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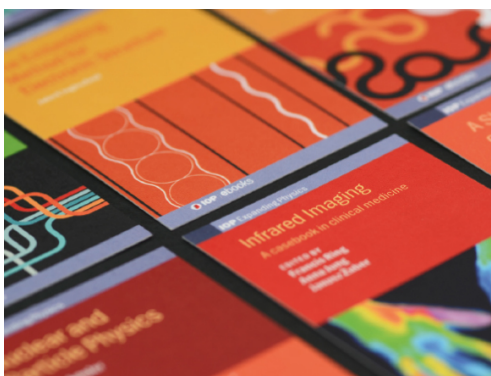
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Initial caesium conditioning in deuterium of the ELISE negative ion source

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Abstract

Negative ion sources used for neutral beam injection in fusion experiments are based on the surface production of H^- or D^- on caesiated low work function surfaces. The amount of co-extracted electrons is much higher in deuterium than in hydrogen and their temporal increase is stronger pronounced. Thus, the transition from a caesium free source by conditioning the source with caesium usually is done in hydrogen. Since for the future application, e.g. in the later operational phases of the international fusion experiment ITER, a direct start-up of the neutral beam heating system in deuterium may be desirable, the test facility ELISE was used for testing initial caesium conditioning in deuterium. This paper describes the conditioning procedure and compares the obtained source performance with results achieved in deuterium after initial conditioning in hydrogen. A comparable general conditioning status can be obtained, i.e. comparable negative ion currents can be extracted for identical source parameters.

Keywords: ITER, neutral beam injection, negative hydrogen ion source, RF driven ion source, negative deuterium ions, initial caesium conditioning

(Some figures may appear in colour only in the online journal)

Introduction

The neutral beam injection (NBI) system at the fusion experiment 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) at a filling pressure p_{fill} of 0.3 Pa.

The development towards the negative ion sources for ITER NBI follows a R&D roadmap defined by the European domestic agency F4E [3, 4]. First step within this roadmap is the RF driven prototype source ($0.3 \times 0.6 \text{ m}^2$ with an extraction area of typically $6 \times 10^{-3} \text{ m}^2$) [5]. The half-ITER-size ion source of the ELISE test facility (Extraction from a large ion source experiment, $1 \times 1 \text{ m}^2$ with an extraction area of 0.1 m^2)

[6, 7] is an intermediate step towards the ITER NBI ion source ($1 \times 2 \text{ m}^2$ with an extraction area of 0.2 m^2) [2]. The latter is in principle identical with the ion source used at the SPIDER and MITICA test facilities under construction at the European Neutral Beam Test Facility PRIMA in Padova [8].

The main production process for negative hydrogen or deuterium ions in these ion sources is the surface process [9] in a low-temperature plasma ($T_e \approx 1 \text{ eV}$, $n_e \approx 10^{17} \text{ m}^{-3}$). The negative ions are produced by conversion of hydrogen atoms and positive ions impinging the caesiated low work function surface (about 2.2 eV for plasma conditions similar to the ones in the ion sources [10]) of the plasma grid (PG), the first grid of the multi-grid, multi-aperture extraction and acceleration system. Extraction of negative ions is accompanied by co-extraction of electrons. These electrons are deflected prior to full acceleration onto an electron dump. The tolerable power load on the dump is technologically limited by its cooling system; for ITER NBI the ratio of co-extracted electrons to extracted negative ions (in the following abbreviated by the term ‘electron–ion ratio’) has to be smaller than one at full source performance.



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When the source is operated without caesium, negative ions are produced predominately in the plasma volume. The transition from volume operation to a surface production dominated source is called initial caesium conditioning process. Caesium is evaporated into the source volume by means of one or more caesium ovens [8, 11]. The evaporation rate (up to several mg h^{-1} [5]) is adjusted by the temperature of the caesium reservoir within the oven. Caesium accumulates at the inner source surfaces and is redistributed during a series of plasma pulses [12, 13]. Small changes in the source performance between single pulses accumulate to a significant performance increase: the extracted ion current increases by a factor of up to ten and the co-extracted electron current decreases by a similar factor [14]. The initial caesium conditioning process typically lasts a few operational days. In order to stay below the power limit of the electron dump it usually is done for reduced RF power, extraction potential and pulse length.

Operation with caesium in deuterium is much more demanding than operation in hydrogen [15]: the extracted negative ion current typically is similar for both isotopes but the amount of co-extracted electrons is significantly larger in deuterium [5]. Additionally, the temporal increase in the co-extracted electron current during pulses is much more pronounced (typical pulse lengths are between about ten seconds and one hour). In order to counteract these effects, the caesium evaporation rate in deuterium typically is larger than in hydrogen. As a result, also the neutral caesium densities in the plasma volume close to the PG are larger: the neutral caesium densities measured by laser absorption in deuterium operation are by a factor of ten higher than in hydrogen.

Up to now, initial caesium conditioning was done in the prototype source and in ELISE in hydrogen operation only. The working gas was switched to deuterium after the transition to surface production of negative ions succeeded, i.e. after in hydrogen a strong increase in the extracted negative ion current and simultaneously a strong decrease of the co-extracted electrons was observed. In the D-T phase of ITER such a procedure might not be possible and deuterium may be used as working gas during initial conditioning. This implies physical differences that can affect the PG surface work function such as different rates for physical and chemical sputtering [12] and different caesium compounds embedded into the caesium layer. This paper describes experiments done at ELISE dedicated to answering the question if these differences affect the obtainable source performance. If a comparable performance can be reached, the lessons learned up to now at the caesiated ion sources for NBI are valid also for the direct start-up of caesiated ion sources in deuterium.

Operation of ELISE with caesium

A schematic view of the ion source used at the ELISE test facility can be seen in figure 1. The plasma is generated by inductive RF coupling into the four cylindrical drivers (RF power $P_{\text{RF}} < 90 \text{ kW/driver}$) and then expands toward the extraction system. ELISE is operated in pulsed mode: plasma

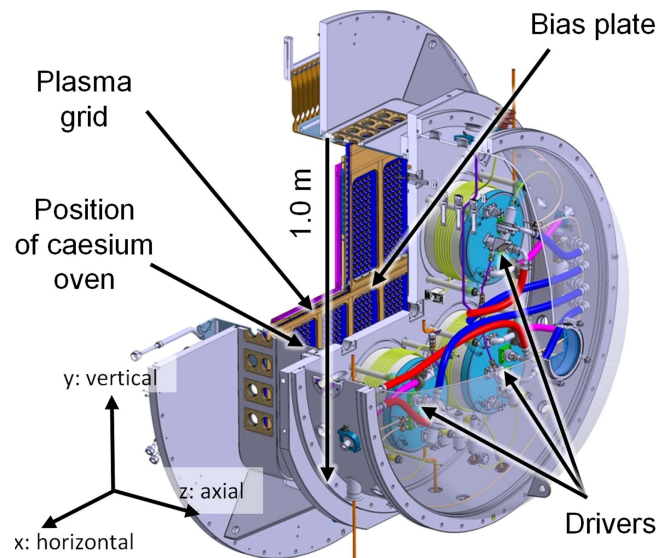


Figure 1. Schematic view of the ELISE ion source. The position of one of the caesium ovens at the left vertical side wall is indicated, the second oven is located at the right source wall.

pulses are possible up to one hour. Due to limitations of the HV power supply used only short extraction phases, so-called beam blips, are possible (length: 10 s; the shortest possible time between two blips is about 150 s).

Two caesium ovens are attached to the vertical side walls (see figure 1). In order to ensure a steady caesium influx, caesium is evaporated constantly during operational days while the ovens are switched off when ELISE is not in operation, e.g. over night. After operational breaks (at night or weekends) the low work function surface may be passivated, making necessary a re-conditioning process, lasting typically up to two hours and consisting of plasma pulses with caesium evaporation.

A horizontal magnetic filter field, created by a current flowing through the PG (usually $I_{\text{PG}} < 4 \text{ kA}$, corresponding to a filter field strength of 3.8 mT at the centre of the PG) and 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 but also for the transport of negative hydrogen ions to the extraction apertures [16, 17]. Additionally, the electron temperature is reduced from about 10 eV in the driver to about 1 eV, resulting in a significant reduction of negative ion destruction by electron stripping [18]. In deuterium operation a much higher filter field strength is necessary (typical values are 3.8 mT in deuterium and 2.4 mT in hydrogen) in order to sufficiently reduce the co-extracted electron current. The filter field can be strengthened or weakened by attaching external permanent magnets. In the strengthening configuration these additional magnets significantly reduce the temporal increase in the co-extracted electrons [19]. A side effect of the horizontal filter field is a vertical plasma drift [18, 20].

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 which is being extended by the so-called bias plate [5]. Usually, the bias current is kept constant

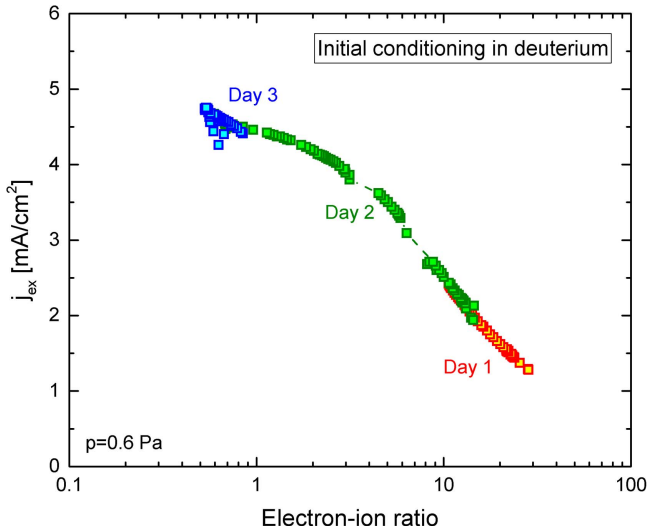


Figure 2. Performance of the ELISE source during three days of caesium conditioning in deuterium, starting with a clean source.

(at values of $I_{\text{Bias}} < 65$ A) during pulses—instead of the bias potential. Result is a constant net charged particle flux onto the PG (within ± 0.05 A during short pulses). It was demonstrated at the prototype source that this operation scenario is beneficial for obtaining stable operation [14, 21].

Negative ions are extracted by an extraction potential U_{ex} of up to 10 kV and then accelerated by the acceleration potential U_{acc} to a total energy of up to 60 kV. Co-extracted electrons are dumped onto the surface of the extraction grid (EG), the second grid of the extraction system. The EG consists of two segments in a vertical arrangement, i.e. a top and a bottom segment. The deposited power is measured separately for both segments and the design limit is 200 kW per segment [6]. A safety interlock is set to 125 kW/segment. Thus, the co-extracted electrons and their temporal increase during pulses can strongly restrict operational parameters like the extraction potential or the RF power and consequently the amount of extracted negative ions or the length of a pulse. In 3.5 m distance to the extraction system the beam is dumped on a diagnostic calorimeter [22].

The work function of the caesiated PG surface can deteriorate by reactions with impurities embedded into or deposited on the caesium layer (from the background gas or the plasma) or by removal of caesium. These deterioration mechanisms can be counteracted by the interaction of the caesiated PG surface with a plasma [23], or by a sufficient caesium flux onto the surface [10], respectively. The interplay of these effects makes it challenging to ensure a low, stable (from pulse to pulse but also during pulses) and homogeneous PG work function during pulses with high extracted negative ion currents (i.e. at a high RF power and/or a high extraction potential) and for long pulses of up to one hour [5]. Such pulses have to be prepared by time-consuming dedicated caesium conditioning procedures [24].

A consequence of the possible work function deterioration is that the extracted negative ion current and the co-extracted electron current for pulses done with identical

source parameters like the RF power and the filling pressure are not necessarily identical. This holds in particular when these pulses are done on different operational days, i.e. a passivation of the low work function surface took place over night (while the caesium ovens are switched off and no active plasma chemistry takes place), followed by re-caesiation.

Utilizing this effect, the extracted and co-extracted currents can be the basis for comparing the caesium conditioning status of ELISE during different pulses: in a well-caesiated source, i.e. working in the surface mode, the co-extracted electron current reacts significantly stronger to small changes in the PG surface work function than the negative ions current [25]. This effect usually is assigned to the fact that in this operational scenario negative ions are the dominant negative space charge carrier in the vicinity of the extraction system while electrons are the minority species (Langmuir probe characteristics show the symmetric shape typical for ion–ion plasmas [26]). Thus, for small electron densities n_e and a constant total density of negative particles, small changes in the density ratio $n_e/n(\text{H}^-)$ can result in a strong relative change of the electron density close to the extraction system (and thus also of the co-extracted electron current) while almost not affecting the negative ions.

Consequently, a comparable negative ion current extracted during pulses with identical source parameters indicate a comparable general caesium conditioning status. If additionally the amount of co-extracted electrons is comparable, the caesium conditioning status is apparently identical. This effect is used in the following to compare the caesium conditioning for deuterium operation after initial conditioning in hydrogen or initial conditioning in deuterium.

Initial caesium conditioning in D_2 and the obtained results

Investigations on initial caesium conditioning in deuterium were done starting with a clean ion source, i.e. no caesium was present and operation was started in volume mode.

Since in volume operation the co-extracted electron currents are in generally much higher as in surface operation, the source parameters used for the conditioning process have to be chosen in a way that the power limit of the EG is not exceeded. For the present investigation lower RF power and extraction potential have been used compared to operation in a well-caesiated source, together with increased filling pressure, bias current and magnetic field strength: $P_{\text{RF}} = 21$ kW/driver, $p_{\text{fill}} = 0.6$ Pa, $I_{\text{bias}} = 55$ A, $I_{\text{PG}} = 4$ kA, $U_{\text{ex}} = 4$ kV.

Short plasma pulses have been performed, $t_{\text{plasma}} = 20$ s with one beam blip of 9.5 s. The pause between two pulses was 5 min. The magnetic filter field was created solely by I_{PG} , i.e. the additional external permanent magnets [19] have not been used.

In pure volume operation an extracted current density j_{ex} of 1.3 mA cm^{-2} is observed for the chosen parameters, at an electron–ion ratio of 28.4. The power deposited by the co-extracted electrons onto the EG surface is well below the

limit: 56 kW for the upper segment and 75 kW for the lower segment. The reason for the vertical asymmetry is the vertical plasma drift caused by the magnetic filter.

After initiating the caesium evaporation, pulses with constant caesium influx have been repeated until stable results have been obtained, i.e. changes in the extracted ion current density j_{ex} and the electron–ion ratio from one pulse to the next pulse were negligibly small. This was the case after three experimental days (235 pulses), i.e. initial caesium conditioning in deuterium lasts no longer than in hydrogen [15].

Figure 2 shows the performance plot (the extracted ion current versus the electron–ion ratio) for these pulses. The plotted values of the extracted negative ion current density represent the average of the current density measured during the second half of the beam extraction phase. The extracted ion current density increased by a factor of about 3.7 (to 4.8 mA cm^{-2}) and the electron–ion ratio decreased by a factor of about 53 (to 0.5). At the prototype source [5] and during conditioning ELISE in hydrogen [15] similar factors have been observed (depending strongly on source parameters like the filling pressure).

On the second and third day operation started with a performance comparable to the day before. This is in agreement with results obtained previously for similar source parameters in hydrogen where during initial conditioning almost no reduction of the performance took place over the nights [15]. However, after a few pulses the source performance degraded (e.g. j_{ex} decreased from 2.4 to 1.9 mA cm^{-2} during the first three pulses of day 2) and 20 to 30 pulses were necessary in order to reach again the best values from the previous day. The reason for this effect is diffusion of a small amount of air into the gas supply system over night and it triggered the replacement of the responsible gas hoses after the end of the campaign.

The performance plot shows two gaps during the second conditioning day. These correlate with longer breaks between two pulses, caused by technical issues and resulting in higher caesium fluence between the pulses. Consequently, a larger amount of caesium is accumulated at the source walls. This typically has a beneficial effect on the source performance and the stability of the co-extracted electrons.

The total plasma-on time during this initial conditioning in deuterium was 1.3 h, the total beam-on time 0.6 h and the time during that caesium injection took place ≈ 22 h (left oven) and ≈ 21 h (right oven). The total amount of injected caesium cannot be determined in a straightforward way. Each oven is equipped with a surface ionization detector (SID) measuring the caesium flux from the oven nozzle [11]. Identification of the absolute evaporated caesium amount requires a calibration factor depending on the geometry of the oven nozzle and the SID. This factor is not known yet and it can be determined only after completely depleting the caesium reservoirs of the ovens. Estimations, based on the calibration for a slightly different geometry result in an upper limit of the injected caesium of 37.7 mg , i.e. the upper limit of the evaporation rate is 1.7 mg h^{-1} , (roughly) equally divided between the both ovens. In agreement with previous investigations this evaporation rate is—despite the larger size of

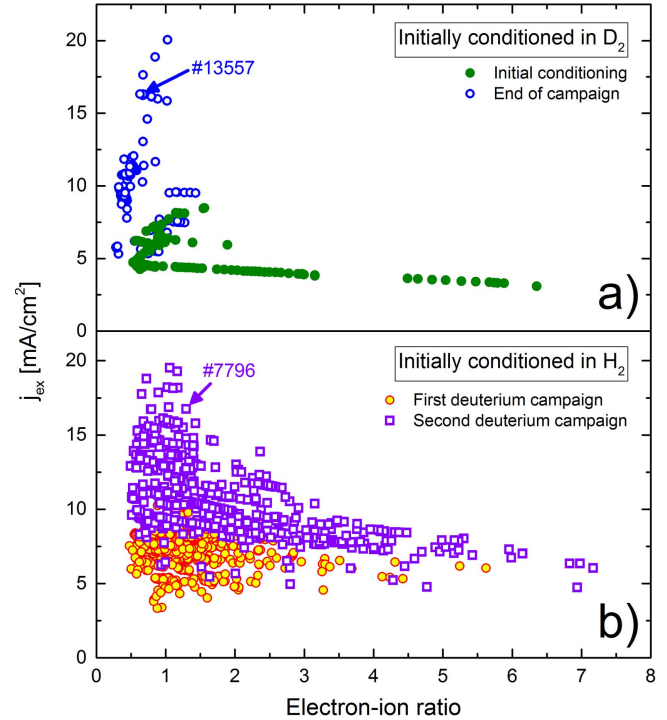


Figure 3. Performance of the ELISE source in deuterium without the external permanent magnets: (a) initial conditioning (starting with a clean source) in deuterium. Full symbols represent pulses at the beginning of the campaign (including the initial conditioning), open symbols the end of the campaign. (b) initial conditioning in hydrogen and then switched to deuterium operation. The arrows mark two pulses done with identical source parameters.

ELISE—comparable to or even smaller than typical values for the prototype source (up to several mg h^{-1} , [5]). These values are larger than the caesium evaporation needed in hydrogen operation: during a hydrogen campaign with comparable source parameters significantly smaller evaporation rates were measured.

The initial conditioning at the beginning of an experimental campaign is the prerequisite for increasing parameters as the extraction potential and the RF power in order to increase the extracted negative ion current while not exceeding the power limit of the EG.

Figure 3(a) shows the performance for all short pulses done during the present deuterium campaign without the external permanent magnets. Full symbols represent pulses done at the beginning of the campaign, including the initial conditioning pulses shown in figure 2. In order to ensure that results for a well-conditioned source (i.e. a low ratio of co-extracted electrons to extracted negative ions) are well recognizable the vertical axis scale has been restricted to electron–ion ratios smaller than 8.

Open symbols in figure 3(a) represent pulses done at the end of the campaign. In between these two sets, 1019 pulses (20 operational days) have been done with the external magnets in different configurations (strengthening or weakening the I_{PG} field [19]). While at the beginning of the campaign reduced source parameters (RF power, extraction potential) have been used, aim of the final pulses was to

obtain the best possible performance. In order to do so, besides increasing the source parameters different caesium conditioning techniques have been tested [24]. The target value for ITER (28.5 mA cm^{-2}) has not been reached. One reason for this is the pronounced increase in the co-extracted electrons during the pulses [15, 19]. Additionally, due to technical limitations [27] the PF power could not be increased to its maximum: about 57 kW/driver were possible instead of 90 kW. A group of results can be seen with $j_{\text{ex}} \approx 16 \text{ mA cm}^{-2}$; these have been obtained with $P_{\text{RF}} = 40 \text{ kW/driver}$ and $U_{\text{ex}} = 10 \text{ kV}$. For the three pulses with higher j_{ex} the RF power was increased up to 57 kW/driver. The increase of j_{ex} with the RF power is the result of an increase in the dissociation degree in the driver (to be determined by optical emission spectroscopy [28]) and consequently an increase in the atomic hydrogen flux impinging the PG.

For comparison, figure 3(b) shows the short pulse performance for the two previous deuterium campaigns, done without the external permanent magnets: 820 pulses were done during the first of the two campaigns, circular symbols and 629 during the second one, squared symbols. Initial conditioning was done in hydrogen up to a clearly finished transition to surface condition (for the reduced parameters used for the initial conditioning). Then, it was switched to deuterium operation.

The pulses shown in figure 3 have been done for a wide range of different source parameters ($P_{\text{RF}} = 21 \dots 57 \text{ kW/driver}$, $p_{\text{fill}} = 0.3 \dots 0.9 \text{ Pa}$, $I_{\text{bias}} = 5 \dots 65 \text{ A}$, $I_{\text{PG}} = 1.0 \dots 4.4 \text{ kA}$, $U_{\text{ex}} = 2.5 \dots 9.5 \text{ kV}$) and additionally the number of pulses without the external magnets done with initial caesium conditioning in D_2 (figure 3(a)) is lower than the one for initial conditioning in H_2 (figure 3(b)). Nevertheless, the following general statements can be made:

- The maximum obtained negative ion current density does not depend on the isotope in that initial conditioning has been done.
- Directly after the initial conditioning in D_2 (full symbols in figure 3(a)) comparable electron–ion ratios (down to ≈ 0.5) have been obtained as for initial conditioning in H_2 (figure 3(b)).
- The dependence of the extracted negative ion and electron currents on the source parameters is in general comparable for initial conditioning in D_2 and H_2 ; results of systematic investigations done after initial conditioning in D_2 are shown elsewhere [19].
- The final pulses of the deuterium campaign based on initial conditioning in D_2 (open symbols in figure 3(b)) show significantly lower electron–ion ratios (down to ≈ 0.3) than seen both at the beginning of this campaign and during previous campaigns.

Exemplarily two pulses (marked by arrows in figure 3) with identical source parameters ($P_{\text{RF}} = 42 \text{ kW/driver}$, $p_{\text{fill}} = 0.35 \text{ Pa}$, $I_{\text{bias}} = 55 \text{ A}$, $I_{\text{PG}} = 4 \text{ kA}$, $U_{\text{ex}} = 10 \text{ kV}$) have been identified for initial conditioning in deuterium (pulse #13557) and in hydrogen (#7796). Time traces of the extracted currents for these pulses are shown in figure 4.

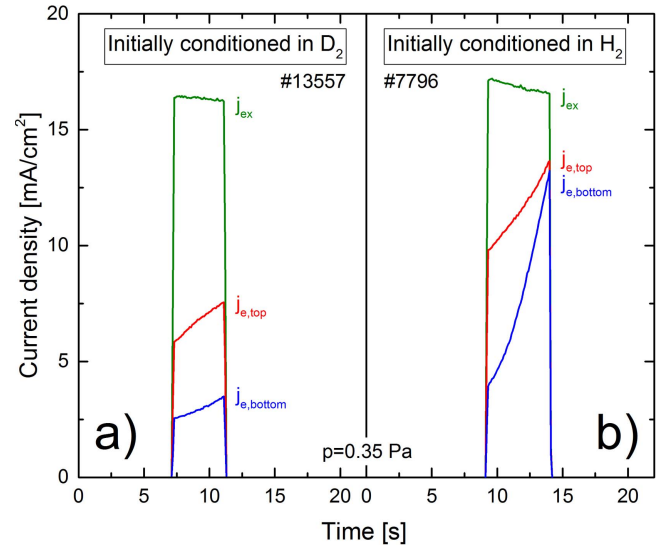


Figure 4. Time traces of the extracted ion current density and the co-extracted electron current density for the upper and lower segment of the extraction system for two deuterium pulses with identical source parameters and: (a) initial conditioning in D_2 . (b) Initial conditioning in H_2 and then switched to deuterium operation.

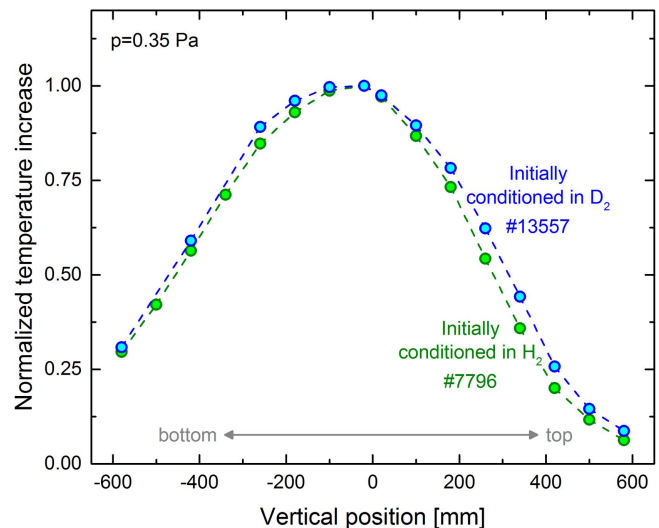


Figure 5. Vertical beam profile measured using thermocouples in the diagnostic calorimeter for two deuterium pulses with identical source parameters, initial conditioning in D_2 and initial conditioning in H_2 and then switched to deuterium operation. The profiles are normalized to temperature increase in the beam centre.

The observation of generally comparable extracted ion currents is confirmed: the measured ion current densities are virtually identical (16.1 A for initial conditioning in D_2 , 16.5 A for initial conditioning in H_2). Additionally, the beam profiles for these pulses, measured using thermocouples embedded into the diagnostic calorimeter (figure 5), are very similar: within the error bar of the measurement ($\pm 10\%$) the profiles are identical, although the beam profile measured after initially conditioning in H_2 seems to be slightly narrower.

For both pulses shown in figure 4 a distinct increase in the co-extracted electrons is seen—as typically observed for operation in deuterium [15]. The co-extracted electrons are by a factor of more than two lower for initial conditioning in deuterium (10.1 A compared to 21.4 A for initial conditioning in H₂).

Additionally, for initial conditioning in hydrogen a slightly stronger vertical asymmetry of the electrons is observed at the beginning of the beam blip ($j_{e,top}/j_{e,bottom} = 2.3$ for initial conditioning in D₂, compared to 2.5 for initial conditioning in H₂) and their temporal increase during the pulse is much stronger pronounced for initial conditioning in H₂: the electron–ion ratio increases up to 1.6, while for initial conditioning in D₂ it increases up to 0.7.

These results indicate that initial conditioning in hydrogen and deuterium is in general comparable, but not fully identical status of the caesiation was obtained. The reason for this small difference in the caesiation can be the larger number of pulses in the present deuterium campaign than in the previous campaigns or a beneficial long-term effect of operating the source with the external magnets.

Although the electron–ion ratios are below one and thus fulfil the ITER requirements it has to be kept in mind that these pulses have been done with reduced RF power. Approaching the ITER values for the extracted negative ion current by increasing the RF power implies a strong increase in the co-extracted electron current and its temporal increase.

Summary and conclusions

For the first time the initial caesium conditioning of the half-ITER-size NNBI ion source test facility ELISE was done in deuterium. The transition from volume to surface production was finished after three days—indicating that the working gas does not impact the duration of the initial conditioning procedure.

Although only an upper limit can be given for the amount of evaporated caesium, it seems that the previously made statement of a comparable or smaller caesium consumption in ELISE than in the prototype source is valid also for this operational scenario. In agreement with results obtained at the prototype source the caesium evaporation rate needed in deuterium operation is significantly larger compared to hydrogen. For short pulses and comparable source parameters the same extracted negative deuterium ion current (acting as indicator for the general status of the caesium conditioning) is achieved for both initial conditioning scenarios (using deuterium or hydrogen) and identical source parameters. The co-extracted electron current density (acting as indicator for small differences in the conditioning) shows differences in the absolute value, in the top-bottom symmetry and in the temporal behaviour. These results indicate that the start-up of negative ion based NBI systems can be done directly in deuterium. When the initial caesium conditioning is finished, the source can be operated without distinguishing between the used start-up scenarios. This result is of high relevance for

planning the NBI operation in later operational phases of ITER.

The most urgent challenge is to obtain low and stable currents of the co-extracted electrons for high RF power, especially in deuterium operation and during long pulses. Full understanding of the observed differences in the co-extracted electron current may be the first step towards the identification of effective measures for further suppressing and stabilizing the co-extracted electrons in deuterium and thus crucial for demonstrating ITER relevant long pulses. These will be main topics of research in ELISE in the near future.

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