Deuterium Results at ELISE

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Abstract. The ITER neutral beam system will be equipped with large RF driven negative ion sources, with a cross section of 0.9 m x 1.9 m, which have to deliver extracted D^- ion beams of 57 A at 1 MeV for one hour. On the ELISE test facility a source of half of this size is being operational since 2013. Goal of this experiment is to demonstrate a high operational reliability and to achieve the extracted current densities and beam properties required for ITER. Technical improvements of the source design and the RF system were necessary to provide reliable operation in steady state with an RF power of up to 300 kW. While in short pulses the required D- current density has almost been reached, the performance in long pulses is determined in particular in Deuterium by inhomogeneous and unstable currents of co-extracted electrons. By refined caesium evaporation and distribution procedures, and reduction and symmetrization of the electron currents considerable progress has been made and up to 190 A/m^2 D^-, corresponding to 66 % of the value required for ITER, have been extracted for 45 minutes.

I. INTRODUCTION

In the ITER source the plasma is generated with a total RF power 800 kW in eight cylindrical RF sources (“drivers”) from which it expands into the main chamber. Negative ions are produced by surface conversion mainly of atoms on the plasma grid surface covered by Caesium. The negative ion beam has to be extracted from 1280 apertures having an area of 2000 cm^2 with a current density of 329 A/m^2 H^- for up to 1000 s and 286 A/m^2 D^- for 3600 s, both at 0.3 Pa. The ratio of co-extracted electrons to extracted ions has to be below one and the beam non-uniformity less than 10%[1]. Prototypes of the ITER source will be tested starting in 2018 at the SPIDER test facility and some years late at MITICA at the NBTF (Neutral Beam Test Facility) at RFX in Padua[2].

The ion source of the ELISE test facility (extraction from a large ion source experiment) is half the size (0.9 x 1 m^2) and has four drivers supplied by two 1 MHz RF generators. Apart from the size the design of the source and the extraction system is similar to that of the ITER source. Due to the available HV power supply beam extraction is only possible pulsed with a duty cycle of 10s/180s, whereas the source can be operated in steady state. The aim of the ELISE experiment is to identify and solve technical and physical issues, which could prevent to reach the ITER requirements for the extracted beams. The resulting modifications could be implemented in the design of the large source in an early stage.

In previous experimental campaigns reliable long pulse operation at high RF power was not possible without several modifications of the initial source design. The extracted currents in hydrogen as well as in deuterium reached in short pulses a high level from which could be expected to meet the ITER requirements with the RF power supply of the ITER source. In long pulses, however, the RF power had to be reduced due to the increasing currents of co-extracted electrons. This was more pronounced in deuterium, such that in 2015 only 60 A/m^2 could be extracted in a one hour pulse[3,4]. In this paper the progress which has been achieved in the last operational period in deuterium is described.

II. THE ELISE SOURCE AND IMPROVEMENTS OF THE DESIGN

In the drivers (outer diameter 300 mm) an internal Faraday shield protects the alumina insulators from plasma erosion. Each RF generator supplies two horizontally neighbored drivers, which are connected in series. Beam extraction up to 60 kV and 20 A is possible with a 3 grid extraction system (area 985 cm^2) divided, like at ITER, in 8 arrays of 5 x 16 apertures with Ø 14 mm. The plasma facing grid (PG) is biased positively with respect to the source to reduce the current of co-extracted electrons. The electrons are deflected by small permanent magnets to the extraction grid. Top and a bottom half of the extraction grid are electrically insulated. This special feature, which is not used at the large source, enables to measure the currents of the co-extracted currents on the grid halves separately. Caesium is evaporated into the main source chamber by two Caesium ovens mounted to the lateral walls. Various plasma and beam diagnostics are available (Langmuir probes, optical emission spectroscopy, tunable laser absorption spectroscopy (TDLAS), beam calorimeter, tungsten wire calorimeter, beam emission spectroscopy). More details about the source, the testbed and the diagnostics can be found in previous publications[5,9,13].

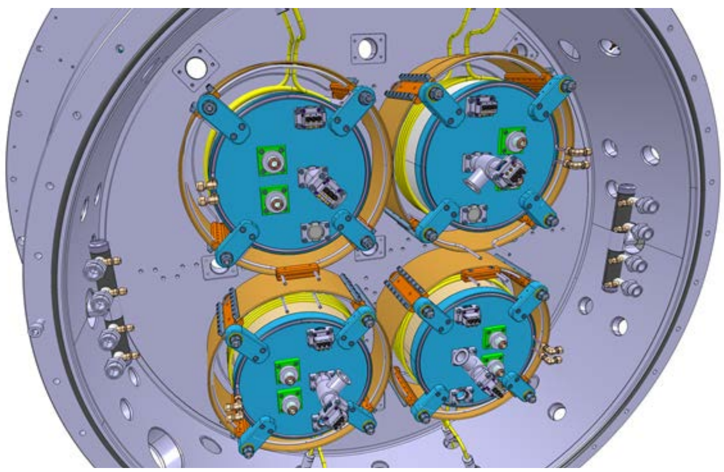

FIGURE 1. The four drivers of the ELISE source

The first necessary design change for reliable source operation at high power was to surround each driver by a copper shield in order to avoid mutual inductance (see Fig. 1). Without shielding severe damages of internal Faraday shields occurred in earlier prototypes[6]. This shield - as other components - had to be further upgraded by active cooling for high power operation of the source for long pulses.

The second was to avoid RF breakdowns at the RF coils which could occur at high RF power. This was achieved by replacing the alumna insulators with quartz and keeping a gap of 2 mm between the RF coil and the insulator. In this way the electric field strength between coil and insulator was reduced by more than an order of magnitude[7]. The RF coil, which is made of 8 mm copper tube, is fixed by silicone combs mounted into the interspace to the insulator. The RF coil, which is made of 8 mm copper tube (water cooled), is fixed by silicone combs mounted in the interspace to the insulator. As the interface between the copper coil and the RF power supply/cooling system is difficult for ITER (brazing not allowed), alternatively stainless steel coils coated with a 0.1 – 0.3 mm thick copper layer have been prepared and will be tested in future. The copper has to be locally removed for the welding of vacuum tight connections.

A further improvement was to replace the initially used self-excited tube based oscillators for the RF power supply by two 150 kW solid-state RF amplifiers, each supplying two drivers switched in series. This change resulted in much more reliable operation at high power due to the stable frequency and a better matching to the source[8].

A magnetic filter field in front of the first grid is essential to reduce the electron current and the electron temperature. It is generated by a current of several kA flowing through the plasma facing grid (PG). In later experiments it was found that strengthening this field by additional permanent magnets attached to the lateral sides of the source reduce the currents of co-extracted electrons considerably and stabilize these currents during long pulses[9].

III HYDROGEN AND DEUTERIUM COMPARISON

The isotope effect has been investigated by codes (Bacon, TrajAn[10]) utilizing only the effect of the different masses on the calculated properties. An important result is that due to the mass ratio of the isotopes the deuterium flux to the PG, where the conversion to negative ions takes place, is smaller by the square root of the mass than for hydrogen at the same density. Another result was that the calculated extraction probabilities for deuterium are lower for the same plasma parameters. But these effects are compensated by the higher ionization and dissociation degree of deuterium plasmas[11] which leads to a larger flux of neutrals and ions onto the plasma grid and hence a larger amount of negative ions that leaves the plasma grid. Finally the extracted current density is almost the same both for hydrogen and deuterium. This has been confirmed by measurements with the smaller prototype at the BATMAN test facility which showed for deuterium a higher negative ion density in the source, but similar extracted ion currents[12].

The plasma density in deuterium is in general higher at the same parameters. In particular close to the plasma grid a 60 % higher density has been measured in the BATMAN source by probes[12]. This is seen as the reason for the higher currents of co-extracted electrons compared to hydrogen operation observed in all experiments.

IV. RESULTS

A. Conditioning in hydrogen

The Caesium which is evaporated into the source is initially deposited mainly on the walls. To achieve the best source performance and stable electron currents it is necessary even in short pulses to distribute the Caesium homogeneously on the plasma grid by series of plasma pulses with or without beam extraction. Refined procedures for this "conditioning" have been developed consisting of combinations long pulses, short pulses and long breaks in between[13]. Until stable currents are reached in long pulses several days or weeks of operation are needed dependent on the starting conditions.

Before the deuterium campaign was started the first conditioning was done in hydrogen. In short pulses in hydrogen a maximum extracted current density of 30.4 mA/cm^2 (29.8 A) with an electron to ion ratio j_{el}/j_{H^-} of 0.4 has been reached with 300 kW total power (see Fig.2). The current was limited only by the HV and the RF power supply and it can be expected that the required 33 mA/cm^2 would be achievable with less than 85 kW/driver.

In long pulses in hydrogen the power of the electron current deposited on the top half of the extraction grid, which is higher than on the bottom half, was the limiting factor. The power load has to be lower than 125 kW to protect the grid from damage. For that reason the maximum total RF power had to be reduced to 200 kW or less. In the best long pulse, which is shown in Fig. 3, a current density 220 A/m^2 (with $j_{el}/j_{H^-} < 0.75$) could be extracted for 1160s.

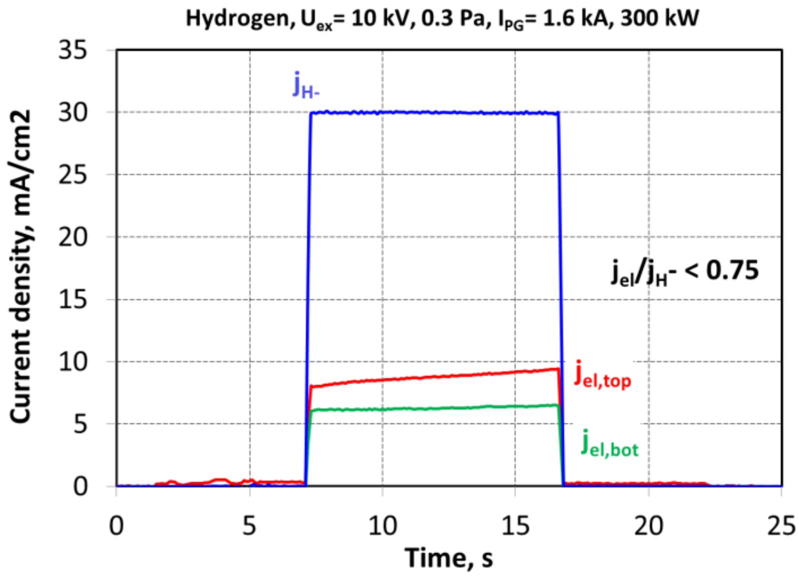

FIGURE. 2. Extracted current densities of the ions and the electrons in a10s pulse in hydrogen

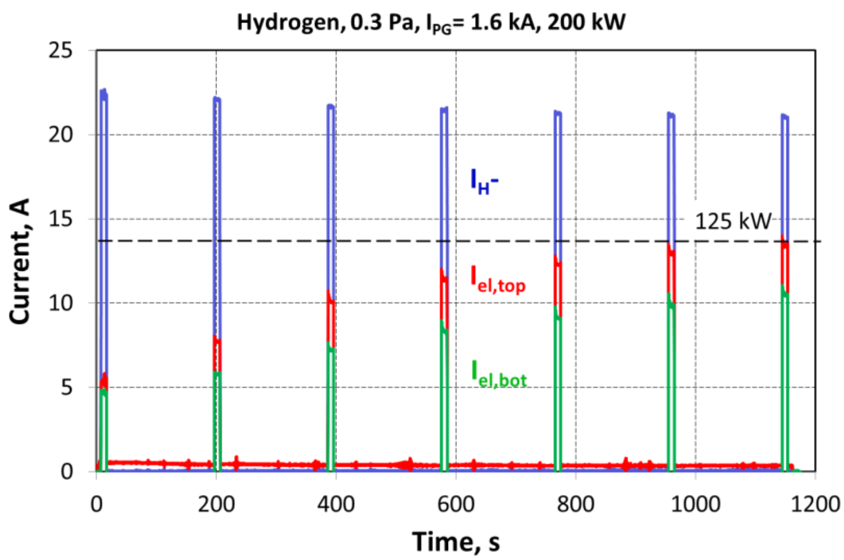

FIGURE 3. 1160s pulse in hydrogen with the 125 kW power limit for the co-extracted electrons on the extraction grid halves

B. Deuterium results with elevated Cs density

The electron currents in deuterium are in general higher and less stable than in hydrogen. The strength of the filter field as well as the bias voltage has to be raised to compensate this increase; both measures reduce slightly the ion currents. The PG currents which are in hydrogen around 2 kA had to be ramped up in deuterium to 3.5 – 4.5 kA corresponding to 3.5 – 4.5 mT close to the PG.

To achieve the maximum ion currents in deuterium the caesium density in the plasma has to be higher by about one order of magnitude. Whereas the neutral Caesium density was in hydrogen below 1 x10^{14} m^{-3}, in deuterium typically 0.5 to 1.5 x 10^{15} m^{-3} has been measured by TDLAS[14]. The higher Caesium density was only possible, because the initially used dispenser caesium ovens were replaced by liquid Caesium ovens, which enable a much higher evaporation rate. In this way ion currents with 220 A/m^2 could be extracted with an RF power of 260 kW as shown as in Fig. 4. The increase of the electron current on the top grid again limited the RF power and the pulse had to be stopped after 6.4 s due to overload of the extraction grid. However, using the new ovens was a major step forward for the source performance in long pulses. The maximum ion current density in a one hour pulse, which was only 60 A/m^2 in the previous deuterium campaign using dispenser ovens, increased to 154 A/m^2 at 180 kW.

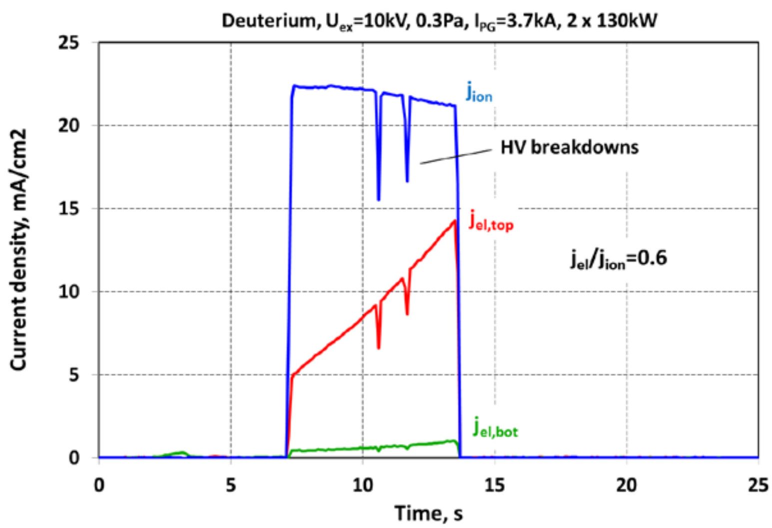

FIGURE 4. Extracted current densities the ions and the electrons in a 6.4 s pulse in deuterium

C. Asymmetry of the co-extracted electrons in deuterium

It is obvious from Figs 2 and 4 that compared to hydrogen the asymmetry of the electron currents is in deuterium much more pronounced than in hydrogen. This was also indicated by measurements with two Langmuir probes close to the PG. On the bottom side of the source the probe characteristics is that of an ion/ion plasma, on the top side the electron saturation current is much higher. Although the top/bottom electron currents are very different, the analysis of the beam diagnostic shows almost the same ion currents from the top and bottom part of the extraction area, but differences in beam profile and divergence[15].

Reason for the electron asymmetry is the magnetic filter field, which causes a cross-B-drifts in vertical direction and an asymmetric overlap of the expanding plasma at the exit of the drivers. In a 2D fluid code[16] the resulting accumulation of the electrons in front of the PG being more intensive at the top side has been confirmed for ELISE. A possible way to influence the plasma flux is to install mechanical structures close to the plasma grid. Such a test had already been carried out with the prototype sources of 1/8 of the ITER size with only one driver. Insertion of a metal rod perpendicular to the magnetic filter field reduced the electron currents. To test this effect at ELISE six metal rods have been mounted close to the PG perpendicular to the magnetic filter field, three from the top and three from the bottom. As shown in Fig. 5 the rods are placed between the beamlet groups.

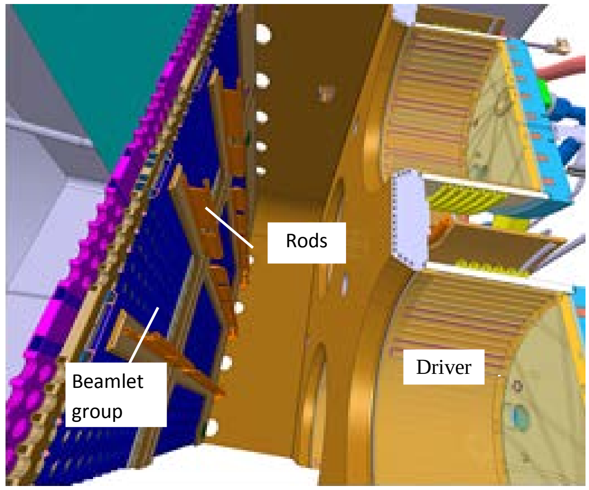

FIGURE 5. Cut of the ELISE source with three rows of rods between the beamlet groups

The potential with respect to the source and the PG could be chosen freely, but the best results were achieved with the rods on plasma grid potential. Measurements with Langmuir probes showed that by insertion of the rods the plasma density in 3.5 cm distance from the plasma grid was much more symmetric and in particular on the top side much lower (see Fig. 6). From the lower plasma load a reduced depletion of Caesium from the PG during long pulses can be expected. The extracted electron currents were more symmetric and significantly lower after this change, such that the RF power could be raised to maximum available power of 300 kW corresponding to 75 kW per driver without exceeding the power limit of the top extraction grid. In Fig. 7 the best short pulse is shown in which 250 A/m^2 has been reached for 10s. Due to the higher PG current the ion current is lower as in hydrogen at the same power.

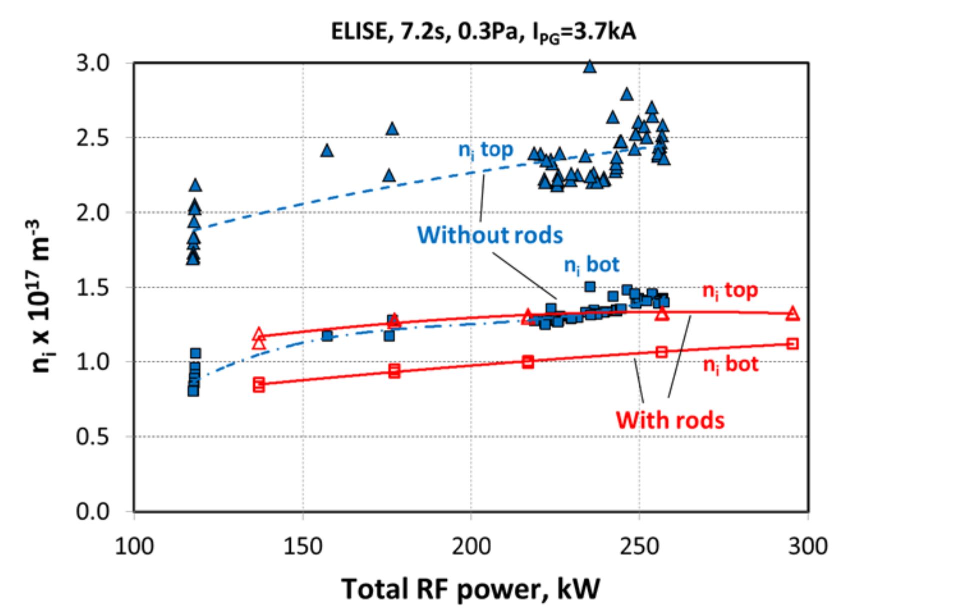

FIGURE 6. Ion density measurements with Langmuir probes close to the top and bottom part of the extraction system with and without potential rods

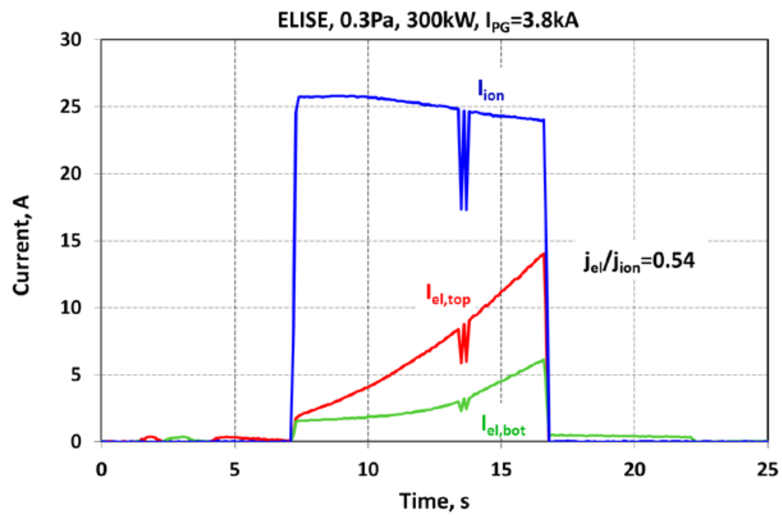

FIGURE 7. 10 s pulse in deuterium with potential rods

The ion current showed no saturation at high power (see Fig. 8). The electron current on the top grid, however, still increases at high power. For the best long pulse, which is shown in Fig. 9, the power had to be reduced to 230 kW. This pulse had to be stopped only for technical reasons, but the achieved ion current density of 190 A/m^2 for 2700 s, however, represents a further significant increase compared to the results without rods.

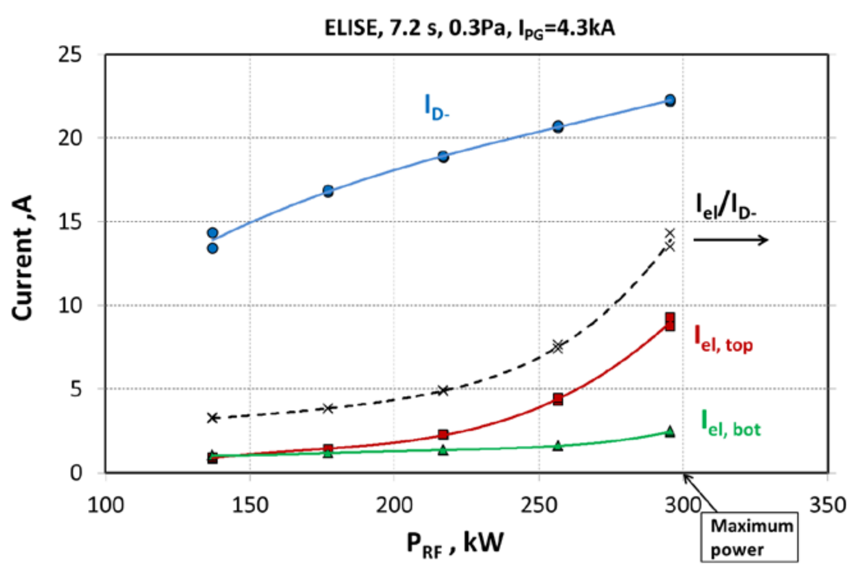

FIGURE 8. Power scan in short pulses in deuterium with potential rods

D. Dynamics of the electron currents in long pulses with pulsed beam extraction

Although the addition of the rods showed some improvement, the instability of the electron currents in particular on the top half of the extraction grid is still dominating the source performance in long pulses. As shown in Fig. 10 the largest step occurs from the first to the second beam extraction pulse. The first pulse, however, demonstrates that very low electron currents are possible for a short time, if there is enough Caesium on the PG. The higher electron currents in the following pulses indicate that the work function of the PG surface increases most probably due to the depletion of the Caesium from the PG.

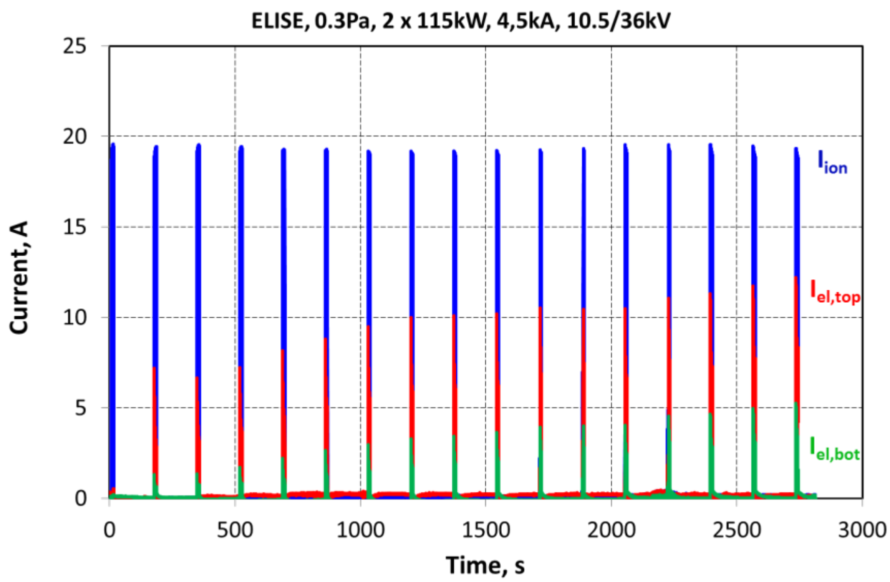

FIGURE 9. 2700 s pulse in deuterium with rods

Most effective for the long pulse stability was a conditioning procedure with a high Caesium evaporation rate before the long pulses. The goal is to generate a “Caesium reservoir” on the PG surface, which is sufficient for the duration of the pulse. Limiting for the Caesium density are HV breakdowns in the extraction system which are also shown in Fig. 10. Further increase can lead to HV deconditioning of the extraction system. Besides that can a high Cs density in the drivers also affect the coupling of the RF power.

“Record pulses” like in Figs. 7 and 9 are only possible under optimal conditions and not easily reproducible. After such high power pulses the long pulse performance is generally lower and conditioning at lower power is necessary again. Attempts to deposit Caesium on the PG during the plasma phase by increasing the Caesium density by a higher evaporation rate or by releasing Caesium from the walls by higher wall temperatures had almost no effect on the currents. The reason is that the Caesium, which is for the most part ionized cannot reach the PG, which is positively biased with respect to the source. In order to reduce this potential barrier the bias voltage was reduced by approx. 9 V and the magnetic filter field was switched-off for a test in the time between the beam blips. The electron currents were in this experiment substantially lower and the ion currents slightly higher. Although this method is not relevant for ITER, because it is not applicable for continuous beam extraction, it shows that acceleration of the Caesium ions towards the plasma grid can be the key for a solution of the electron current problem, if the work function can be stabilized in this way.

The first two beam extraction pulses of the long pulse shown in Fig. 10 reveal the dynamics of the currents during beam extraction at ELISE. Beginning from the second pulse the electron currents start within the beam extraction from a high value and decrease after that. This is possibly contributed to Caesium that is deposited during the plasma phase on the back plate of the source and sputtered during the extraction phase by the back streaming positive ions coming from the extraction system. The energy of the sputtered Caesium ions respectively is sufficient to reach the PG with a higher probability. This effect has already been confirmed by 3D simulations of the Caesium dynamics[4] and demonstrates that the results with pulsed extraction are not totally transferable to continuous beam extraction.

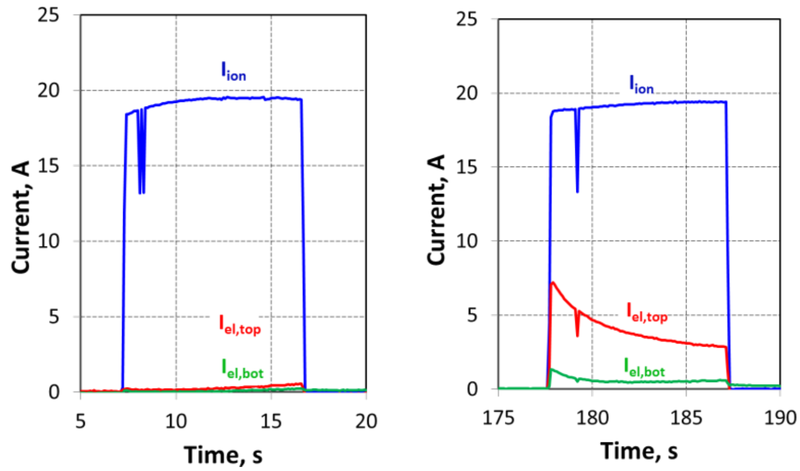

FIGURE 10. First and second beam extraction of the 2700 s pulse in deuterium shown in Fig. 9, the spikes are HV breakdowns

III. CONCLUSION

Considerable progress has been made towards the ITER requirements for the deuterium ion current densities, which have almost been reached in short pulses. Although the source performance in long pulses has been greatly improved, it is still limited in deuterium more than in hydrogen by the increase of the electron currents. Possible reason for this is the depletion of the Caesium from the plasma grid and thus the change of the work function. The best results were achieved by raising the Caesium density in the plasma up to the HV breakdown limit in order to transport enough Caesium to the plasma grid before the pulse. The Caesium handling based on the distribution of large amounts of Caesium before the pulses has for long pulses, apart from the high Caesium consumption and problems with HV holding, the disadvantage of a low degree of reproducibility. As alternatives to Caesium are not available at the moment[4], the stabilization of the Caesium layer on the plasma grid during the pulses, possibly by accelerated Caesium ions, is the main issue of future developments for long pulse operation.

Caused by the plasma drift the distribution of the electron currents is very inhomogeneous. This can lead to local overload on the extraction grid, even if the electron ion ratio is below one. Using internal rods to reduce the plasma density in front of the plasma grid the asymmetry of the electron currents could partly be diminished.

The dynamics of the electron currents during the short beam extraction phase, which may be caused by release of Caesium by back streaming ions shows that for realistic results a continuous beam extraction is necessary.

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