Requirements for an Imaging Heavy Ion Beam Probe at ASDEX Upgrade

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Heavy ion beam probes (HIBPs) [1] feature the possibility to measure the electrostatic potential, electron density and magnetic field fluctuations in the confinement region of magnetically confined high-temperature plasmas. HIBPs are the only diagnostics to directly measure the particle transport $\Gamma \propto |\tilde{\phi}||\tilde{n}| \sin \alpha_{n\phi}$ of modes due to its unique property of measuring the cross-phase $\alpha_{n\phi}$ between density and potential fluctuations, $\tilde{n}$ and $\tilde{\phi}$, respectively, at the same volume element with high time resolution [2].

In order to avoid the difficult integration of a classical HIBP setup with an energy analyzer outside the main vacuum vessel into the developed experimental setup of the tokamak ASDEX Upgrade (AUG), an alternative approach of a HIBP with a much more compact detector solution and a neutral heavy atom beam as primary beam is envisaged. The technological feasibility of this new approach has been investigated numerically and in laboratory tests as described in the following.

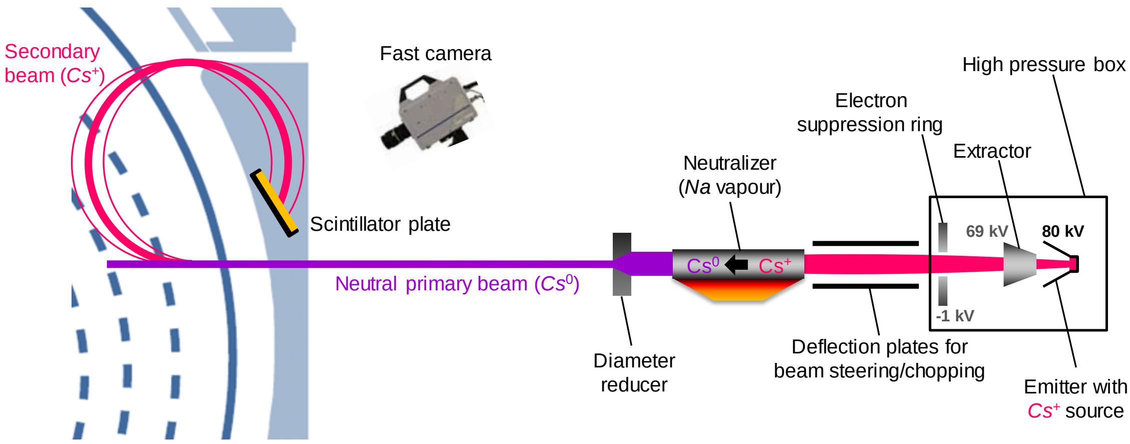

Figure 1: *Setup of the imaging heavy ion beam probe (i-HIBP). A neutral primary beam is injected into the plasma. The secondary beams generated by ionizing collisions are collected with a scintillator. The analysis of the camera images of the scintillator provides information about the plasma density, electrostatic potential and poloidal magnetic field at the point of ionization in the plasma.*

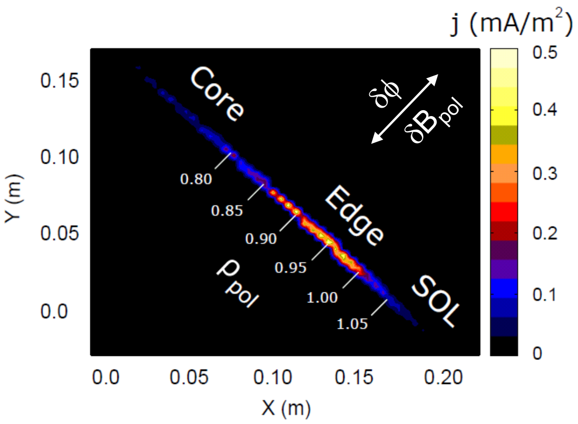

Figure 2: *Simulated strike line intensity of impinging ions on the scintillator. The expected intensities indicate that i-HIBP measurements in a region around the LCFS ($\rho_{pol} = 1$) are possible [5].*

For this setup, a neutral heavy atom beam - typically cesium or rubidium at 80 keV - is injected into the plasma by means of an alkali beam injector type, which is routinely used for diagnostic beams at many tokamaks and stellarators for beam emission spectroscopy applications [3]. As schematically shown in Fig. 1, this type of injector extracts beams of alkali ions in the order of a few mA by thermionic extraction from a β-eucryptite ion source. After acceleration to the desired energy, the ion beam is neutralized by means of a sodium vapor cell with an efficiency of up to 90 %. In order to achieve an appropriate spatial resolution (see below), the diameter of the neutral beam has to be reduced from about 2 cm to the sub-millimeter range by means of an aperture plate. The thin neutral beam, the primary beam, propagates then further to the plasma where it is ionized by collisions with plasma particles along the whole primary beam axis. This leads to a fan of secondary ion beams, which is deflected by the magnetic field B of the tokamak and propagates according to the Larmor radius $\rho_L = |\frac{mv_\perp}{qB}|$ of the heavy ions of mass m, charge q, and with velocity $v_\perp$ far into the limiter shadow, where it can be detected with a scintillator plate. Each impinging heavy ion initiates the emission of about 100 photons from the scintillator which are recorded with a high speed camera. The use of scintillators in combination with high speed cameras is a well established technique used in fast ion loss detectors for fast ion studies at several fusion devices in the world [4]. Since this technique enables the detection of the whole intensity pattern produced by the fan of the secondary beam in 2D on the scintillator, we call this measurement principle imaging heavy ion beam probe (i-HIBP)[5]. As it is described in the following, the i-HIBP can provide information about the electron density n_e, poloidal magnetic field B_p, and about the electrostatic potential ϕ_p at the edge of the plasma.

The intensity pattern on the scintillator as seen by the camera is a tilted line as depicted in Fig. 2. The intensity along this strike line shows a maximum for a secondary beam starting at a normalized poloidal flux coordinate of $\rho_{pol} = 0.95$, i.e. slightly inside the last closed flux surface (LCFS). Ionization and attenuation processes of the primary and secondary beam determine the expected ion flux on the scintillator allowing for probing the plasma in the radial range of $\rho_{pol} = 0.85$ to $\rho_{pol} = 1.05$. Taking into account the collisional processes involved in the

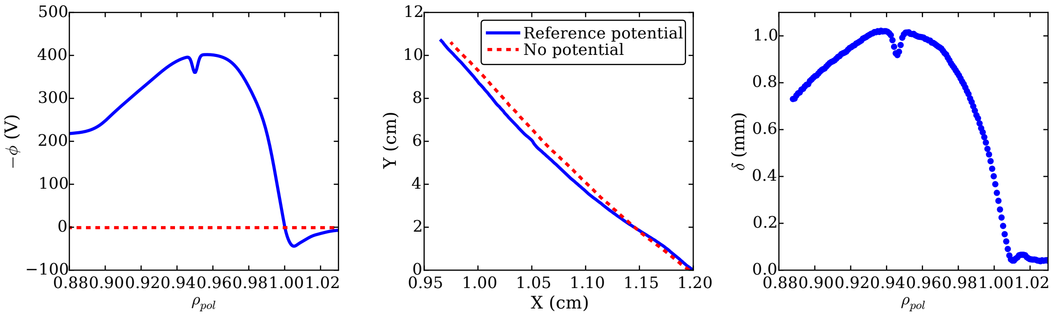

Figure 3: *Simulation of the effect of an electrostatic plasma potential: If a potential in the plasma is present (left), the strike lines on the scintillator are perturbed (middle). The difference between the strike lines of the perturbed and unperturbed case (right) reveal the shape of the potential profile [5].*

plasma-beam interaction, a density profile can be estimated from the intensity pattern of the strike line by means of a forward model approach similar as used for lithium beam emission spectroscopy [6]. This strike line is not just a vertical line as it would be expected if solely effected by the toroidal magnetic field B_t, but it is in addition tilted into toroidal direction by several centimeters due to the influence of the poloidal magnetic field component B_p. Due to this deflection, the poloidal magnetic field component B_p and related toroidal currents j_{pol} can be estimated from the strike line pattern.

The third quantity accessible with the i-HIBP is the electrostatic potential ϕ_p in the confinement region of the plasma. Since an electrostatic potential at the point of ionization will change the energy and, thus, the velocity $v_\perp$ of the secondary beam, the Larmor radius is changed leading to a local displacement of the strike line. This is demonstrated in Fig. 3. By means of a numerical program solving the equation of motion for ions in a given magnetic and electric field, the expected particle trajectories for a typical AUG H-mode plasma (discharge #29302) are shown. Two cases are compared: a reference case with a typical potential profile including perturbation at $\rho_{pol} \approx 0.95$ as depicted on the left (solid line) and a case of a zero potential (dashed line). The presence of a finite potential leads to a slight displacement δ of the strike line compared to the case without an electrostatic potential (Fig. 3, middle). The displacement curve (Fig. 3, right), calculated as the difference of the two strike lines and mapped to the points of ionization in the plasma, resembles the shape of the potential profile including tiny local features at $\rho_{pol} \approx 0.95$ and clearly shows, that the local features in the potential profile can be resolved. However, the magnitude of the displacement is in the sub-millimeter range requiring a small beam diameter d in order to be able to resolve the tiny deflections on the scintillator.

Therefore, laboratory tests have been undertaken in order to evaluate the lower limit of the beam diameter d achievable with an aperture. As sketched in Fig. 4 a neutral cesium beam

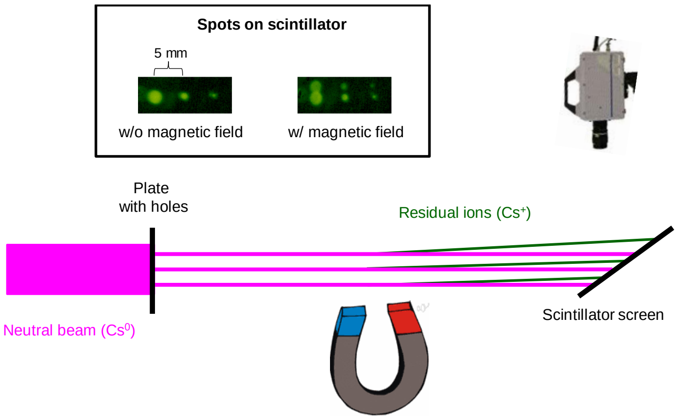

Figure 4: *Laboratory tests have shown that the beam diameter can be collimated down to 0.25 mm as necessary for high resolution of the electrostatic potential measurement. By means of a magnet, the neutral and charged parts of the beam can be separated indicating a neutralization efficiency* $> 60\%$.

was shot onto a plate with holes of different size ($d = 1.0, 0.5, 0.25$ mm) and the resulting beams with reduced diameter was detected on the scintillator with a camera. The measurements clearly show that there is no lower limit of the beam diameter since even the smallest diameter of $d = 0.25$ mm led to a well defined beam. The divergence observed in the laboratory experiments indicated that a beam with a 5 mm width on the scintillator is realistic to be achieved for a setup installed in AUG. By means of a magnetic field applied to the beamlets behind the aperture plate, the neutralization efficiency of the sodium vapor cell could be estimated: while the neutralized cesium beam component follows a straight line, the residual ions are deflected by the magnetic field. Since the intensity of the residual ion spot on the scintillator was found to be lower then the neutral beam spot, a neutralization efficiency of more than 60% was achieved.

Thus, the laboratory tests confirmed that the requirements of a small beam diameter, acceptable divergence and a sufficient neutralization efficiency for the i-HIBP can be achieved. Due to these results together with the results of the numerical evaluation, we are confident that the i-HIBP concept as it is under development at AUG will provide valuable measurements of n_e, B_p, and ϕ_p for edge physics investigations.

References

[1] T. Crowley et al., IEEE Transactions on Plasma Science **22**, 291 (1994)
[2] A.V. Melnikov et al., Nucl. Fusion **57**, 072004 (2017)
[3] G. Anda et al., Rev. Sci. Instrum. **89**, 013503 (2018)
[4] M. Garcia-Munoz et al., Rev. Sci. Instrum. **80**, 053503 (2009)
[5] J. Galdon-Quiroga et al., Journal of Instrumentation **12**, C08023 (2017)
[6] R. Fischer et al., Plasma Physics and Contr. Fus. **50**, 085009 (2008)

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