to 244 mm diameter). The majority of the light is detected by the APDCAM system with 2MHz sampling rate while about 2.5% of the light is measured by a CMOS camera (PhotonFocus, 1280 x 1024) for overview and spatial calibration purposes. Despite the 500 kHz analogue bandwidth the APD system has a peak signal-to-noise ratio up to 50, enabling the study of fast transients and turbulence.

4.2 Interference filter temperature control

Special attention was paid to filtering the beam light emission. The Sodium light emission occurs at two intensive spectral lines separated by 0.5 nm around 589 nm. A Carbon II line is located exactly on one of the Sodium lines, therefore cutting the Carbon emission was possible by measuring only one of the emission lines. To allow flexibility of the setup a filter was ordered which can be temperature tuned so as at room temperature it transmits both Sodium lines, while at about 60°C the Carbon line and one of the Sodium lines is strongly cut.

Designing a precise temperature control unit (to reach uniform temperature on the whole surface) for the 230 mm diameter filter was a special challenge. Its solution can be seen on Figure 5. Due to the big diameter the filter is composed by four pieces (by Andover Corp.) that are glued together onto an aluminum fixing frame plate. Heat is produced by 8 resistors (47 Ohm, 10 W each) which are mounted on heat sinks. The heat is distributed by fans which circulate hot air between the filter and double windows (with antireflexion coating).

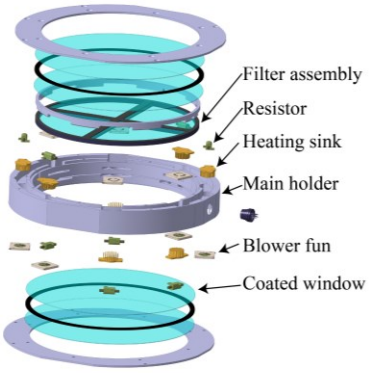

Fig. 5. Temperature control of the interference filter.

5. First measurement results

Although launch of the alkali BES system was planned for OP1.2b it was possible to start the measurements during OP1.2a, first with sodium vapour neutralization. For OP1.2b it was changed to potassium. An example density reconstruction based on the CMOS image is shown at Figure 6. The electron density is reconstructed using the Bayesian method [12].

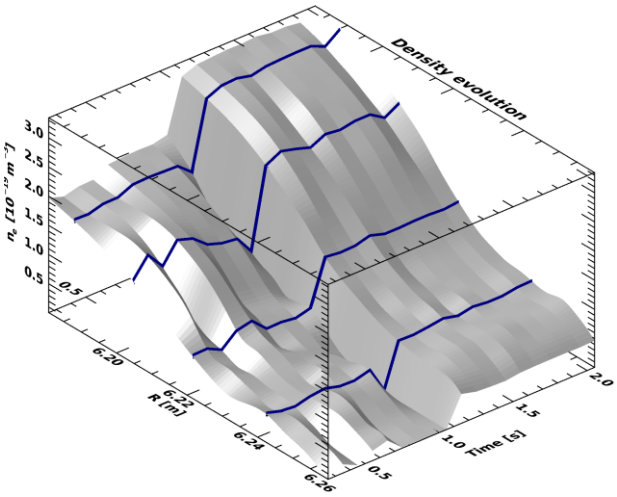

Fig. 6. Reconstructed density profile based on the CMOS camera (shotnumber: 20180821.012).

Results of the fast measurement system is shown on Figure 7 and 8. On Fig. 7. density jump can be seen at the island region in the 100 µs time scale while on Fig. 8 a density peak can be seen in the island region of W7-X.

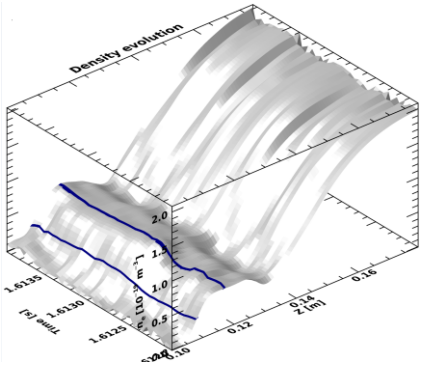

Fig. 7. Fast density reconstruction by the APDCAM detector.

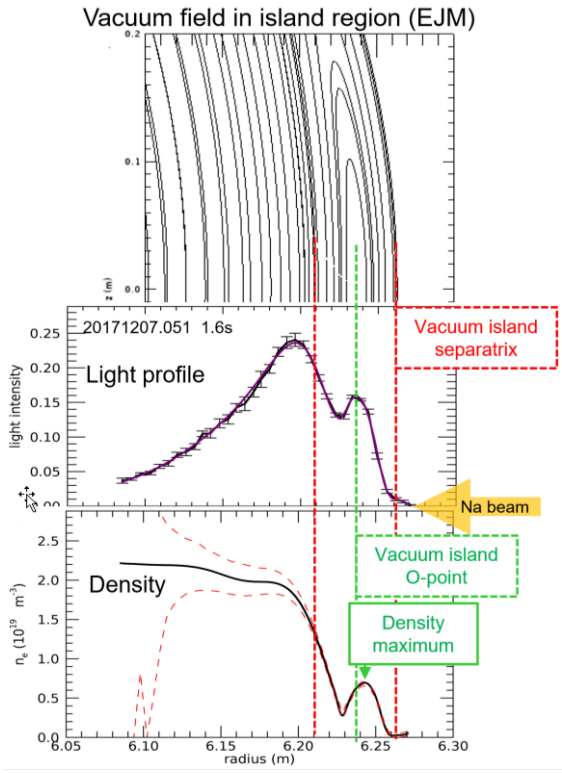

Fig. 8. Density reconstruction by the APDCAM detector.

Acknowledgments

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