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Diagnosing the edge plasma in Wendelstein 7-X with an alkali atom beam

One key aim of the Wendelstein 7-X (W7-X) experiment is to study plasma exhaust using an island divertor. In the standard $\iota = 1$ configuration of this experiment, 5 independent islands surround the confined plasma. Each of these islands connects to itself after one turn in the toroidal direction. The confined plasma is bounded by a separatrix— the dividing surface between magnetic flux surfaces in the core plasma, and the islands. The islands are intersected by divertor plates where the plasma is neutralized and the resulting gas can be pumped out. Due to the pumping gap between the two divertor plates, not all magnetic surfaces are cut and there is a region around the O-point where field lines are connected neither to the divertor plates nor to the core plasma. The situation is additionally complicated by finite plasma pressure and manufacturing tolerances that distort the ideal configuration; therefore, it is essential to have a good measurement of the plasma parameters in this complicated 3D environment. Such a measurement is provided by reciprocating probes which can briefly move various probe heads into the island region and diagnose it in detail. However, the probes cannot enter too deeply because they are damaged by the plasma or the plasma is strongly perturbed by them. An alternative technique is the thermal helium-beam diagnostic, which is less perturbing but can also reach only the outer part of this region. Deeper in the plasma, reflectometry is the key diagnostic, but it has difficulties when the density profile becomes too complex, especially when local maxima appear.

To cover the important transition region from the confined edge plasma to the island region, designers of W7-X foresaw a lithium-beam diagnostic, which is used on many tokamak experiments and was also successful on the predecessor stellarator Wendelstein 7-AS [1,2]. As shown in Fig. 1, such a diagnostic extracts a few-milliampere current of lithium ions from a heated ceramic source and accelerates the ions to energies of a few tens of kilovolts. The few-cm-wide beam passes through a cell filled with sodium vapor where lithium ions pick up an electron, and thus a high-energy neutral lithium beam is injected into the plasma. By using some deflection plates before the neutralizer, the beam can be steered to different directions, or with high enough deflection voltage, even prevented from reaching the plasma.

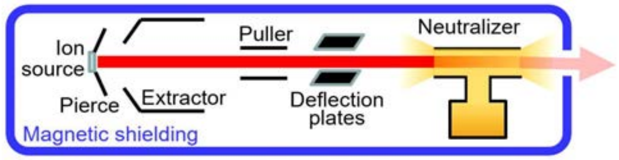

Fig. 1. Schematic of an alkali beam injector.

The neutral beam can freely propagate through the magnetic field of the fusion device. Beam atoms get excited by the plasma particles and emit light at a characteristic wavelength. The light intensity is proportional to the excitation rate coefficient and the plasma density. As the rate coefficient has only a slight dependence on temperature, the emitted light is nearly proportional to the plasma density. However, there is a catch! After excitation the atoms reside in the excited state for some time before undergoing a spontaneous transition with light emission. During this time the atoms travel some distance which, due to the high beam energy, is 2–3 cm in the case of lithium. This means small and steep density structures are smeared along the beam injection path. Deeper in the plasma, the beam atoms are also ionized and leave the beam on a Larmor trajec-

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An alkali beam diagnostic with a 50-keV sodium beam measures the density profile and turbulence in the edge and island region of Wendelstein 7-X. Efficient optics and detectors enable time resolution in the 10 microsecond range. Outward propagating blobs (filaments) are abundant, and their propagation is affected by the island configuration. 1

tory. The result is that the beam light decays and no measurement is possible deep in the plasma. However, beam ionization also helps because the beam light decay sets the absolute magnitude of the plasma density. Using an appropriate model of the excitation and ionization processes the plasma density distribution can be determined from the relatively calibrated beam light distribution. This method also has high time resolution since the beam particles travel with about 10^6 m/s velocity. They cover a typical plasma edge in much less than a microsecond, creating a snapshot of the plasma density even if plasma turbulence, which is at frequencies typically below 1 MHz is considered. The limitation is the collected light intensity and background light, which call for large optical systems and good detectors.

For W7-X, a port was dedicated to the lithium beam diagnostic in the equatorial plane in the so-called bean shape cross-section, through the center of the edge island chain of the standard configuration. For the light observation, a large-diameter port looking at the edge plasma was allocated. A Eurofusion grant for this diagnostic was given to the Wigner Research Center for Physics in Budapest, as this group has extensive experience in this field [3].

Due to the expected steep and complicated density profile, concerns were raised as to whether the Li-beam diagnostic can provide the necessary spatial resolution. Fortunately, the applicability of sodium as beam material was demonstrated earlier by IPP researchers on ASDEX Upgrade [4], and the necessary atomic physics data were also prepared by Technical University Wien. Therefore, a sodium ion source was built and the alkali beam injector [5] installed on W7-X in the last weeks of the 2017 OP 1.2a campaign.

After considering various options for the optical setup it was decided to avoid any complicated endoscope design and build a 200-mm-diameter optical system on top of the port. An endoscope with shutter and cooled window would have limited the first lens size so that the collected light intensity would have been the same as on top of the port. In the chosen solution there is no need to protect the window even in the steady-state phase of W7-X in OP 2. Following earlier experience on tokamaks, a few percent of the light was coupled to a CMOS camera in order to get a direct observation of the beam shape in the plasma. Most of the light is detected by avalanche photodiode detectors [6] (APDs) with 500-kHz bandwidth amplifiers, so that plasma turbulence can be measured. In order to keep good radial resolution and to maximize light intensity, the light collection area of one APD channel was set to 0.5 × 4 cm (radial × toroidal). This could not be coupled effectively to the circular detectors with lenses; therefore a fiber bundle array was built with 0.6 × 5 mm input and 2-mm-diameter circular output face for each of the 40 detector channels. Outside the islands low light level was expected; therefore 14 MPPC detectors were also installed, providing a considerably better signal-to-noise ratio—below 10^9 photon/s. The whole detector system is built into a standard APD-CAM-10G framework from Fusion Instruments used on many fusion devices. As this device transmits data on a 10-Gbit digital data link directly to PC memory, megahertz rate sampling is possible even during the planned 20- to 30-minute long discharges in OP 2.

A special problem was filtering of the beam light in order to remove plasma radiation. At the expected high plasma densities, Bremsstrahlung and impurity line radiation was expected to be significant. Therefore a narrow filter was needed. Interference filters have sharp cutoff in wavelength when the passing light is nearly parallel, which can be achieved only with a large-diameter filter, in case of the W7-X alkali beam, 240 mm. Such a large filter could not be manufactured; therefore it was designed using 4 quadrants [Fig. 2(c)]. In contrast to lithium, sodium atoms radiate at two close wavelengths separated by 0.6 nm. Therefore a 1-nm-bandwidth filter was manufactured in four quadrants by Andover Corp. and assembled in a frame. To measure the remaining background, a fast HV switch was built for the deflection plates, producing the ability to switch the beam on-off at several 100 kHz; thus even a fast modulated background can be subtracted [3]

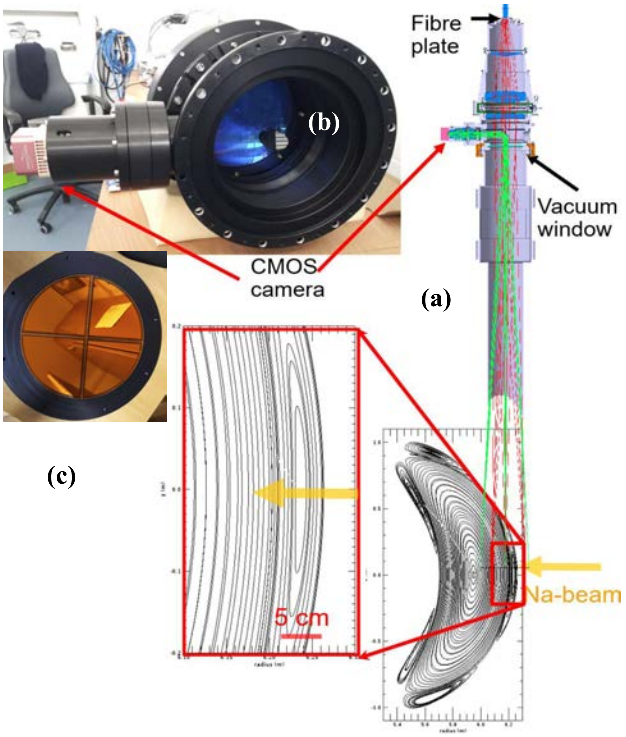

Fig. 2. (a) Geometry of the alkali beam diagnostic; photos of the (b) optics and (c) the filter.

and density profiles can be determined with about 20-microsecond time resolution. Indeed, first measurements in 2017 revealed excellent signal quality. However, extremely high and modulated background was found in a narrow radial region on the outboard side of the island. This background was identified as the radiation of the thermal sodium atoms escaping from the neutralizer cell, excited and ionized at the far plasma edge. The strong modulation is due to blobs (filaments) arriving at the plasma edge, similar to tokamak observations. The fast beam modulation proved to be essential here; the density profile could be calculated even when the background light was nearly 100 times the local beam light! For the 2018 campaign the neutralizer was switched to potassium which turned out to be even more beneficial than sodium as it requires lower temperatures. This change completely removed the strong background and enabled measurement to the far scrape-off layer. Although this extremely complex diagnostic was not available due to technical problems in some part of the OP 1.2b campaign it provided excellent data in about half of the operation.

Although data analysis has just started, some interesting observations can already be made. Perturbations similar to blobs (filaments) in tokamaks are always observed with the alkali beam diagnostic in the edge of W7-X. Correlation with the video camera system shows that these perturbations have a toroidal length of at least several meters and a quasi-periodic structure in the poloidal direction. They propagate radially outward at a few hundred m/s and propagation is clearly affected by the presence of the island, as they appear to go around the O-point. Strong periodic modulation of the edge plasma with a few 100 Hz is often observed in W7-X [7]. This is obvious in the alkali beam data as well. Enlarging one such perturbation event, it also becomes clear that the filament activity is also modulated [Fig. 3(a) and (b)]. As expected in the standard configuration, the density profile is strongly affected by the island.

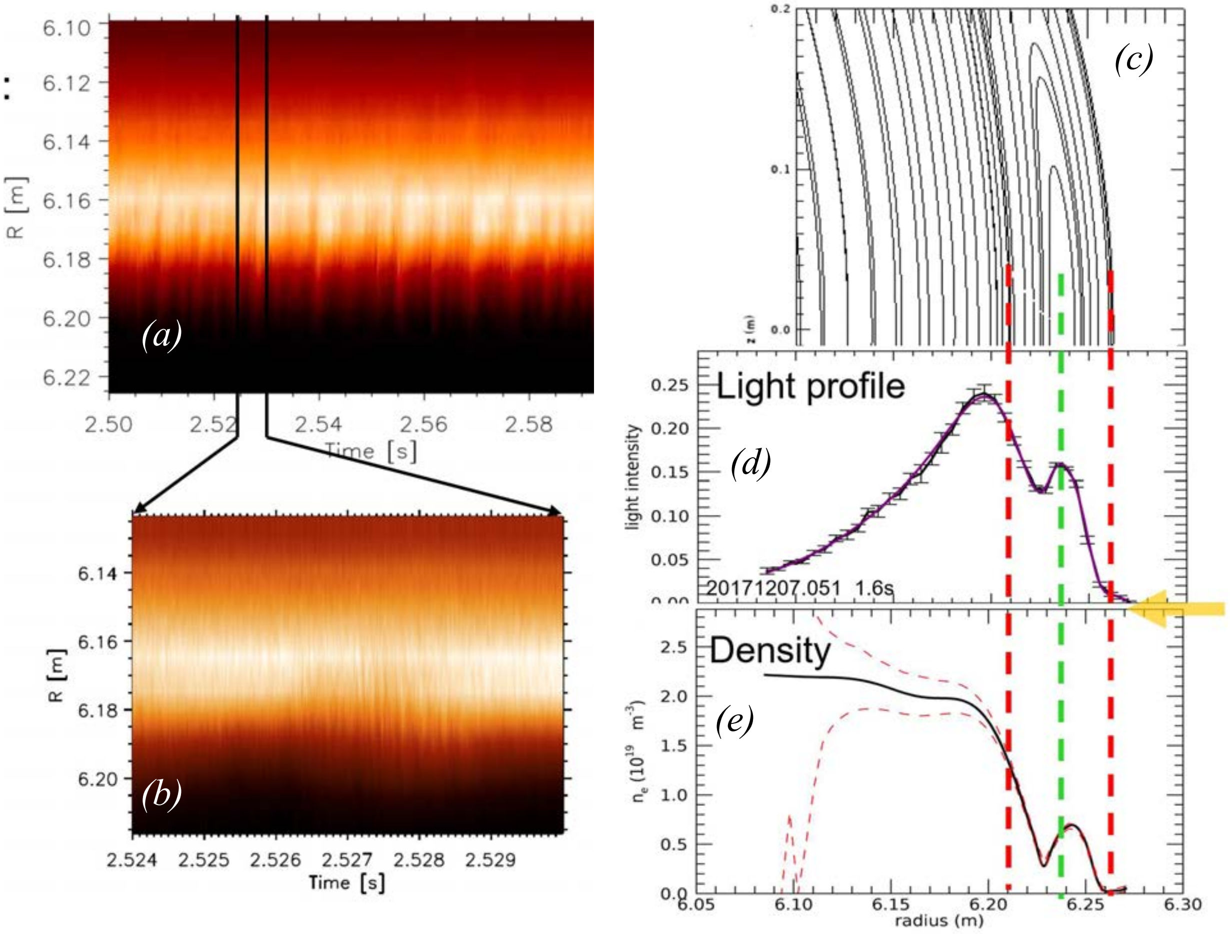

Fig. 3. (a) Beam light intensity as a function of time and major radius in a high-iota discharge with strong edge oscillations and (b) detail of one perturbation. (c) Magnetic flux surfaces in the edge and island region of the standard configuration. (d) Measured beam light and (e) calculated density profile (black curve) in a low-density discharge. The red dashed lines are error estimates.

In some cases it even shows a peak close to the O-point [Fig. (c)–(e)].

The alkali beam diagnostic is ready for long-pulse operation in OP.2. A 100-s-long measurement has already been demonstrated. Some spectral measurements were also done in 2018; they are being analyzed in order to explore any possibilities arising from spectrally resolved measurements, like charge-exchange spectroscopy or magnetic field measurement from Zeeman splitting of sodium lines.

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