Influence of External Magnets and the Potential Rods on the Plasma Symmetry in the ELISE Ion Source

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Abstract. The Neutral Beam Injection (NBI) system for ITER requires large scale sources for negative hydrogen ions. The ELISE test facility at IPP Garching uses a 1/2 scale ITER-source (extraction area of 0.1 m^2 at ELISE, source size 1×1 m^2) and shall demonstrate the feasibility of the ITER parameters (extracted $j_{H^-} = 329$ A/m^2 for 1000 s, $j_{D^-} = 286$ A/m^2 for 3600 s, with a co-extracted electron current below the ion current at a source filling pressure of equal or below 0.3 Pa). In long pulses the co-extracted electron current density j_e is strongly increasing and usually limits the source performance. Two modifications for stabilizing and lowering j_e have been applied to ELISE: on the one hand adding bars of permanent magnets outside of the source strengthening the magnetic filter field and on the other hand the installation of potential rods perpendicular to the magnetic field lines close to the extraction system. The vertical plasma symmetry is a crucial parameter because it can lead to an inhomogeneous beam or inhomogeneously co-extracted electrons. Since $\vec{F} \times \vec{B}$ drifts lead to a vertically asymmetric plasma, an influence of both modifications on the plasma symmetry is expected by modifying the magnetic field or electric potential topology in the source. Double probes are used to get insight into the positive ion densities in the upper and the lower half close to the extraction system. A stronger B-field leads to a more asymmetric plasma. In contrary, the potential rods symmetrize the vertical plasma distribution close to the extraction system.

INTRODUCTION

Neutral Beam Injection (NBI) is an essential component of the upcoming ITER fusion device for plasma heating and current drive. Two injectors with a total heating power of 33 MW are foreseen [1, 2], which must be capable to deliver their design power stably for the duration of ITER pulses (up to 1 h in deuterium or 1000 s in hydrogen). The neutral beam injector of ITER will be based on a source of negative ions, which needs to deliver an extracted current density of 286 A/m^2 D^- or 329 A/m^2 H^- from an extraction area of 0.2 m^2. The desired heating power is achieved after acceleration to 1 MeV in deuterium (or 870 keV in hydrogen) when taking into account losses due to particle stripping in the accelerator, due to the efficiency of neutralization and losses during beam transport.

Negative ions are produced in the source mainly by surface conversion of hydrogen atoms [3, 4, 5] created in a low-temperature, low-pressure hydrogen plasma ($T_e = 10$ eV, $p = 0.3$ Pa) into negative ions on a surface with low work function. To achieve a sufficient production yield, caesium with a work function of 2.14 eV is evaporated into the ion source. In order to reduce the destruction rate of negative ions by electron stripping in the plasma, the electron temperature is reduced close to the conversion surfaces via a magnetic filter field to a temperature of below 2 eV. Electrons are co-extracted in addition to negative ions from the source. They need to be removed out of the extracted particle beam prior full acceleration, which is done by magnets installed in the second grid (extraction grid, EG) of the multi-stage extraction and acceleration system, dumping the electrons directly on the EG. The created heat load limits the tolerable amount of electrons to a fraction below the extracted ion current ($j_e/j_{ex} < 1$, with j_e denoting the co-extracted electron current density and j_{ex} the extracted ion current density). The magnetic filter field leads to a vertically asymmetric plasma distribution due to $\vec{F} \times \vec{B}$ drifts [6].

The ion source of ther ITER NBI is based on a modular design: the prototype ion source developed at IPP (Max-Planck-Institut für Plasmaphysik) Garching has become the ITER reference design in 2007 [7]. The plasma is generated in one cylindrical RF driver in the prototype source and the magnetic filter field is created by permanent magnets. ELISE (Extraction from a Large Ion Source Experiment) uses a 1/2 ITER scale source, which went into

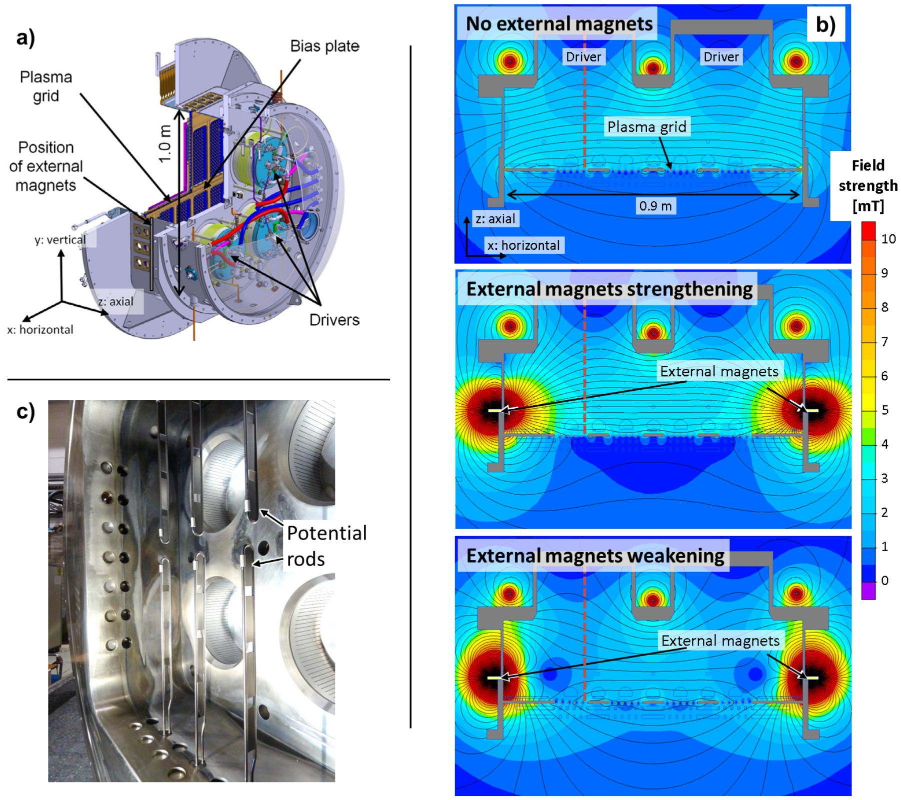

FIGURE 1. a): Sketch of the ion source of ELISE. b): Magnetic field topology for the cases without external magnets (top), external magnets strengthening the filter field (center) and external magnets weakening the filter field (bottom). I_{PG} = 2.5 kA. c): Picture of the expansion chamber showing the six vertically installed potential rods.

beam operation in 2013 at IPP Garching [8]. The ELISE source uses 4 drivers for the plasma generation and a vertical current through the plasma grid (PG, plasma-facing first grid of the extraction system) up to several kA for generating the magnetic filter field. The first full-size source SPIDER [9] is in plasma operation since 2018 at Consorzio RFX Padova. A challenge towards reaching the ITER parameters is the stability of the co-extracted electron current in long pulses, which strongly increases with time observed at the prototype source [10] as well as at ELISE [11]. Beside long pulses, co-extracted electrons are particularly an issue at high RF power and in deuterium operation (much increased amount and higher temporal instability). In addition, a strong vertical asymmetry of j_e is observed in many operational scenarios at ELISE [11]. Co-extracted electrons often limit the amount of extracted negative ions due to a power limit on the EG, since the source has to be run with reduced parameters (RF power or extraction voltage) for lowering j_e. Thus, stabilizing, reducing and symmetrizing the co-extracted electron current is of utmost relevance towards the ITER NBI.

Two modifications for reducing and stabilizing j_e have been applied to ELISE in the last experimental campaigns: external magnets, mounted in bars and placed at the lateral walls outside the source, show a beneficial effect in particular for stabilizing pulses [12]. The installation of so-called potential rods close to the extraction system help to symmetrize and stabilize j_e [13]. For further optimization of the source, a better understanding of the influence of these modifications on the source plasma is highly desirable. In this paper, the influence on the plasma symmetry close to the PG, determined by two double probes, is presented.

SETUP AT ELISE

A cut view of the ion source of ELISE is shown in figure 1 a). The plasma, created in four drivers, expands into one common expansion chamber. Two RF generators power the drivers with up to 150 kW per generator (each generator supplies two drivers in series). Cs is evaporated into the source from two ovens mounted on the left and right side of the expansion chamber. The beam extraction system consists of three grids: the plasma grid (PG), the extraction grid (EG) and the grounded grid (GG). Each grid consists of 640 apertures (14 mm diameter in the PG); these are grouped to 8 beamlet extraction groups. The area between these beamlet extraction groups is covered by a so called bias plate. The PG is positively biased against the rest of the source chamber (including the bias plate), leading to a reduction of the co-extracted electron current [14]. A total high voltage of up to −60 kV can be applied to the source for beam extraction; the extraction voltage between PG and EG is typically set up to 10 kV. The extraction grid is vertically divided into two segments allowing for measuring the co-extracted electron current individually for the top and bottom half. A more detailed description of ELISE can be found elsewhere [15, 16].

The magnetic filter field topology in the ion source of ELISE is shown in figure 1 b). Without external magnets, the filter field is solely created by the vertical PG current and the magnetic field strength scales linearly with I_{PG}; three return conductors close to the drivers are mounted in order to lower the B-field inside the drivers. Outside the expansion chamber, bars of permanent magnets (3 rows of CoSm magnets with a total size of $3.9 \times 0.9 \times 42$ cm^3) can be mounted with their polarity either strengthening or weakening the magnetic filter field. Whereas the external magnets modify strongly the field topology close to the side walls, the topology is in contrary less influenced in the more central region: shown in figure 2 is the horizontal B-field component B_x along an axial line through the center of one driver (indicated with a red dashed line in figure 1 b)). The external magnets modify mainly the field strength in the expansion region and its gradient from the driver to the plateau several cm close to the PG. At a distance of 3 cm to the PG, the external magnets increase B_x significantly by roughly 1 mT in strengthening configuration and decrease B_x strongly by the same amount of 1 mT in the weakening configuration.

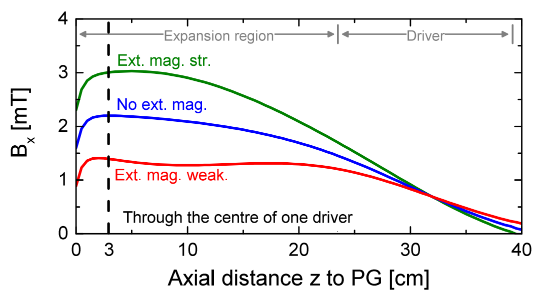

FIGURE 2. Horizontal B-field component B_x along an axial line of sight through the center of one driver for the cases with external magnets strengthening the B-field, weakening the B-field and without external magnets (I_{PG} = 2.5 kA).

Six vertical, water-cooled potential rods (Ni coated Cu) have been mounted in summer 2017 close to the PG (they are shown in figure 1 c)). The potential rods have been kept at the same potential as the PG (i.e. bias potential) for all results shown in this work. The idea behind biasing the rods is to attract electrons from the plasma sheath onto the rods. The rods feature horizontal openings in order not to disturb diagnostics mounted in horizontal ports (as optical emission spectroscopy).

For determining the positive ion density close to the plasma grid, two double probes are mounted in ELISE at an axial distance of 2 cm to the PG vertically symmetric in the top and bottom part of the source. Their positions are illustrated in figure 3. Double probes have the advantage in RF plasmas that they do not suffer from the lack of RF compensation, since both probe tips are floating in the plasma and the current-voltage characteristics is measured between both tips without reference to the source body. The tungsten probe tips (300 μm diameter, 1 cm length) are positioned in front of the outermost beamlet extraction group.

All presented ELISE pulses have been short (i.e. 20 s plasma time including a 10 s beam extraction phase). The double probe characteristics is measured in the middle of the extraction phase; all shown extracted currents (negative ions and electrons) are averaged over the second half of the extraction phase. The measurements have been carried out in a ceasiated source. Although it has been condition the source similarly well, some differences between the modifications might be caused by a slightly different caesiation (in particular the extracted currents react very sensitive on the caesiation).

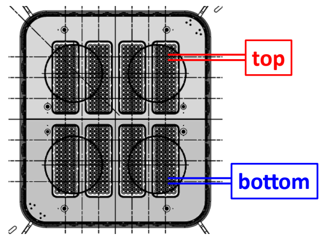

FIGURE 3. View onto the plasma grid of ELISE with the positions of the two double probes indicated. The black circles indicate the projections of the four drivers.

RESULTS

Influence of external magnets

Performing scans with variation of the PG current are well suited for the determination of the influence of source modifications on the plasma asymmetry, because the PG current directly influences the vertical $\vec{F} \times \vec{B}$ plasma drifts. The influence of the PG current on the positive ion density measured with the top and bottom double probe is shown in figure 4 a) for the cases *without external magnets*, with the external magnets *strengthening* the filter field and with the external magnets *weakening* the filter field. No potential rods are mounted in these cases. In general, a slight increase of the plasma density at the top probe and a decrease of the plasma density at the bottom probe appears for increasing PG current and thus increasing filter field strength. The external magnets mounted in the *strengthening* configuration lead to an increase of the density at the top probe whereas the density at the bottom probe is decreased compared to the case *without ext. magnets* (and vice versa in the case *weakening*). Thus, the plasma becomes – as expected – more asymmetric at stronger B-field.

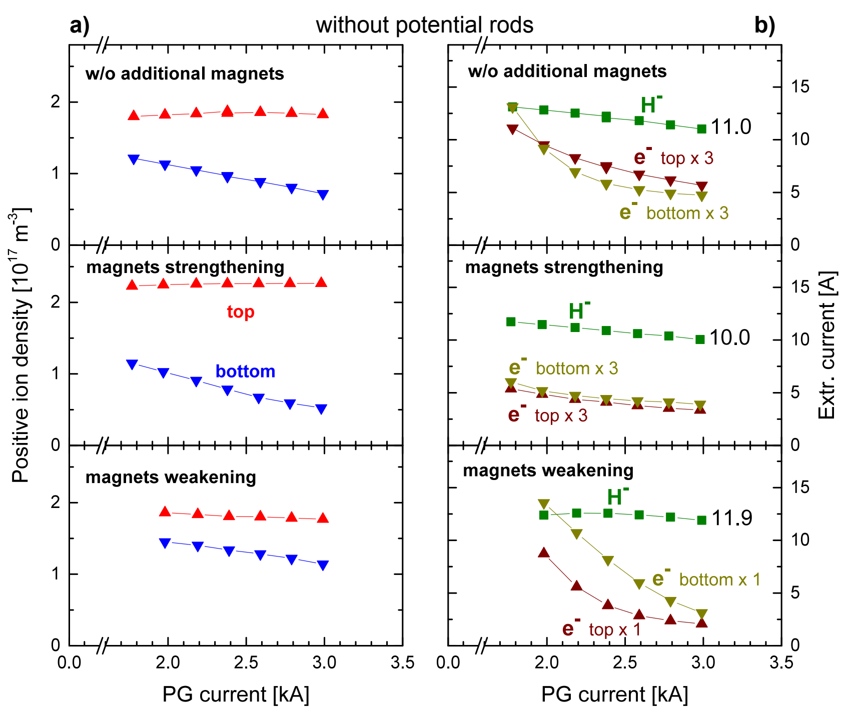

FIGURE 4. PG current variation (hydrogen, filling pressure 0.6 Pa, RF power of 64 kW / generator). a): Positive ion density (double probes) determined top and bottom for the cases *without ext. magnets* (top), with external magnets *strengthening* the filter field (center) and with external magnets *weakening* the filter field (bottom). b): Extracted H^- current and co-extracted electron current (upper and lower grid segment) for the same cases.

The effect of the variation of the PG current on the extracted currents (H^-, e^- top and bottom) is shown in figure 4 b) for the three different configurations of external magnets. The general trends are the following:

- The extracted ion current is decreased by roughly 1 A when increasing the PG current by 1 kA. The same decrease of 1 A ion current happens at each step when switching the configuration from *weakening* → *without ext. magnets* → *strengthening*.
- The co-extracted electron current is decreasing strongly for increasing I_{PG} in the case *weakening*; this decrease is less pronounced in the case of *without ext. magnets* and only weakly pronounced in the case *strengthening*. The current is generally much higher for the weakening case (take note of the different scaling in the plots).

No distinct correlation is found between the plasma asymmetry and the asymmetry of co-extracted electrons: whereas, for example, in the case *weakening* the plasma becomes more asymmetric for higher values of I_{PG}, the co-extracted electron currents become more symmetric. Possible explanations for the lack of correlation are on the one hand the fact that in the quasi-neutral plasma the positive ion density does only correlate with the electron density if assuming a spatially constant amount of negative ions. A possible different vertical caesiation of the source could, however, lead to different production yields of negative hydrogen ions. A further possibility of the missing correlation is the high impact of the applied bias on the amount of co-extracted electrons [17]. The vertically asymmetric plasma potential at ELISE leads, however, to different bias regimes in the top and bottom part. In addition it needs to be taken into account that the electrons are extracted from the region of the meniscus (i.e. the transition from the quasi-neutral plasma to the extracted particle beam which is formed closely upstream of each extraction aperture), whereas the double probes are mounted far more deep in the plasma at 2 cm distance to the PG.

In order to determine whether the external magnets modify the plasma asymmetry differently compared to adjusting the PG current, figure 5 a) shows the positive ion density (top and bottom) as function of the magnetic field strength B_x at a position of axially 3 cm upstream of the PG (in the center of the projection of one driver, as indicated in the figures 1 b) and 2). A direct comparison between the effect of varying the PG current with the external magnets is only possible when comparing the field strength on such a selected location due to different topologies of the B-field. At the chosen position, switching the configuration *weakening* → *without ext. magnets* → *strengthening* increases B_x by roughly 1 mT each step which corresponds to an increase of the PG current of roughly 1 kA. Although the three configurations do not result in exactly the same curve, they partly merge into one another. This means that the plasma transport from the drivers towards the PG is mainly affected by the magnetic filter field strength along the driver projections in the expansion chamber and it is less influenced by the highly differing field topology close to the side walls. However, it needs to be taken into account that it is known that the axial field gradient and its axial position plays an important role for the transport of the plasma in the expansion chamber [18, 6]. The difference of this gradient for the three configurations (see figure 2) might be the reason why the curves in figure 5 do not exactly merge.

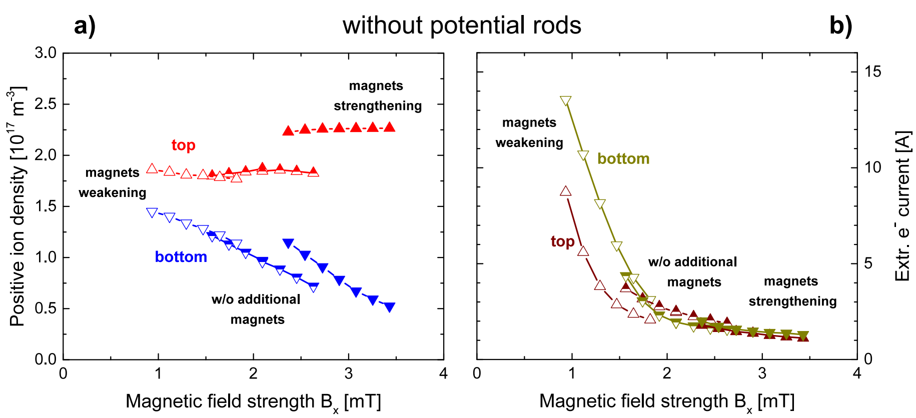

FIGURE 5. PG current variation (hydrogen, filling pressure 0.6 Pa, RF power of 64 kW / generator), data presented as function of the magnetic field strength B_x 3 cm upstream of the PG in the center of one driver projection. a): Positive ion density top and bottom. b): Extracted electron current for the top and bottom grid segment. Open symbols: external magnets *weakening* the filter field. Half filled symbols: *without ext. magnets*. Full symbols: external magnets *strengthening* the filter field.

The extracted electron currents as function of B_x are shown in figure 5 b) for the three configurations. Similarly, they partly merge into one another for the three configurations. The co-extracted electron current increases drastically at a field strength of below ≈ 2 mT [19]. At the used parameters, the external magnets do not significantly help improving the source performance (a similar reduction of the co-extracted electron current from *weakening* → *without ext. magnets* → *strengthening* can be achieved by increasing the PG current). This result is, however, only valid for short pulses and particularly at higher pressure [12] – an elevated pressure of 0.6 Pa has been used for the investigations in this work in order to allow a broader parameter space for source operation. In long pulses, a better temporal stability of the co-extracted electron current is observed at ELISE in the *strengthening* configuration [12]. This difference might be explained by the fact that the different magnetic field topology influences the positions of the plasma impinging the chamber walls [12] and is thus influencing the redistribution of caesium in long pulses. The latter is known to have a major impact on the stability of long pulses [20].

Influence of potential rods

The positive ion density as function of the applied PG current (external magnets in *strengthening* configuration) is shown in figure 6 for the cases of with and without installed potential rods. Whereas the plasma density at the bottom probe is only weakly reduced by about 10% with the installed rods, the density at the top probe is decreased by more than a factor of 2 by the potential rods. A reduction of the plasma density is expected due to the significant surfaces of the potential rods, which are installed perpendicular to the magnetic field lines. Interestingly, the plasma becomes much more symmetric using the potential rods. In addition to the better plasma symmetry, also the co-extracted electron current becomes more symmetric [13].

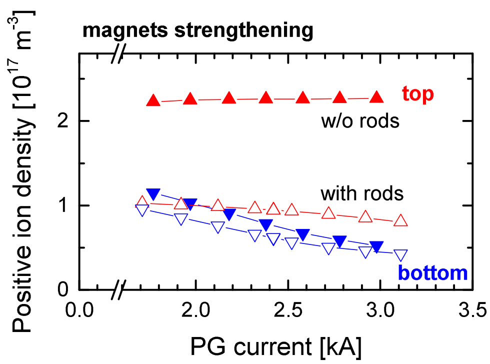

FIGURE 6. Positive ion density at the top and bottom double probe as function of the PG current (hydrogen, filling pressure 0.6 Pa, RF power of 64 kW / generator). Full symbols: without installed potential rods. Open symbols: with potential rods.

SUMMARY AND CONCLUSIONS

Two double probes have been used to determine the influence of external magnets and the potential rods on the plasma symmetry at ELISE. The plasma becomes more asymmetric at larger B-field due to an increased effect of $\vec{F} \times \vec{B}$ drifts. This effect is independent whether the B-field is increased or decreased by external magnets (*strengthening* or *weakening* the filter field, or *without ext. magnets*) or variation of the PG current. For variation of the PG current in the three configurations of the external magnets, the measured curves of positive ion density almost merge into one another when plotting as function of the B-field strength 3 cm upstream of the PG (in the center of a driver projection). A similar merging is seen in the extracted electron currents. Thus, no additional beneficial effect of the magnets is seen in the investigated short pulses (filling pressure of 0.6 Pa) – in contrary, it is observed that in *strengthening* configuration the external magnets show a certain improvement of the stability in long ELISE pulses.

The potential rods symmetrize the vertical plasma distribution in ELISE: the positive ion density at the bottom probe is only slightly decreased by 10%, whereas the density at the top probe is decreased by a factor of more than two. A deeper investigation of the influence of the potential rods on the plasma with a comparison to the extracted currents (ions and electrons) is foreseen in the near future.

Both configurations are beneficial to decrease the co-extracted electrons and consequently allow an enlargement of the parameter space (RF power and extraction voltage) for achieving higher negative ion currents while keeping $j_e/j_{H^-} < 1$. Therefore it is recommended to use those components in large ion sources – in particular in those were the vertical elongation is larger, i.e. the full size ITER source as SPIDER, and thus a higher asymmetry (of the plasma and co-extrcated electrons) is possible.

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