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 transition from a caesium free source to negative ion production predominately by the surface process 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.

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 (0.3×0.6 m^2 with an extraction area of typically 6·10^{-3} m^2) [5]. The half-ITER-size ion source of the ELISE test facility (Extraction from a Large Ion Source Experiment, 1×1 m^2 with an extraction area of 0.1 m^2) [6,7] is an intermediate step towards the ITER NBI ion source (1×2 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 ($T_e \approx 1$ eV, $n_e \approx 10^{17}$ 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 has to be smaller than one.

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 [5]) is adjusted by the caesium reservoir temperature. Caesium forms reservoirs on the inner surfaces and is redistributed during a series of plasma pulses [12,13]. Result is a gradual but drastic increase of the source performance from pulse to pulse: 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 of the co-extracted electron current during pulses is much more pronounced. 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: measured by laser absorption in deuterium operation are by a factor of ten higher densities than in hydrogen.

Up to now, initial caesium conditioning was done in the prototype source and ELISE in hydrogen operation only. The working gas was switched to deuterium after the transition to surface production of negative ions was clearly finished, i.e. a strong increase of 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 will not be possible and deuterium will 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_{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 extraction phases, so-called beam blips (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. overnight. After operational breaks (at night or weekends) the low work function surface is passivated and a re-conditioning process is necessary, consisting of plasma pulses with caesium evaporation.

A horizontal magnetic filter field, created by a current flowing through the PG (usually I_{PG}<4 kA, corresponding to a filter field strength of 3.8 mT at the center 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 [19]. A side effect of the horizontal filter field is a vertical plasma drift [18,20].
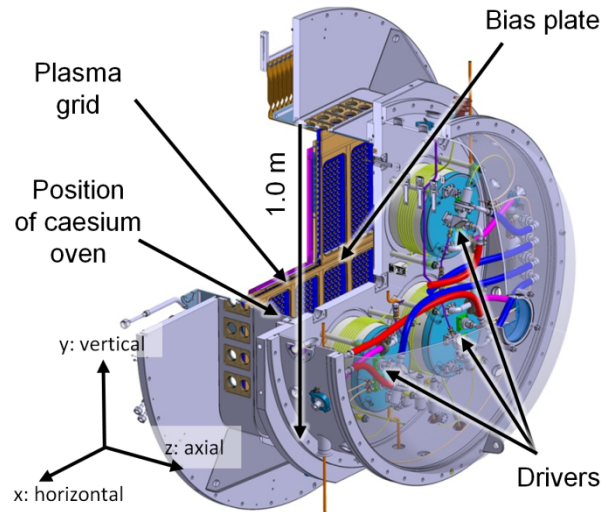
Figure 1: Schematic view of the ELISE ion source. The position of one of the caesium oves at the left vertical side wall is indicated, the second oven is located at the right source wall.

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 [5]. Usually, the bias current is kept constant (at values of I_{Bias}<65 A) during pulses – instead of the bias potential. Result is a constant net charged particle flux onto the PG (to 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 extraction grid 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 [3]. A safety interlock takes effect at 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 hits 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, i.e. 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, 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 the surface mode negative ions are the dominant negative space charge carrier in the vicinity of the extraction system while electrons are the minority species. Consequently, the co-extracted electron current reacts significantly stronger to small changes in the PG surface work function than the negative ions current [25]. 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 within this publication 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. Reduced source parameters have been chosen due to the typically high co-extracted electron currents in volume operation and the power limit of the EG: P_{RF}=21 kW/driver, p_{fill}=0.6 Pa, I_{bias}=55 A, I_{PG}=4 kA, U_{ex}=4 kV.

Short plasma pulses have been done, t_{plasma}=20 s with one beam blip of 9.5 s. The pause between two pulses was 5 minutes. 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, i.e. initial caesium conditioning in deuterium lasts no longer than in hydrogen [15].

Figure 2 shows the performance plot (the extracted ion current vs. 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
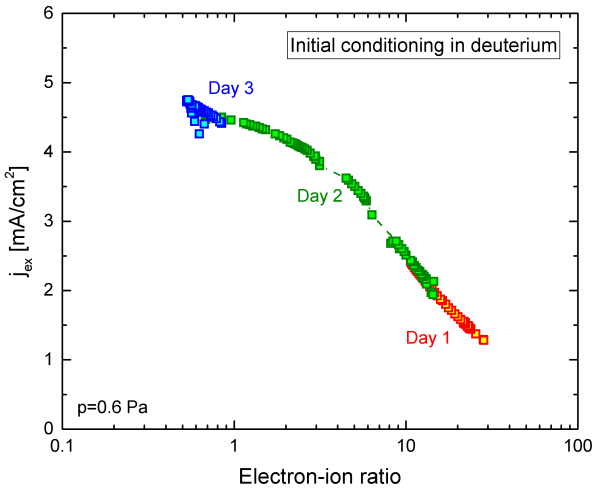
Figure 2: Performance of the ELISE source during three days of caesium conditioning in deuterium, starting with a clean source.

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 beginning 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 mA/cm^2 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 overnight 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 deposited in the reservoirs at the source walls. This typically has a beneficial effect on the source performance, in particular on the long pulse stability.

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, (roughly) equally divided between the both ovens. In agreement with previous investigations this evaporation rate is – despite the larger size of ELISE – comparable to or even smaller than typical values for the prototype source (up to several mg/h [26]). These values are larger than the caesium evaporation needed in hydrogen operation: during a hydrogen campaign with comparable source parameters by more than a factor of ten 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 3a shows the performance for all pulses done during the present deuterium campaign without the external permanent magnets. Full symbols symbolize 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 3a 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. The target value for ITER (28.5 mA/cm^2) has not been
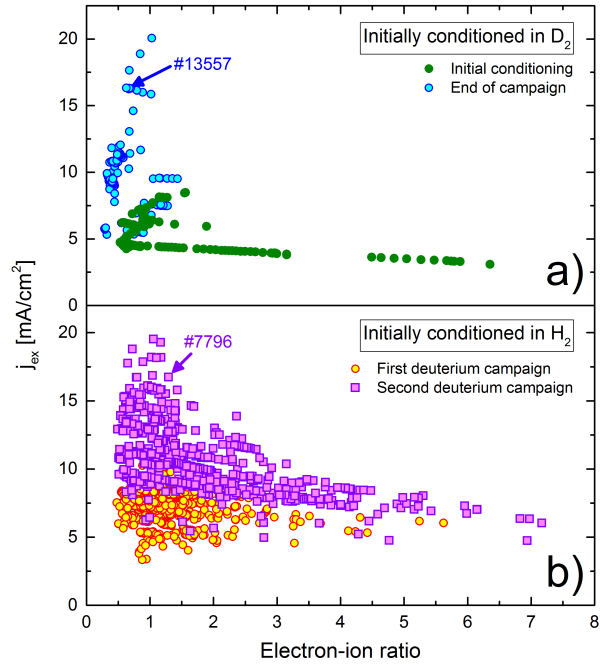

Figure 3: Performance of the ELISE source in deuterium without the external permanent magnets: a) initial conditioning (starting with a clean source) in deuterium. Full symbols represent pulses at the beginning of the campaign (including the initial conditioning), open symbols the end of the campaign.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

reached. One reason for this is the pronounced increase of the co-extracted electrons during the pulses [19,15]. Additionally, due to technical limitations [27] the PF power could not be increased to its maximum: reached were about 57 kW/driver instead of 90 kW.

As comparison, Figure 3b shows the 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.

Although the pulses shown in Figure 3 have been done for a wide range of different source parameters (P_{RF}=21…105 kW/driver, p_{fill}=0.3…0.9 Pa, I_{bias}=5…65 A, I_{PG}=1.0…4.4 kA, U_{ex}=2.5…9.5 kV) and the number of pulses without the external magnets done in deuterium with initial caesium conditioning in D_2 (Figure
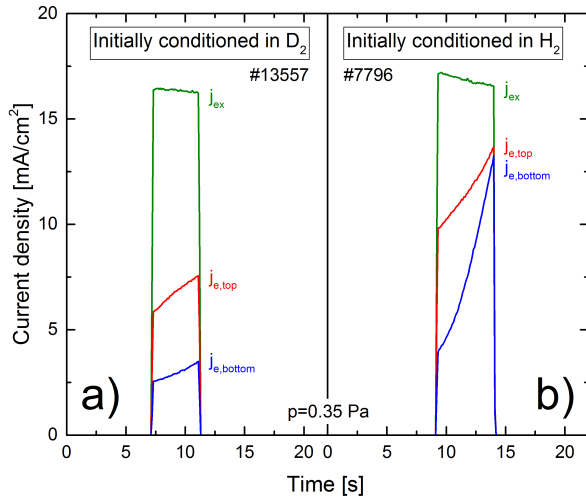
Figure 4: Time traces of the extracted ion current density and the co-extracted electron current density for the upper and lower segment of the extraction system for two deuterium pulses with identical source parameters and: a) initial conditioning in D₂. b) initial conditioning in H₂ and then switched to deuterium operation.

3a) is lower than the one for initial conditioning in H_2 (Figure 3b), 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 3a) comparable electron-ion ratios (down to ≈0.5) have been obtained as for initial conditioning in H_2 (Figure 3b).
- The final pulses of the deuterium campaign based on initial conditioning in D_2 (open symbols in Figure 3b) 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_{RF}=42 kW/driver, p_{fill}=0.35 Pa, I_{bias}=55 A, I_{PG}=4 kA, U_{ex}=10 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.

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 profiles of the extracted negative ion beams measured at the diagnostic calorimeter are almost identical for the two pulses (not shown here).

For both pulses a distinct increase of 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 H_2). Additionally, for initial conditioning in hydrogen a stronger vertical asymmetry and a stronger increase of the electrons during the pulse is observed.

These results indicate that for initial conditioning in hydrogen and deuterium an 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 electron-ion ratios of ≈0.3 or ≈0.5 clearly 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 of the co-extracted electron

current. Thus, understanding the reason for the comparable ion currents but different electron-ion ratios at reduced source parameters may be crucial for demonstrating ITER relevant long pulses. This topic will be investigated in more detail in upcoming deuterium campaigns.

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 (acting as indicator for small differences in the conditioning) shows differences in the absolute value, the top-bottom symmetry and the temporal behavior.

These results indicate that the start-up of negative ion based NBI systems can be done directly in deuterium. 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, especially in deuterium operation and during long pulses. Fully understanding 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. These will be main topics of research in ELISE in the near future.

Acknowledgements

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