Towards the ITER NBI: impact of the plasma parameters on the performances of a large ITER-like beam

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Introduction

ITER neutral beam injection (NBI) beamlines are based on RF source where negative ions are created, mainly by conversion of neutrals and positive ions on a low work function surface, and then extracted and accelerated by an multi-grid multi-aperture electrostatic extraction and acceleration system. ITER requirements[1] foresee an accelerated current density of $200\,\mathrm{A/m^2}$ in deuterium ($240\,\mathrm{A/m^2}$ in hydrogen) for a pulse length of 3600 s (1000 s in H). The extracted negative ion current density is calculated from the accelerated one by considering 30% stripping losses, i.e. particle neutralization before full acceleration, in the grid system thus being for ITER $286\,\mathrm{A/m^2}$ in D ($329\,\mathrm{A/m^2}$ in H). The electron-to-ion ratio is foreseen to be lower than one to reduce the power load on beamline components and the source filling pressure must be ≤ 0.3 Pa to minimize the stripping losses. The beam divergence must be lower than 7 mrad and the beamlet-beamlet power uniformity better than 90%.

The ELISE test facility[2] with half the size ($1\,\mathrm{m} \times 1\,\mathrm{m}$ surface and an extraction area of $0.1\,\mathrm{m^2}$) of the ITER NBI source and an ITER-like plasma facing grid, is part of the R&D roadmap towards the ITER NBI. The ELISE source is equipped with an extraction and acceleration system made of three grids: the plasma facing grid (PG) is ITER-like with 640 chamfered apertures arranged in groups (2 rows of 4 groups, each group has 16×5 apertures) called beamlet groups; the extraction grid (EG), where the extraction potential (up to 10.5 kV) is applied, embeds deflection magnets that dump the co-extracted electrons onto the EG; the grounded grid (GG) at ground potential. In order to reduce the electron density and the electron temperature close to the PG, a magnetic filter field of the order of few mT is generated by a current (up to 4.5 kA) vertically flowing along the PG. Additional external magnets are installed thus affecting the magnetic field topology and strengthening the field. To further decrease the co-extracted electrons, the PG is positively biased with respect to the source walls. The RF generator can run in steady state while extraction is possible for 10 s every 150 s. The beam produced at ELISE is ITER relevant in size ($1\,m \times 1\,m$) and accelerated current. The beam optics at high source performance is limited by the total HV available (total HV up to 60 kV). The beam is stopped onto a diagnostic calorimeter placed at 3.5 m distance from the GG. Several diagnostic systems are installed at ELISE as well as electrical measurements on source, grid and beamline components. The total extracted ion current is electrically measured downstream of the EG while the electron current is measured on the EG. Cavity ring-down spectroscopy (CRDS)[3] at the top and bottom side of the source allows for line-of-sight integrated, absolute measurement of D^- (H^-) density. An RF-compensated Langmuir probe gives local measurement of the positive ion density, plasma potential and, indirectly, of the electron density.

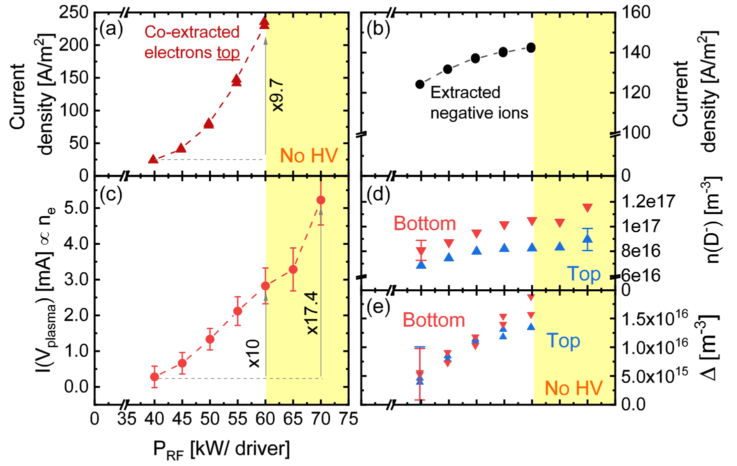

Figure 1: *Several signals as a function of the RF power, the shaded area indicates the pulses performed without extraction. (a) Co-extracted electron current density measured on the top grid half of the EG. (b) Extracted negative ion current density. (c) Current at the plasma potential from the I-V curve measured by the Langmuir probe. (d) Negative ion density measured by CRDS during the plasma phase. (e) Difference between plasma phase and extraction phase for the negative ion density.*

The beam is characterized in terms of accelerated current, beam size and beam divergence. Beam emission spectroscopy (BES)[4] diagnostics is applied to retrieve the beam divergence and the local beam intensity. The 16 horizontal lines of sight of the BES diagnostics intercept the beam at approximately 2.7 m downstream of the GG. IR calorimetry technique[4] applied on the surface of the diagnostic calorimeter gives the 2D map of the power density deposited onto the diagnostic calorimeter. The vertical and horizontal beamlet group width as well as the accelerated current for the top and bottom beam segments are determined by a 2D fitting routine. BES diagnostics and IR calorimetry determines properties of the large beam which do not necessary reflect the properties of a single beamlet.

In this work, plasma and beam properties are discussed in relation to the RF power increase performed; one of the main challenges of deuterium operation is presented: the high amount of co-extracted electrons which causes an high power load on the EG.

Deuterium operation at ELISE test facility

The RF power variation is performed in deuterium at 0.3 Pa filling pressure with 7 kV of extraction and 35 kV of acceleration potential. The PG biasing is between 30 V and 33 V and the PG current is set to 4 kA corresponding to ≈4 mT at 2 cm distance from the PG. Additional magnets are installed. The extracted negative ion current density shows an increase with the RF power (see figure 1(a)) and the beginning of a saturation. The co-extracted electron current also increases, being at 60 kW per driver higher than the ion current (figure 1(a) in comparison to 1(b)); from this point the variation was performed without extraction. The negative ion density measured by CRDS increases with RF power as shown in figure 1(d), suggesting that the atomic density is increasing with RF power. The beam properties are determined by the negative ions that are extracted from the plasma: the quantity Δ plotted in figure 1(e) is the difference between negative ion density measured with and without extraction. This quantity is increasing with the RF power and it starts to saturate at around 60 kW per driver (see figure 1(e)).

The saturation of the negative ion extracted current shown in figure 1(a) is related to the saturation of the quantity Δ shown in 1(e).The current at the plasma potential from the Langmuir probe (proportional to the electron density) is increasing with the RF power (see figure 1(c)). The increase in the co-extracted electron current (figure 1(a)) is proportional to the increase of electron density in the plasma measured close to the PG: the co-extracted electron current is correlated to the electron density in the plasma.

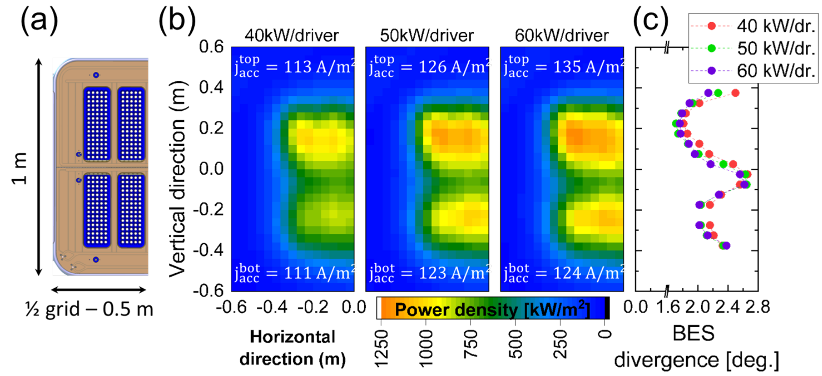

Figure 2: *In (a) half of the PG grid is shown. In (b) the beam 2D maps at different RF power are then shown. In every plot, the accelerated current is reported for each beam segment. The beam is left-right symmetric thus only half of the 2D map is shown. In (c) the beam divergence as measured by BES diagnostics along the vertical profile is shown.*

The beam structure (i.e. beamlet groups and top - bottom beam segments) mimics the aperture arrangement shown in figure 2(a). The accelerated current is defined by the beam intensity and the beam width and represents the current carried by each beam segment. The accelerated current increases with RF power and shows a saturation only for the bottom segment (values reported in figure 2(b)); the symmetry defined with the accelerated currents is better than 90%. The bottom beam intensity is increasing (see figure 2(b)) but the accelerated current is saturating at 50 kW per driver: the vertical beam width is decreasing with power due to a better beam optics, being the beam more intense and narrower thus giving the same accelerated current. On the top beam segment, the vertical beam width increases with RF power thus giving an increase of the accelerated current having a similar beam intensity. The divergence profiles shown in figure 2(c) highlight a lower beam divergence for the top beam segment with respect to the bottom one. The difference between beam segments is due to a different distribution of the extracted current inside the beamlet groups in the two beam segments.

Conclusions

The performances achievable for high power, deuterium operation at the ELISE are limited by the high amount of co-extracted electrons. Co-extracted electrons and electron density measured in the plasma are correlated and increase with the RF power. The extracted negative ion current increases with power and starts to saturate. The extracted negative ion density is related to the negative ions extracted from the plasma, i.e. the difference between the plasma phase and the extraction phase. At high power, fine tuning of source parameters and an improvement of the Cs management is needed to reduce the co-extracted electrons, to maximize the extracted negative ion density and to improve the pulse stability. For correlating plasma and beam properties, the physics close to the extraction area is of high relevance: plasma diagnostics should be installed closer to the PG; complementary to the diagnostics, modelling activities are needed in order to interpret the plasma measurements. The beam accelerated current symmetry is better than 90%. The bottom accelerated current shows a saturation in contrast with the top one that constantly increases. The minimum beam divergence reached in the two beam segment is different indicating a different local extracted current density. Beam diagnostics should be closer to the grids in order to investigate single beamlets properties and local properties of the beam.

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