Influence of the magnetic field topology on the performance of the large area negative hydrogen ion source test facility ELISE

D. Wünderlich, W. Kraus, M. Fröschle, R. Riedl, U. Fantz, B. Heinemann and the NNBI team

Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, 85748 Garching, Germany

Abstract

In negative hydrogen ion sources a too high amount or a too rapid increase of co-extracted electrons can prevent achieving the required negative ion current density and restrict the pulse duration. One important measure for reducing and stabilizing the co-extracted electron current is a magnetic filter field. The half-ITER-size NNBI test facility ELISE – in which the filter field is created by a current flowing through the extraction system – is used for performing experiments on the reaction of the source performance on modifying the filter field topology: external magnet bars are attached to the source in different polarities and extensive parameter variations have been done in volume and surface operation. A significant correlation of the extracted ion and electron currents and their temporal stability with the field topology is seen: with the external magnets strengthening the standard filter field a strong reduction of the co-extracted electrons and additionally a reduced increase of these electrons during the pulses is observed. In this configuration it was possible to perform the very first one hour deuterium pulse in ELISE – an important step toward fulfilling the requirements to the ion source for ITER NBI.

Introduction

The neutral beam injection (NBI) system at ITER will be used for heating and current drive [1,2]. An essential part of the NBI beam line is the negative hydrogen ion source, capable of delivering an extracted current of 57 A for 3600 s in deuterium operation and 66 A for 1000 s in hydrogen (corresponding to current densities of 28.5 mA/cm^2 and 33.0 mA/cm^2, respectively).

In order to minimize the destruction rate of negative ions in the accelerator the source has to be operated at a filling pressure of 0.3 Pa. Additionally, to limit the power loads in the extraction system, the amount of co-extracted electrons has to be equal or smaller compared to the extracted negative ions. Up to now, these parameters have not been achieved simultaneously.

ELISE (Extraction from a Large Ion Source Experiment) [3,4] is part of a R&D roadmap defined by the European domestic agency F4E for the construction of the neutral beam heating systems [5,6]: the half-ITER-size ion source of the ELISE test facility (0.9×1.0 m^2 with an extraction area of 0.1 m^2) is an intermediate step between the RF driven ITER prototype source (0.3×0.6 m^2 with an extraction area of typically 6·10^{-3} m^2) [7] and the ion source for the ITER NBI system (1.0×2.0 m^2 with an extraction area of 0.2 m^2) [8]. The latter is in principle identical with the ion source used at the SPIDER and MITICA test facilities under construction at the neutral Beam Test Facility PRIMA in Padova [9,10].

A schematic view of the ion source of ELISE can be seen in Figure 1. The plasma is generated by inductive RF coupling into the four cylindrical drivers (P_{RF}<90 kW/driver) and then expands toward the extraction system. ELISE is operated in pulsed mode: plasma pulses are possible up to one hour, with short beam blips (length: 10 s; the shortest possible time between two blips is approximately three minutes).

These ion sources are usually operated in the so-called surface mode [11]: the main production process for negative hydrogen ions is the surface process where ions are produced by conversion of impinging hydrogen atoms and positive ions on the caesiated surface (i.e. a surface with a low work function) of the plasma grid (PG), the first grid of the multi-grid, multi-aperture extraction and acceleration system (consisting in ELISE of the PG, the extraction grid and the grounded grid, while for the ITER NBI system seven grids in total are foreseen [12]). Caesium is evaporated into the source volume by means of two caesium ovens [13], attached to the vertical side walls. The plasma volume close to the extraction system (axial dimension: a few cm) where most processes relevant for the production and the transport of the negative ions take place is called extended boundary layer. For a well caesiated source, the plasma of the extended boundary layer can be strongly electronegative [14].

If the source is operated without caesium – in the so called volume mode – the negative ions are produced predominately in the plasma volume. The extracted ion current is significantly lower compared to operation with caesium and the co-extracted electron current significantly higher [15,16].

A horizontal magnetic field – the so-called filter field – with a strength of a few mT (sufficient for magnetizing electrons but not the ions) plays a crucial role for the suppression of the co-extracted electron current and also for the transport of negative hydrogen ions to the extraction apertures [17]. The magnetic filter is generated by a current, I_{PG}, flowing through the PG in vertical direction [18]. By varying I_{PG}, the strength of the filter field can be adjusted (the ELISE system is designed for currents up to 8 kA, the currently installed power supply can deliver up to 5.3 kA at maximum and usually the applied current is below 4 kA).

The number of co-extracted electrons is reduced by a factor of up to ten (depending on the source parameters) by the magnetic filter. Reason is a low probability for cross-field diffusion of magnetized electrons. An additional reduction of the co-extracted electrons is obtained by a positive bias potential applied to the PG with respect to the source body and the so-called bias plate [7], see Figure 1.

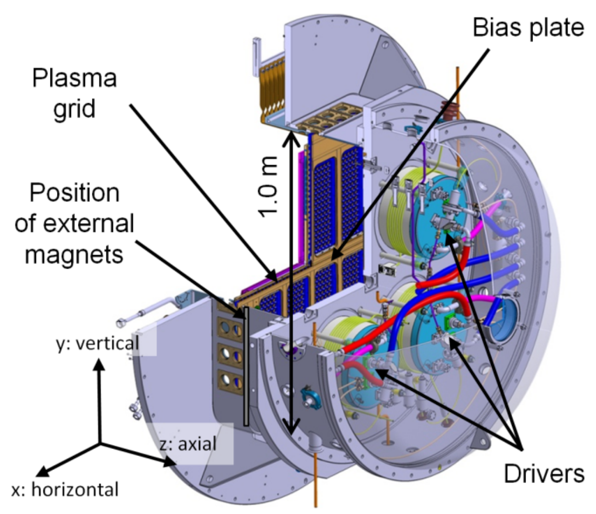

Figure 1: Schematic view of the ELISE ion source. The position of the external magnets used for modifying the filter field topology is depicted by the green bar (at the left side wall only). Additionally indicated is the used coordinate system.

The co-extracted electrons are magnetically deflected onto the surface of the extraction grid, i.e. the extraction grid is acting as an electron dump. If the power deposited onto this grid is too high, beam extraction is stopped by a safety interlock. The design limit of power deposited onto the extraction grid is 200 kW per segment [3], the safety interlock takes effect at 125 kW/segment. Thus, a high co-extracted electron current can prevent increasing the extraction voltage or the RF power in order to increase the extracted negative ion current. If the co-extracted electron current strongly increases during a pulse it can limit the length of the pulse. Typically, in deuterium plasmas the amount of co-extracted electrons is higher and their temporal instability is more pronounced than in hydrogen [19].

Investigations performed at the smaller prototype source, where the filter field is generated by permanent magnets, have shown that the source performance (the extracted negative ion current density and the amount of co-extracted electrons) is strongly correlated with the position, strength and topology of the filter [17].

Although the filter field concept used at ELISE has proven to enable a good source performance [16], it is by far not optimized yet. So far, extensive studies have been performed on the influence of different values of I_{PG} on the ELISE source performance [16]. Additionally, first investigations on the question how the source performance and its temporal stability react on modifications of the filter field topology have been performed in hydrogen and only in volume operation [20]. These investigations have been based on the simplest way for modifying the field topology, namely the addition of permanent magnets to the two vertical side walls of the ion source. Although the polarity of the permanent magnets was reversed by accident in these preliminary tests [21], it was obvious that additional magnets can have great impact in particular on the electron currents. Considering the correct polarity it seems that strengthening the field leads to a significant reduction.

For this paper these preliminary experiments were repeated and extended. The influence of modifying the filter field structure on the plasma structure was investigated using an optical camera (section 2). The effect of the external magnets on the source performance was investigated in hydrogen and in deuterium in volume operation (section 3) and in surface operation (section 4). Finally, for both isotopes the influence of the external magnets on the long-pulse stability was investigated (section 5).

The magnetic filter field in ELISE

CoSm permanent magnets (horizontal/axial/vertical cross section: 3.9 cm×0.9 cm×110 cm) have been added externally to the vertical side walls of the ELISE source. The smallest possible axial distance to the PG, 7.5 cm, (defined by the diagnostic ports in the side walls close to the PG [3]) has been used. The position and alignment of one of the two magnets is indicated in Figure 1. The second one cannot be seen since it is covered by the source walls.

The main component of the external magnetic field is directed in the horizontal direction, i.e. parallel to the main component of the I_{PG} field. Three different field configurations have been tested: without the external magnets (only the I_{PG} field, this is called the standard field configuration) and with the additional field either weakening or strengthening the I_{PG} field.

Figure 2 shows the 2D structure (along a horizontal/axial cross section, vertical position y=±20 cm, i.e. the center of the upper or lower pair of drivers) of the total filter field strength B_{tot} generated by I_{PG}=2.5 kA and for the three possible configurations: Figure 2a) the standard configuration, Figure 2b) with the external magnets in the weakening configuration and Figure 2c) in the strengthening configuration. The return conductors for I_{PG}, arranged vertically, are located between the drivers [18].

The topology of the field lines is modified by the external magnets over the total ion source volume from the drivers up to the PG: The field lines are almost parallel to the PG in the standard field configuration. For axial distances to the PG larger than 7.5 cm (the position of the external magnets) close to the vertical side walls of the ion source the field lines are pushed in the weakening configuration toward the back plate while in the strengthening configuration they are pushed toward the PG.

For axial distances to the PG below 7.5 cm in both the standard configuration and the strengthening configuration the electron flow from the drivers toward the extraction system is hindered by horizontal field lines. In the weakening configuration, field free regions are formed close to the side walls (horizontal distance to the walls ≈14 cm, axial distance to the PG ≈8 cm).

The horizontal component B_x shown in Figure 3 is one of the most relevant parameters for describing the cross-field diffusion of magnetized electrons toward the PG. Figure 3a) shows horizontal profiles of B_x (axial distance to the PG: z=7.5 cm, orange horizontal lines in Figure 2); the standard field is depicted by the blue line, the configuration with the weakening magnets by the red line and the strengthening magnets by the green line.

In all three configurations, the horizontal profile of B_x is more or less flat close to the center of the source (|x|<20 cm). Here, B_x is slightly decreased in the weakening configuration and slightly increased in the strengthening configuration. Close to the side walls strength of the standard field is more or less constant while $|B_x|$ increases strongly for both field configurations based on the external magnets. Magnetic mirrors are formed with the consequence that in this region the loss

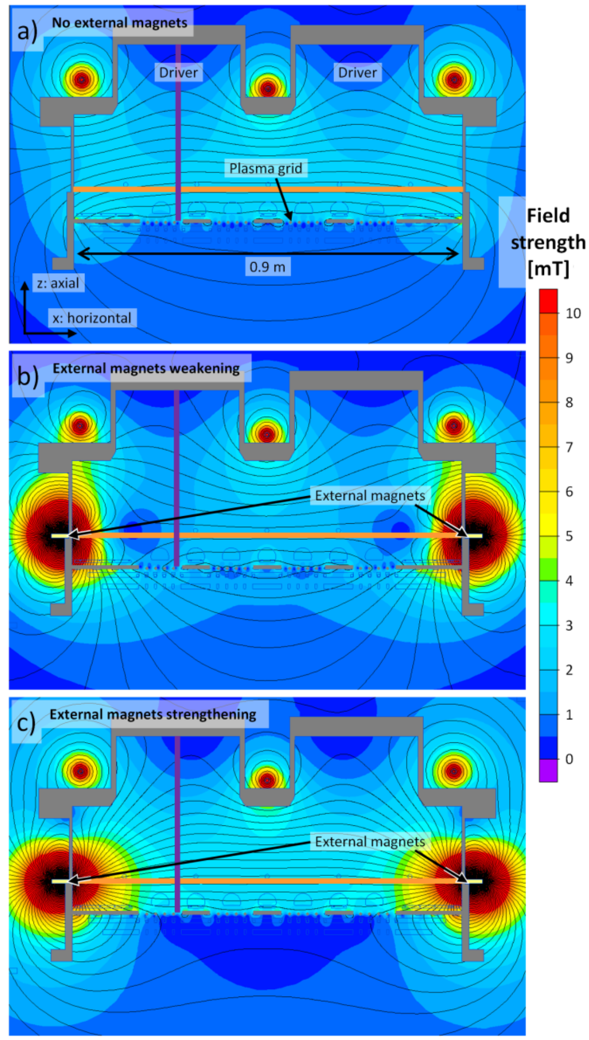

Figure 2: 2D structure (horizontal/axial cross section) of the field strength B_{tot} resulting in ELISE from the superposition of the PG filter field (I_{PG}=2.5 kA) and the external magnets. a) Standard field, without the external magnets. b) External magnets in the weakening configuration. c) External magnets in the strengthening configuration. Symbolized by the orange and purple lines are the positions along that the profiles shown in Figure 3 have been taken.

of electrons by transport along the field lines to the side walls is effectively reduced. In the weakening position the superposition of the two opposing magnetic fields results in the two field free regions where electrons can be transported much more effectively toward the PG.

Figure 3b) shows axial profiles of B_x (through the center of one of the drivers, purple vertical line in Figure 2). B_x increases from the drivers toward the PG for all configurations of the filter. In the case of the weakening magnets no distinct maximum but a broad region with an approximately constant value of B_x arises. The maximum value of B_x along the plotted profiles is 2.2 mT in the standard configuration (field integral $\int B_x \cdot dl$=0.58 mTm). This value is increased to 3.0 mT ($\int B_x \cdot dl$=0.74 mTm) by the strengthening magnets and decreased to 1.4 mT ($\int B_x \cdot dl$=0.42 mTm) by the weakening magnets.

Concluding, the changed values of B_x and $\int B_x \cdot dl$ affect the cross-field diffusion of charged plasma particles toward the PG and the extraction system. The formation of magnetic mirrors or field free regions close to the side walls result in modified probabilities for the loss of magnetized electrons to the walls.

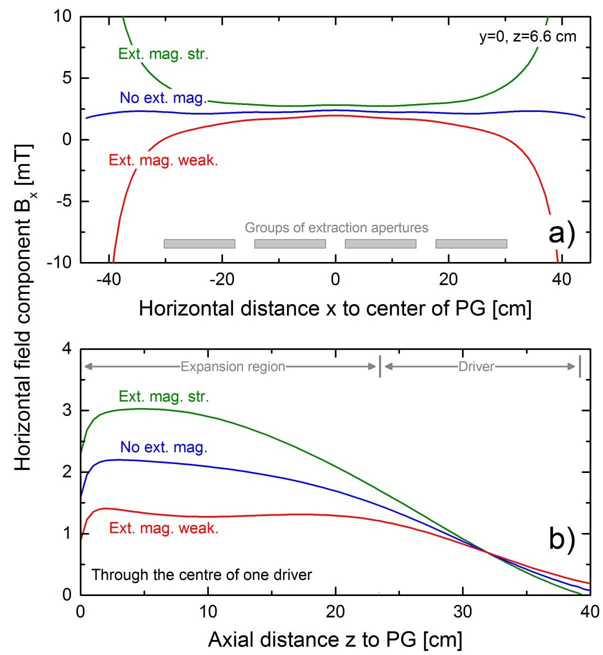

Figure 3: Profiles of the horizontal component B_x of the filter field resulting from the superposition of the PG filter field and the external magnets. Blue line: standard field, without the external magnets. Red line: external magnets in the weakening configuration. Green line: external magnets in the strengthening configuration. a) Vertical profile, axial distance from the PG: 7.5 cm. b) Axial profile through the centre of one of the drivers.

Influence of the modified field topology on the plasma structure

At ELISE a CCD video camera installed in one corner of the source vessel can be applied for assessing the influence of source parameters on the plasma structure (or, to be more precise, on the structure of the plasma radiation). For doing so, pulses have been done in hydrogen and deuterium for all three configurations of the filter field. The parameters of these pulses have been chosen to be as identical as possible for hydrogen and deuterium (RF power: P_{RF}=20 kW/driver, filling pressure: p_{fill}=0.6 Pa, current drawn by the bias potential applied to the PG: I_{Bias}=55 A). In negative hydrogen ion sources for identical source parameters in deuterium the co-extracted electron current is generally much higher compared to pulses in hydrogen [Fantz2012]. In order to reduce this higher electron current, a decreased value of the extraction voltage U_{ex} (hydrogen: 4 kV, deuterium: 3 kV) and an increased value of I_{PG} (hydrogen: 2.5 kA, deuterium: 4 kA) was used for deuterium.

The results for hydrogen are shown in the upper row of Figure 4 and the ones for deuterium in the lower row. The images taken for the standard field configuration are shown on the left, the images for the weakening magnets in the middle and the ones for the strengthening magnets on the right. For all images identical settings (i.e. exposure time) have been used for the camera. In the lower part of the images the plasma grid and the bias plate is visible and on the upper side the plasma flows out of the four drivers (compare with Figure 1). On the left side is the right vertical side wall (as seen from upstream the ion source), on the right side the lower horizontal wall. In both walls the diagnostic ports can be seen, in the vertical side wall additionally the opening to that the right caesium oven is attached. On the right vertical side wall the position of the external magnets is indicated by grey lines.

In the standard field configuration the most intensely radiating part of the plasma forms tubes that hit the side walls of the ion source in a few centimeters distance to the back plate. By attaching the external magnets in the weakening or strengthening configuration, the position of the intersection of these tubes with the side wall is moved by several centimeters toward the back plate or toward the PG, respectively. A likely explanation for this movement is the modification of the field lines, as illustrated by Figure 2.

Although different values for I_{PG} have been used for the two isotopes, the observed plasma structure for hydrogen and deuterium is almost identical. This result illustrates that the plasma expansion from the drivers toward the PG is mass dependent.

Compared to hydrogen the deuterium plasmas look much more purple. The purple light seen in the camera image is caused by the Balmer alpha emission line of the hydrogen atom (the by far strongest emission line of hydrogen in the visible wavelength range, λ=656 nm). In the case of a not fully recombining plasma and for otherwise identical plasma parameters a higher H_α emission can be caused by a higher dissociation degree, i.e. a higher ratio of n(H) to n(H_2). Thus, the more purple plasma in

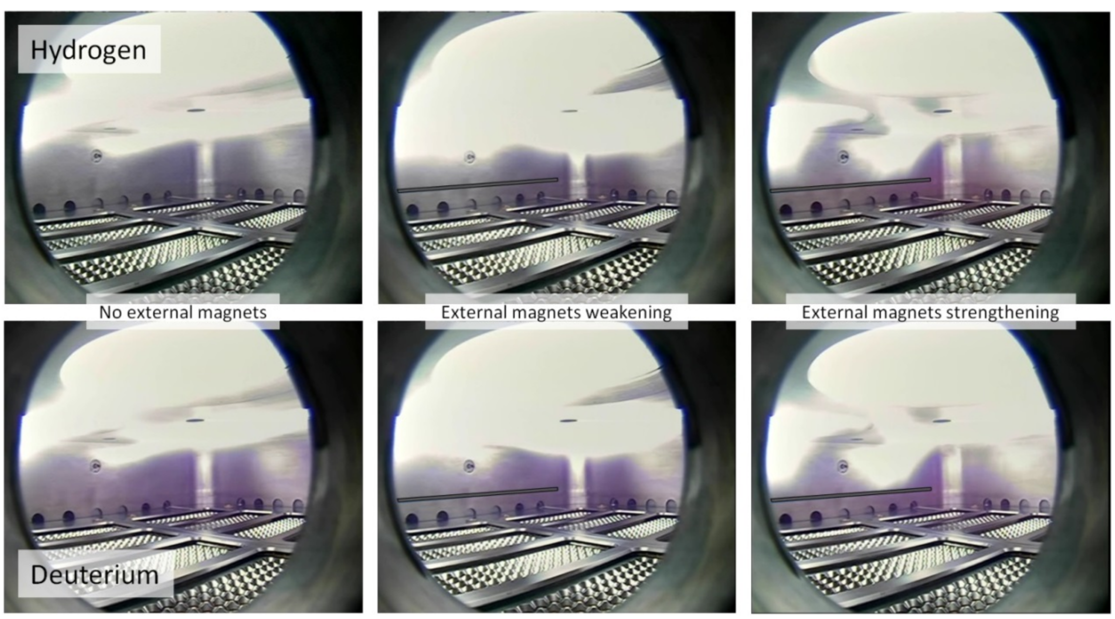

Figure 4: Plasma structure in hydrogen (upper row) and deuterium (lower row) for a standard pulse and the three configurations of the filter field: without external magnets (left), with weakening external magnets (middle) and with strengthening external magnets (right). In the central and the right images the position of one of the external magnet bars is indicated (by the grey lines)

deuterium is in general agreement with measurement results from the prototype source demonstrating that the dissociation degree is higher in deuterium compared to hydrogen [22].

Results in Volume Operation

The effect of the additional external permanent magnets in volume operation was investigated during several parameter variations. These variations have been performed in both hydrogen and deuterium and for the three possible configurations of the filter field (i.e. the standard I_{PG} field and with the external magnets weakening or strengthening the I_{PG} field). Starting from a standard pulse, variations of I_{PG}, p_{fill}, I_{Bias} and P_{RF} have been performed. The parameters of the standard pulse are identical to the ones of the pulses presented in the previous section. The length of the plasma pulses was 20 s, with a beam phase of 10 s.

Figure 5, Figure 6, Figure 7 and Figure 8 show the results of the performed variations. Shown in all figures are the extracted negative hydrogen ion current density j_{ex} and the electron-ion-ratio measured in hydrogen (left side of the figure) and deuterium (right side of the figure). The results for the standard configuration are depicted by blue squares, the results for the external field in the weakening configuration by down pointing red triangles and the ones for the strengthening field by up pointing green triangles.

The general behavior of j_{ex} and the electron-ion-ratio during the parameter variations for volume operation is in good agreement with the results of previous experiments [15]:

- High electron-ion-ratios are reached; these are much higher in deuterium compared to

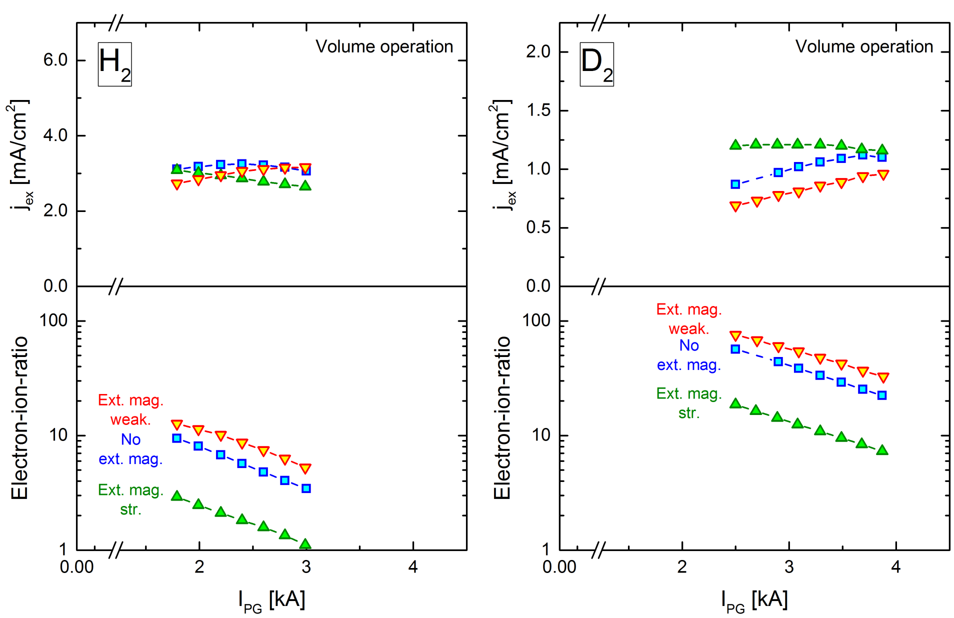

Figure 5: Extracted negative ion current density and electron-ion-ratio for a variation of the PG current in hydrogen (left side) and deuterium (right side). ELISE was operated in volume operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

hydrogen.

- With increasing I_{PG} the amount of co-extracted electrons is reduced (see Figure 5). Reason is that the cross-field electron diffusion from the drivers toward the PG is decreased. For high values of I_{PG} the magnetic field can affect the transport of the much heavier negative ions also ($m(H^-)/m_e$=1836) and the amount of extracted negative ions can be effectively reduced [17]. Thus, I_{PG} usually is chosen as compromise between suppressing the co-extracted electrons as much as possible while affecting only marginally the extracted negative ions.
  In the performed variations the extracted negative ion current density does not react strongly on I_{PG}. Exceptions are the pulses in deuterium with the standard field and the weakening external magnets: j_{ex} decreases with decreasing I_{PG}. At the same time a very high amount of co-extracted electrons (electron-ion-ratio above 25) is measured, indicating a high electron density in the extended boundary layer. Obviously, the space charge generated by these electrons reduces the transport of volume produced negative ions toward the plasma grid and the extraction probability of these ions is effectively decreased.

- The electron-ion-ratio increases strongly with decreasing filling pressure (see Figure 6). In contrast, the extracted negative ion current density does not react strongly on the variation of p_{fill}, again with the exception of pulses in deuterium with a high extracted electron-ion-ratio.
- With increasing bias current (i.e. more negative space charge carriers are drawn onto the surface of the plasma grid) the extracted electron-ion-ratio decreases – as intended (see Figure 7). Due to the high mass of the negative ions the influence of the PG bias potential on the trajectories of the ions during their transport toward the extraction apertures and thus on the

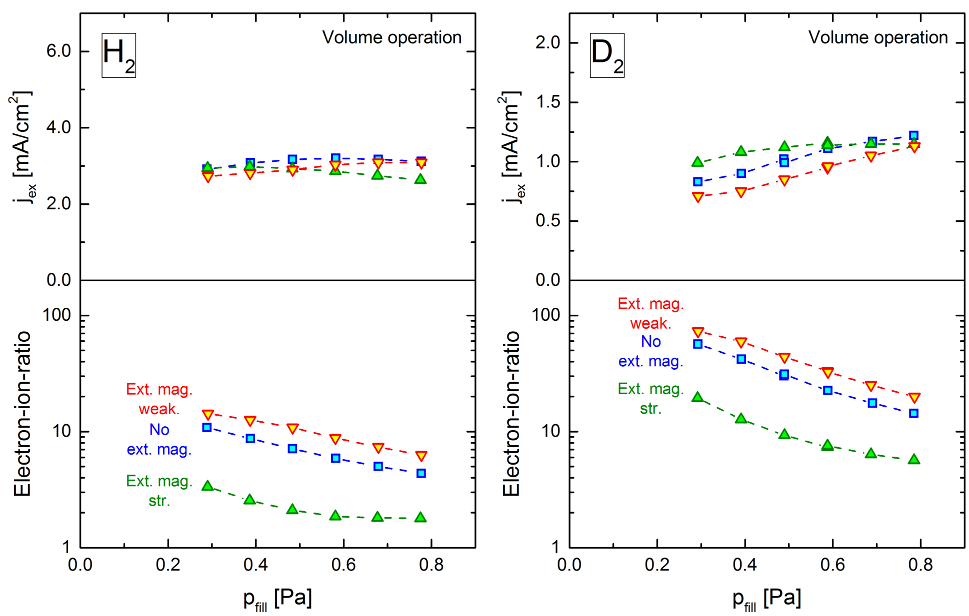

Figure 6: Extracted negative ion current density and electron-ion-ratio for a variation of the filling pressure in hydrogen (left side) and deuterium (right side). ELISE was operated in volume operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

extracted negative ion current density is small. An almost constant behaviour of j_{ex} vs. I_{Bias} is expected. For hydrogen – in agreement with the results shown in [15] – this expectation is confirmed. In deuterium, for decreasing I_{Bias} the extracted negative ion current density decreases. This effect again is correlated with a very high electron density in the extended boundary layer.

- For both isotopes the extracted negative ion current density increases linearly with the RF power (Figure 9). Taking into account the experience made at the prototype source, for further increasing P_{RF} a saturation of j_{ex} is expected [23]. The electron-ion-ratio increases only slightly with P_{RF} for hydrogen and more strongly for deuterium. The latter effect demonstrates that it is in general more difficult to suppress the co-extracted electrons in deuterium operation [16].

Irrespective of the used isotope and of the source parameters, the amount of co-extracted electrons increases by a factor of around 1.5 when changing from the standard field configuration to the weakening configuration and it decreases by a factor of around three when changing to the strengthening configuration.

The effect of the external magnets on the extracted negative ion current density is small: for hydrogen, it is smaller than 0.5 mA/cm^2. In deuterium the relative influence of adding the magnets on j_{ex} is larger, again most probably caused by the space charge of the plasma electrons (in deuterium for the standard field and the weakening external magnets electron-ion-ratios above 25 are observed during each of the parameter variations; this is not the case for the strengthening external magnets).

The described observations illustrate a very beneficial effect of the external magnets in the

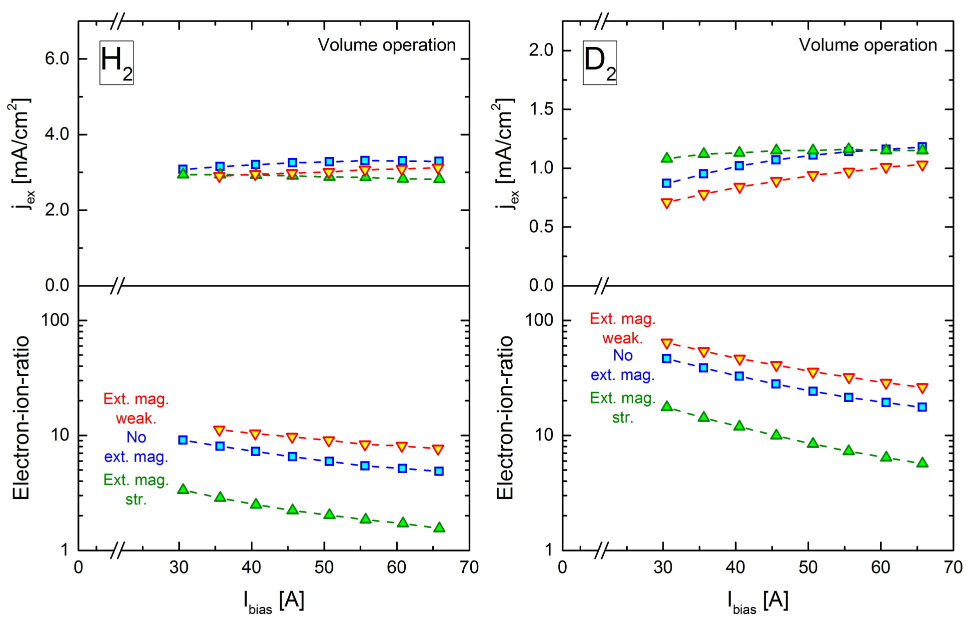

Figure 7: Extracted negative ion current density and electron-ion-ratio for a variation of the bias current in hydrogen (left side) and deuterium (right side). ELISE was operated in volume operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

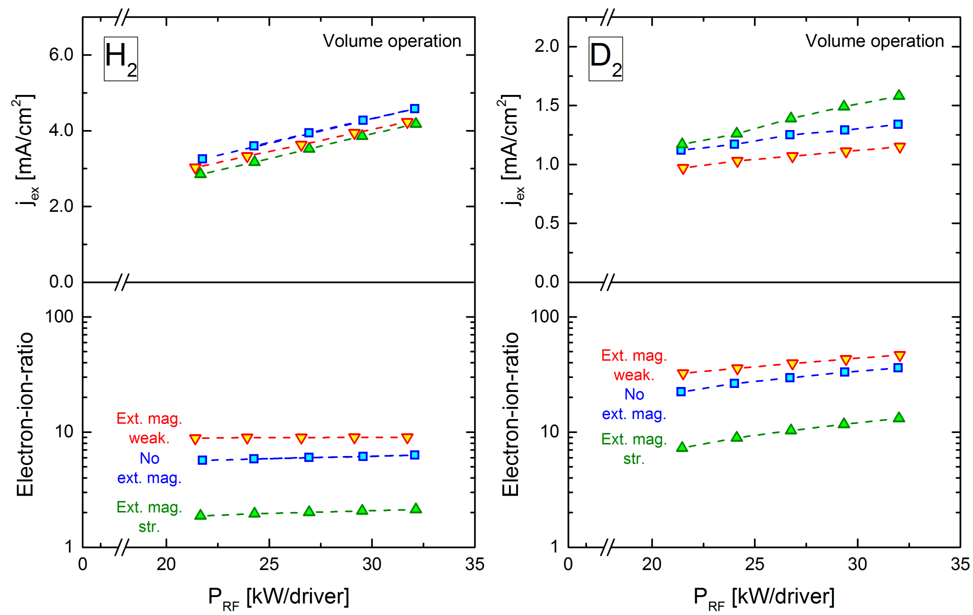

Figure 8: Extracted negative ion current density and electron-ion-ratio for a variation of the RF power in hydrogen (left side) and deuterium (right side). ELISE was operated in volume operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

strengthening configuration for operation of ELISE in volume operation: the small losses in j_{ex} caused by the external magnets can be counteracted by increasing P_{RF} with simultaneously increasing only slightly the co-extracted electrons (strongly reduced by the magnets). This result is in general agreement with results obtained at the prototype source [17] with the filter field generated by permanent magnets.

Although the modified filter field topology created by adding the strengthening external magnets is by far not optimized, it results in a significant improvement of the source performance in volume operation: in hydrogen for the highest magnetic field used and a filling pressure of 0.6 Pa an ion current density of around 2.6 mA/cm^2 could be extracted at an electron-ion-ratio of around 1.1, a result that is extraordinary good for negative hydrogen ion sources based on the volume effect [24].

Results in Surface Operation

Starting again from a standard pulse, variations of I_{PG}, p_{fill}, I_{Bias} and P_{RF} have been performed in a well caesium conditioned source. Due to the generally lower electron current in surface operation it was possible to increase – compared to the investigations in volume operation – P_{RF} and U_{ex} in order to increase the extracted negative ion current without co-extracting too much electrons: P_{RF}=30 kW/driver, p_{fill}=0.6 Pa, I_{Bias}=55 A, U_{ex}=8 kV in hydrogen and 6 kV in deuterium, I_{PG}=2.5 kA in hydrogen, 4 kA in deuterium. The length of the plasma pulses and the beam phase (20 s and 10 s, respectively) was not changed compared to the experiments in volume operation.

The extracted negative ion current density and the electron-ion-ratio for the performed parameter variations are shown in Figure 9, Figure 10, Figure 11 and Figure 12. The general behavior of the extracted currents during the variations is in agreement with previous investigations [16]. In surface

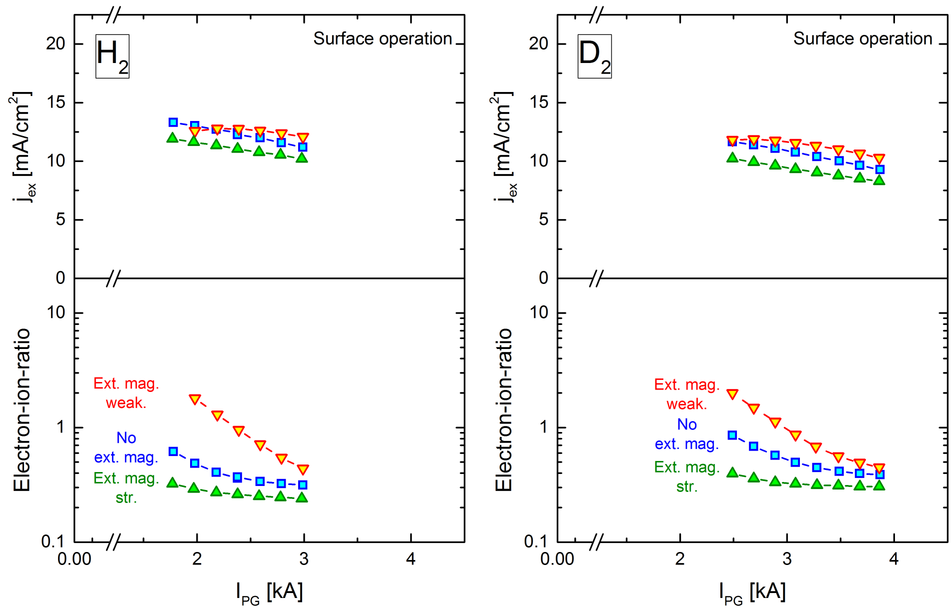

Figure 9: Extracted hydrogen ion current density and electron-ion-ratio for a variation of the PG current in hydrogen (left side) and deuterium (right side). ELISE was operated in surface operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

operation the influence of modifying the modified field topology on the extracted negative ion current density is small and the following discussion will be focused mainly on the electron-ion-ratios:

- Compared to the experiments in volume operation, the extracted negative ion current densities measured are significantly higher (by a factor of around three to four). The electron-ion-ratios are decreased by a factor of around ten and are for most pulses well below one. At the prototype source similar factors have been observed [7] (depending strongly on source parameters like the filling pressure).
  For the chosen source parameters the negative ion current densities and electron-ion-ratios measured for hydrogen and deuterium are much closer together compared to volume operation, with one exception: In the weakening configuration the electron-ion-ratios for hydrogen are noticeably increased compared to deuterium. Reason is that for hydrogen lower I_{PG} are used (standard pulse in hydrogen: 2.5 kA, deuterium: 4.0 kA). In combination with the reduction caused by the weakening permanent magnets the total filter field strength is sufficiently small to result in a strong increase of the cross field diffusion of magnetized electrons toward the extraction system.
- The change of the electron-ion-ratio induced by the external magnets strongly depends on I_{PG} (see Figure 9): for the lowest used I_{PG} (1.8 kA in hydrogen, 2.5 kA in deuterium), an increase by a factor of more than two and a decrease by a factor of around two is seen for the two configurations of the external magnets, respectively. These factors are comparable to the results in volume operation. For increasing I_{PG} the factors decrease until for the highest values of I_{PG} (3.0 kA in hydrogen, 3.9 kA in deuterium) they are below 30 %. This result is in contrast to the

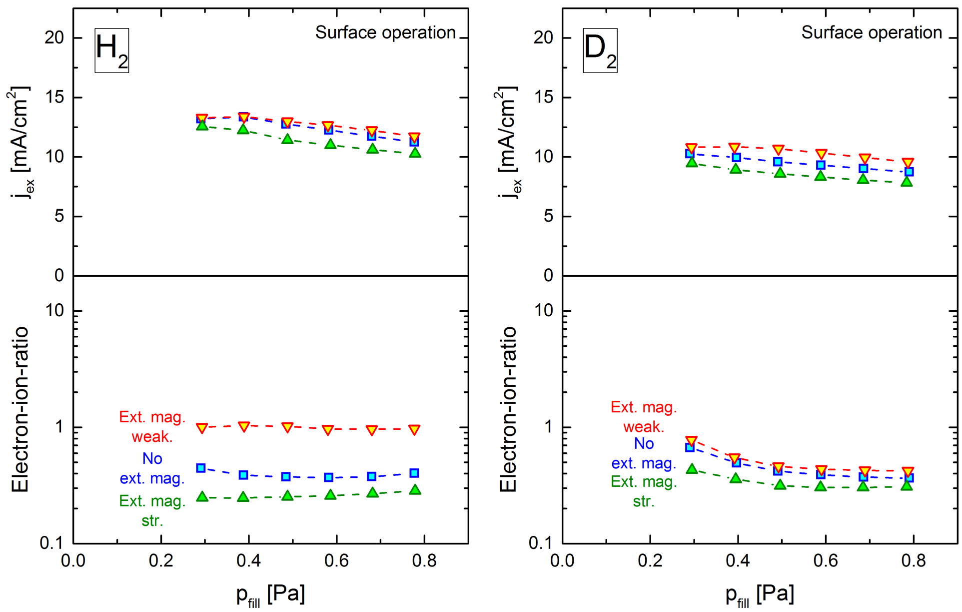

Figure 10: Extracted negative ion current density and electron-ion-ratio for a variation of the filling pressure in hydrogen (left side) and deuterium (right side). ELISE was operated in surface operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

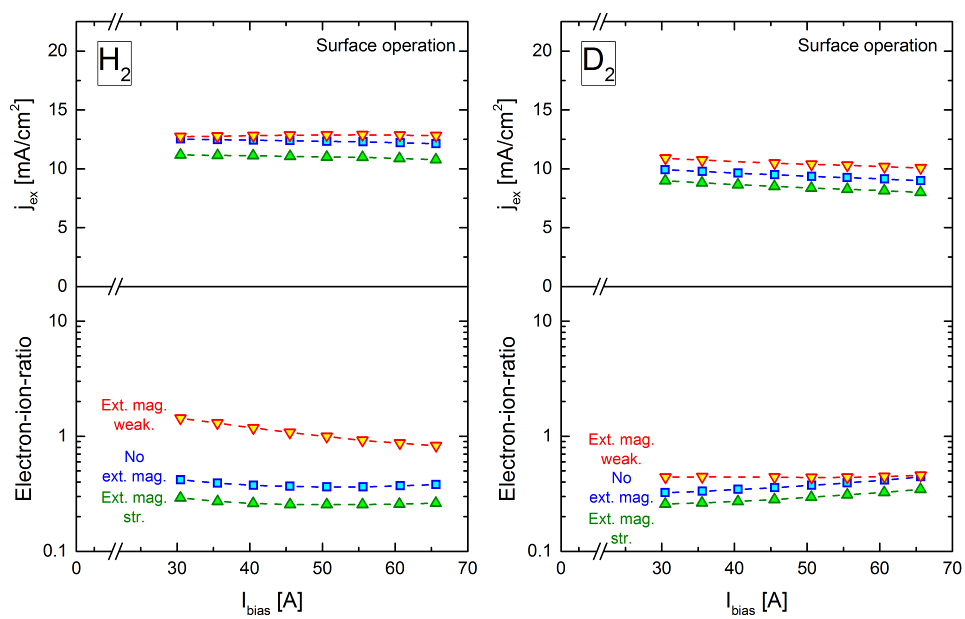

Figure 11: Extracted negative ion current density and electron-ion-ratio for a variation of the bias current in hydrogen (left side) and deuterium (right side). ELISE was operated in surface operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

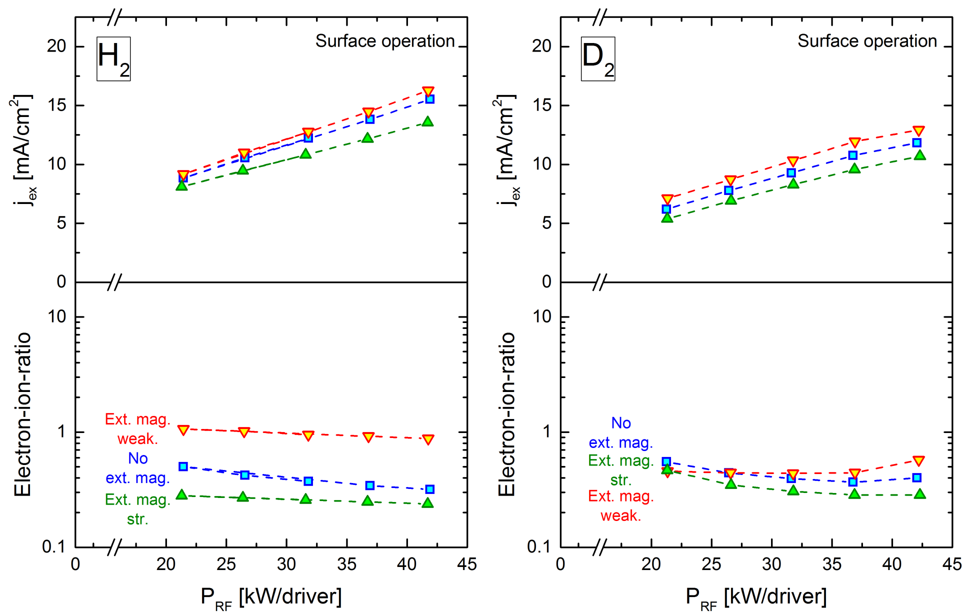

Figure 12: Extracted negative ion current density and electron-ion-ratio for a variation of the RF power in hydrogen (left side) and deuterium (right side). ELISE was operated in surface operation without the external magnets and with the external magnets in the weakening and strengthening configuration.

results in volume operation where the effect of the external magnets on the electron-ion-ratio was more or less independent of I_{PG} (see Figure 5).

- The difference between the extracted negative ion currents measured at the ITER relevant filling pressure of 0.3 Pa for the three field topologies is slightly smaller compared to higher pressures (see Figure 10). Additionally, the reduction of the electron-ion-ratio caused by the strengthening configuration (compared to the standard field) is higher at 0.3 Pa: a reduction of around 40 % is observed. This result – that holds for both isotopes – indicates that the source performance can be improved by the modified field topology particularly for ITER relevant source parameters.
- As can be seen in Figure 11, in hydrogen the electron-ion-ratio is more or less independent of I_{bias} (with the exception of the weakening field configuration) while in deuterium decreasing the bias current even slightly reduces the electron-ion-ratio. In contrast to volume operation it is no longer necessary to draw a high bias current in order to suppress the co-extracted electrons. This is a consequence of the high negative ion density in the extended boundary layer, reducing the electron diffusion towards the PG by means of space charge effects. Similar observations have recently been made at the prototype source for a very good status of the caesium conditioning.
- No definite statement can be made about the dependence on P_{RF} of the reduction or the increase of the electron-ion-ratio observed during the P_{RF} variation (Figure 12): in hydrogen, the step from the standard field configuration to the strengthening magnets is particularly effective for low RF power while in deuterium this is the case for high RF power. Whether this effect is

caused by slight differences of the caesium conditioning during the performed measurements or by a generally valid isotope effect is not yet known.

Influence of the modified field topology on the long pulse stability

This section presents results of long pulses performed at ELISE in surface operation with the strengthening external magnets. The pulses have been done both in hydrogen and deuterium and at an ITER relevant filling pressure.

The upper part of Figure 13 shows j_{ex} and the electron-ion-ratio (one averaged value per beam blip) for the best long pulse performed up to now in hydrogen. The length of the plasma pulse was 30 minutes and the plasma pulse comprises 10 beam blips. The source parameters are as follows: P_{RF}=30 kW/driver, p_{fill}=0.3 Pa, I_{Bias}=20 A, U_{ex}= 8 kV, I_{PG}=2.8 kA. The RF power has been limited due to technical reasons.

The obtained source performance (j_{ex} above 13.3 mA/cm^2 and an electron-ion-ratio below 0.23) and in particular the temporal stability of the extracted currents (no significant change of the extracted currents over the pulse length) is significantly better compared to the best long pulses (one hour) in hydrogen without the external magnets where a extracted negative ion current density of 9.4 mA/cm^2 was obtained [25]. For the first beam blip significantly lower j_{ex} and higher electron-ion-ratio are measured; this is caused by a jump in the matching of the RF circuit that occurred during this phase of the pulse.

Extrapolating the results of the shown stable half-hour-pulse, it seems to be unproblematic to prolong the pulse length up to one hour or to further increase the source performance.

The lower part of Figure 13 shows j_{ex} and the electron-ion-ratio for a one-hour-pulse in deuterium (one averaged value per beam blip, 20 beam blips) with the following source parameters: P_{RF}=20 kW/driver, p_{fill}=0.3 Pa, I_{Bias}=40 A, U_{ex}= 4.5 kV, I_{PG}=4.0 kA. The RF power and the extraction voltage are significantly below the values used for the 30 minutes pulse in hydrogen. Reason is the more pronounced instability of the co-extracted electrons during long pulses in deuterium [19]. Aim was to keep the electron-ion-ratio below one. While j_{ex} decreases only slightly (above 5.7 mA/cm^2) during the pulse, a pronounced increase of the electron-ion-ratio is observed (from 0.30

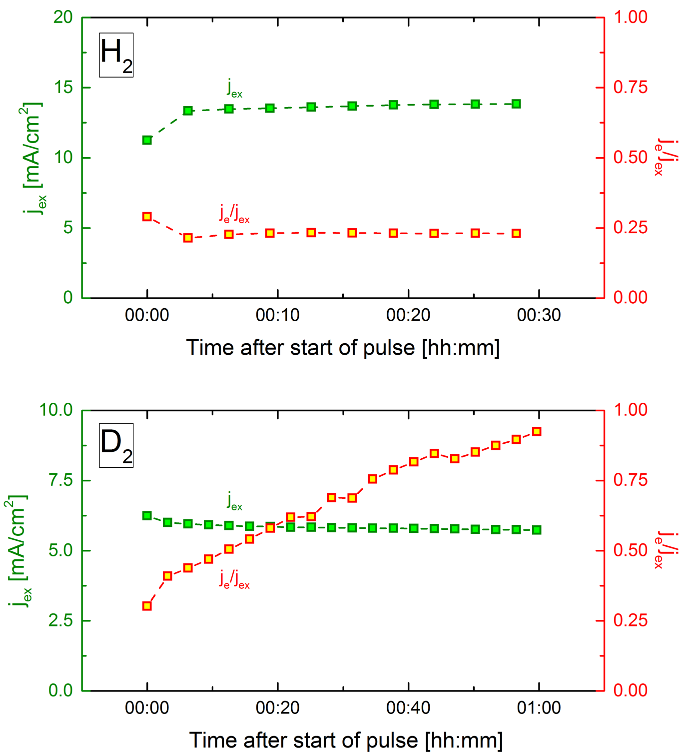

Figure 13: Extracted negative ion current density and electron-ion-ratio for the best long pulses performed in ELISE up to now in hydrogen (upper part) and in deuterium (lower part).

for the first beam blip to 0.92 for the last beam blip).

This pulse was the first one-hour-pulse in deuterium performed at ELISE. In the standard filter field configuration such pulses have not been possible; even during plasma pulses of 180 s length (two beam blips) for comparable source parameters the electron-ion-ratio for the second blip increased significantly above one [16].

As shown in [25], another measure besides modifying the filter field topology that can improve the long pulse stability is simply increasing I_{PG}. However, for an increased standard field not only more stable currents but also a strong reduction of the extracted ion current is observed while using the strengthening external magnets only slightly reduces j_{ex}. This demonstrates that the external magnets do not act as a simple amplification of the standard I_{PG} field but also the modified field topology plays an important role. Changing the field topology modifies – besides the cross-field diffusion of electrons toward the PG – also the trajectories of other charged particles in the plasma like positive caesium ions. Since caesium is ionized to a large degree in such ion sources [26] the latter may have a positive effect on the caesium conditioning of the ion source.

Although the obtained long pulse results – in particular the value of j_{ex} and the stability of the co-extracted electron current in deuterium – are still significantly away from the ITER requirements, the modified field topology represents an important step toward fulfilling these requirements.

Summary and conclusions

At the half-ITER-size NNBI test facility ELISE the influence of a modified filter field topology on the source performance was investigated. Extensive parameter variations have been performed in both volume and surface operation, in hydrogen and in deuterium. In volume operation the amount of co-extracted electrons is significantly reduced (by a factor of three) by external magnets strengthening the standard filter field. This effect is more or less independent of the source parameters. Additionally the extracted negative ion current density is almost not affected by the magnets.

In surface operation the effect of the external magnets on the co-extracted electrons is less pronounced and it depends stronger on the source parameters than in volume operation. Especially for the ITER relevant filling pressure of 0.3 Pa a particularly beneficial effect of the strengthening magnets is observed: the electron-ion-ratio is reduced by around 40 % while the extracted negative ion current density is almost not affected.

Besides enabling a better source performance, the external magnets in the strengthening configuration result in a significantly improved long pulse stability of the source performance and they enabled performing the very first one hour deuterium pulse in ELISE.

The observed effects are not only caused by amplification of the standard I_{PG} field; also the modified field topology plays an important role. Both the field strength and the topology affect the cross-field diffusion of electrons generated in the drivers toward the plasma grid. Additionally playing a role may be the impact of the field topology on the trajectories of positive cesium ions and consequently on the caesium conditioning.

For obtaining a full understanding of the involved physical aspects further experimental investigations are necessary, ideally in cooperation with modelling efforts. As first step toward a fully optimized filter field structure for fulfilling the requirements continuative experiments at ELISE are in preparation using other configurations of the external magnetic field.

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