Overview Of The Beam Physics Investigation At The ELISE Test Facility

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Abstract. Strict requirements are foreseen for the Neutral Beam Injection system (NBI) for ITER: a high extracted current density has to be achieved (33 mA/cm^2 for H$^-$ and 28.6 mA/cm^2 for D$^-$) together with very small beam core divergence (< 7 mrad) and a beam uniformity of better than 90%, for a large beam extracted from 1280 apertures. The ion source filling pressure has been set to < 0.3 Pa, in order to keep the stripping losses in the accelerator to a tolerable level, and the ratio of co-extracted electrons to ions should be less than one. In the roadmap towards the development and design of the ITER NBI system, the ELISE test facility is an intermediate step, having half the size of the final ITER NBI source. As well as important scientific and engineering results, ELISE provides highly valuable experience in the operation and performance of a large RF-driven negative hydrogen ion source. At the ELISE test facility it is possible to have an insight into the physics of the large beam by means of several diagnostics. The Beam Emission Spectroscopy (BES) diagnostic provides information on the beam uniformity as well as the divergence, along a vertical and a horizontal profile. Analysis of infra-red (IR) imaging of the beam striking a calorimeter provides a 2D map of the beam power density. Three main topics will be here reported: 1) Studies of the vertical beam homogeneity often show a vertical (top/bottom) difference in terms of beam intensity and, as a consequence, in terms of divergence (i.e. different beam optics for different extracted beam currents). 2) The investigation of the possibility to measure the broad beam component (this being a small fraction of the beam with a significantly higher divergence than the majority) by means of the BES diagnostic, leads to different methods for a proper fit of the H_α main Doppler peak. Different fit methods correspond to different hypotheses on the origins of the broad component itself. 3) The investigation of the stripping losses inside the extraction system aims to provide a robust method for the BES data analysis, in combination with modeling of the gas density profile along the beamline, in order to give a proper estimation of the stripping losses to be compared with predictions as extrapolated from calculation for ITER (< 10% up to the extraction grid).

THE ELISE TEST FACILITY AND BEAM DIAGNOSTICS

The RF-driven ion source has been chosen as reference for the ITER Neutral Beam Injection (NBI) system [1,2]. The physical requirements for the ITER negative ion source have been achieved for the small prototype source (1/8 of the ITER NBI source), but not simultaneously [1]. The target of the ELISE test facility [3,4] is to demonstrate the feasibility to simultaneously achieve the required ITER NBI source parameters for a large extraction area (half the ITER size, about 0.9 m × 1 m: 640 apertures gathered in 8 beamlet groups as displayed in Fig. 1(a)). At ELISE, H_2/D_2 plasmas can be run in continuous mode, however the 60 kV beam extraction is limited to 10 s each 150 s due to technical limitations in the HV power supply.

In order to investigate the properties of the large beam, several beam diagnostics have been implemented in ELISE. Measurement of the electrical currents in the grid system and beamline components provides information on the total extracted negative ion current. Information can also be obtained on the charged particles (assumed to be only co-extracted electrons) impinging on the second grid (extraction grid, EG), the charged particles hitting the third grid (grounded grid, GG) and the first components of the beamline downstream from the GG. In addition, currents on EG and on GG are independently measured in the two grid segments (*top* and *bottom*), providing some spatial resolution. As well as electrical current measurements, three main beam diagnostics have been implemented along the beamline: a tungsten (W) grid calorimeter located 1.8 m downstream from the GG, a Beam Emission Spectroscopy diagnostic (BES) 2.57 m from the GG, and a diagnostic calorimeter 3.5 m from the GG [5]. The W-grid calorimeter is used for beam monitoring, providing qualitative images of the shape of the beam striking the wires. The BES diagnostic [5] collects the H_α light from the interaction of the fast beam particles with the background gas, providing vertical and horizontal profiles (using 16 × 4 lines of sight) of the beam divergence and estimation of the stripping losses, as obtained from the analysis of Doppler shifted H_α spectra. In particular, the vertical profile of the Doppler peak intensity (which is proportional to the negative ion beam current density for an assumed flat background gas density in the tank) can be fitted to a pair of Gaussian profiles, thus providing information (intensity and beam broadening) on the two halves of the accelerated beam (*top* and *bottom*). The diagnostic calorimeter, consisting of 900 actively-cooled copper blocks (total area of 1.2 m × 1.2 m), is equipped with 48 thermocouples for beam profile measurement, which are used in combination with infra-red (IR) measurements to provide a 2D map of the beam power impinging on the calorimeter, with a spatial resolution of 4 cm. As the calorimeter is actively cooled, water calorimetry gives the accelerated beam current impinging on it. An example of a deuterium beam at an extracted negative ion current of 11.5 mA/cm^2 is displayed in Fig. 1(b-d). The contour plot of the 2D map of the beam power density deposited on the calorimeter is shown in panel (b): from the image, a *top* and a *bottom* part of the beam, associated with the top and bottom grid segments, can be easily identified. The corresponding vertical beam profiles from two diagnostics is displayed in panel (c): the vertical profile of the beam power deposited onto the calorimeter (red circles) is in very good agreement with the vertical beam profile determined by the intensity of the Doppler peaks in the BES spectra (green squares), both detecting a slightly narrower but more intense beam in the top. The corresponding vertical profile of the beam divergence angle, as measured by the BES, is displayed in Fig. 1(d), showing lower values of beam divergences in the top beam segment, as would be expected given their higher intensities as in (c). In general, for divergences smaller than 3 deg., the two accelerated beam segments can be easily identified, showing usually narrower and more intense beam intensity with smaller local divergences on the top. However, the corresponding total top and bottom beam currents estimated from IR fitting analysis (beam modelled as a sum of Gaussian profiles, one for each of the beamlet groups) are very similar, suggesting that a different beam current density is extracted from the two grid halves.

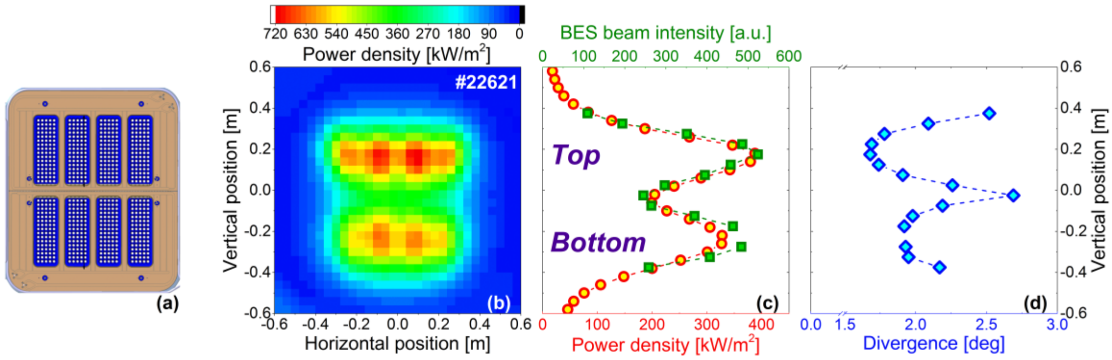

FIGURE 1. (a) Scheme of the ELISE grid system: 640 apertures gathered in 4 beamlet groups for each grid segment. (b) Contour plot of the beam power impinging onto the calorimeter for the deuterium pulse #22621 (0.3 Pa, U_{ex}=6kV, U_{acc}=30kV), as detected by an IR camera and (c) the corresponding vertical profile of the beam intensity from IR data (red circles, horizontal averaged values) and the BES diagnostic (green squares). (d) Corresponding vertical profile of the beam divergence from BES.

BEAM PHYSICS AT ELISE AND FUTURE ACTIVITIES

At ELISE, the more recent activity on the beam properties characterization is focused on three main topics: 1) the homogeneity of the beam intensity (*top*/*bottom*), which is strictly correlated to the beam divergence and its vertical profile; 2) the investigation of the presence of a broad component in the beam, which can be detected by BES in correlation with the electrical currents measured in the grid system; 3) a proper estimation of the stripping losses along the beamline, especially in the gap between the first two grids.

- **Beam vertical homogeneity.** Information from all available beam diagnostics has been combined for the first time to investigate the beam homogeneity in ELISE. As displayed in Fig.1, the high spatial resolution of the beam diagnostics allows for a reliable estimation of the accelerated beam currents independently for the top and bottom sections. It is possible to therefore calculate separate top and bottom values for the local normalized perveance (perveance defined as $\Pi = I / U^{3/2}$, being I the extracted current and U the extracted voltage; it is normalized to the maximum perveance Π_0 as from the Child-Langmuir law [7]): Fig. 2 shows the divergence behavior as a function of the local normalized perveance. The optics of the two beam segments shows different trends, suggesting different extracted current densities. The relation between beam current and the beam optics (through the perveance correlation) is given by the extracted current, not the accelerated one. Unfortunately, the local extracted currents cannot be directly retrieved from the measurements of the electrical currents on the beamline components, due to stripping (inside the grids) and neutralization processes. A method to retrieve the top/bottom extracted currents in a large source with grid segments is still under investigation. Once the local extracted currents can be retrieved, these measurements will be combined with the properties of the plasma in front of the extraction system and the Cesium distribution in the source, which in principle could account for different extracted current densities, meniscus shapes [6], and beam optics. How then to set the source operational parameters in order to achieve a vertically homogeneous beam (in both current and divergence) will be the further step to investigate.

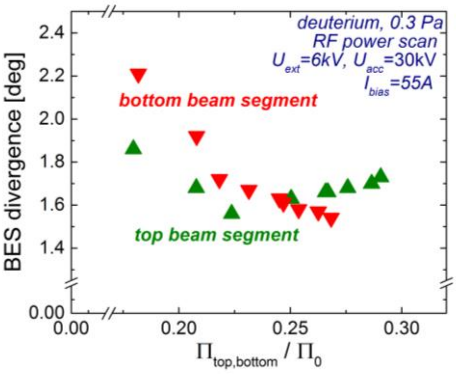

FIGURE 2. Divergence correlation with the local normalized perveance for the top (green) and bottom (red) beam segment.

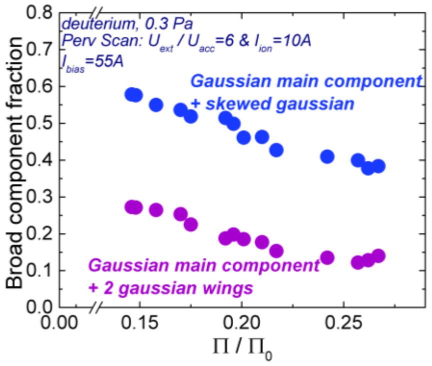

FIGURE 3. Broad component fraction for the two different Doppler fit methods as a function of the normalized perveance (perveance scan).

- **Broad component.** The Doppler H_α peaks in the BES spectra have tails larger than expected for a pure Gaussian peak, which can be interpreted as either a population of particles having very large divergences (large skewed Gaussian peak above the main narrower Gaussian component [8]), or (as more recently introduced) as particles exiting the grid system with “special” angles (Gaussian peak for the main component plus two Gaussian “wings” for the tails). As there are currently two differing physical interpretations, each with their own distinct fitting method, two different sets of results are possible for the same experimental data. For example, as displayed in Fig. 3, the fraction of the beam found in the broad component is plotted against perveance for the two interpretations. The method described in Ref. [8] suggests that over half of the beam is contained within the broad component, whereas the new method suggests a fraction of 10 – 20 %. Discussions and decisions on the most appropriate of these methods are still ongoing. The interpretation and the reasoning are of high relevance for the ITER beam, since there the broad component (halo) should not exceed the 15% of the beam itself.
- **Stripping losses.** ITER foresees 30% of stripping losses in total; about 10% of which is in the gap between the first two grids. At ELISE, the experimental estimation of stripping losses in the first gap from BES results to be around 4-5% in deuterium at 0.3 Pa. However, this does not take into account the stripped particles that do not exit the grid system. For a proper estimation, modeling activity is needed in order to assess the amount of stripped particles lost inside the grid system. This new activity of modeling is taking place in the framework of the collaboration between IPP and the NBTF [9] team.

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