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Abstract. The test facility ELISE, equipped with a large radio frequency (RF) driven ion source (1x0.9 m2) of half the size of the ion source for the ITER neutral beam injection (NBI) system, is operational since beginning of 2013. The first experimental campaign was dedicated to a thorough qualification of the test facility and its diagnostic tools at low RF power (80 kW in total, i.e. 20 kW per driver) in volume operation, i.e. operation without cesium, where the negative hydrogen ion production is done in the plasma volume only. This paper reports on the main results of the second and third experimental campaigns, where Cs was inserted in the ion source for an enhancement of the negative ion production by the surface process. The second experimental campaign was done still with low RF power, both for hydrogen and deuterium, with pulse lengths of up to 500 s. The results of this campaign are rather encouraging, especially in hydrogen, where large current densities with respect to the low RF power could be achieved at a ratio of co-extracted electrons to extracted ions of 0.5-0.6 at the relevant source pressure of 0.3 Pa. Similar large extracted ion currents could be achieved also in deuterium, but with larger amounts of co-extracted electrons. The required ratio of co-extracted electrons to extracted ions of one could be achieved only in short pulses. The third experimental campaign aimed then for approaching the required ITER NBI parameters with respect to the ion and electron extracted currents, both for hydrogen and deuterium, by increasing the RF power with short pulses, i.e. beam-on times of up to 10 s and RF-on time up to 20 s. Current densities near the ITER NBI requirements could be achieved in hydrogen at a ratio of co-extracted electrons to extracted ions of 0.5-0.6 at the relevant source pressure of 0.3 Pa. As it was the case for the low RF operation, the required filter field was significantly lower than expected from the experience with the small prototype RF source. Similar large extracted ion currents could be achieved also in deuterium, but with larger amounts of co-extracted electrons; the main problem in deuterium operation are the non-stable currents of the co-extracted electrons, most probably caused by the high dynamic of the Cs redistribution in the system. The reasons for this larger instability are still under investigation.

INTRODUCTION

For heating and current drive the ITER NBI system [1,2] requires a negative hydrogen ion source capable of delivering up to 57 A of D^- ions for up to one hour. In order to achieve the required 40 A of accelerated current at 1 MeV — corresponding to an accelerated current density of 200 A/m^2 — the negative hydrogen ion losses in the accelerator must be minimized by operating the source at a pressure of 0.3 Pa. Furthermore, the limitation of the power loads in the extraction system requires an amount of co-extracted electrons to be equal the amount of extracted negative ions at maximum. Presently these parameters have not yet been achieved simultaneously, partly due to a lack of adequate test facilities. Thus the European ITER domestic agency F4E has defined an R&D roadmap for the construction of the neutral beam heating systems [3,4]. An important step herein is the test facility ELISE (Extraction from a Large Ion Source Experiment, [5]) for a large-scale extraction from a half-size ITER RF

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source (1x0.9 m^2 with an extraction area of 0.1 m^2) is operational at the Max-Planck-Institut für Plasmaphysik since beginning of 2013 [6,7,8]. The early experience of operating such a large RF driven source gives already an important input for the design of the Neutral Beam Test Facility PRIMA in Padova [9] and the ITER NBI systems (heating beams and diagnostic beam [2,10], the latter being built by the Indian ITER Domestic Agency) and for their commissioning and operating phases. PRIMA consists of the 1 MeV full power test facility MITICA [11], operational in 2017, and the 100 kV ion source test facility SPIDER [12], operational in 2015.

The first experimental campaign of ELISE has been dedicated to basic tests of all the subsystems and the diagnostic setup with low RF power (about 40 kW per generator, in total 80 kW, less than 25% than the available 360 kW) for a characterization of such a large RF driven ion source in volume operation, i.e. for operation without Cs, where the negative ions are solely produced in the plasma volume. Special emphases were also laid on RF operation at low pressure (at or below 0.3 Pa) and for long pulses of several 100 s (see Refs. [6,7,13,14]).

One of the novel special features of ELISE is the fact that for the first time the electron current can be measured with some (low) spatial resolution, as the currents on the upper and the lower part of the extraction grid can be measured individually. This gives access to possible asymmetries of the extracted electron currents which have been observed during the start-up phase [6]. A detailed study [15] showed that these asymmetries are not correlated with plasma asymmetries in a certain distance from the plasma grid, but occur most probably due to electron drifts in the magnetic filter field close to the meniscus.

In order to achieve the ITER relevant negative hydrogen ion currents with sufficient low currents of co-extracted electrons at the required low source filling pressure of 0.3 Pa, the use of the surface H^- production process is presently mandatory: here the negative hydrogen ions are produced at the plasma grid surface near the extraction apertures by converting mainly neutral hydrogen atoms [16,17]. The necessary low work function of the plasma grid surface is achieved by evaporating cesium onto that surface [18,19,20].

This paper reports the main results of the second and third experimental campaigns of ELISE. The second campaign consists of the operation of the source for the first time with Cs, for pulse lengths of up to 500 s, both in hydrogen and deuterium. The RF power, however, was still limited to about 40 kW per generator in order to minimize the risk for damages in the RF circuit.

The third experimental campaign aimed then for approaching the required ITER NBI parameters with respect to the ion and electron extracted currents, both for hydrogen and deuterium, by increasing the RF power with short pulses, i.e. lengths of up to 10 s beam. With increasing beam power, emphasis was also laid on measurements of the beam homogeneity with the available diagnostic tools (beam emission spectroscopy and dedicated calorimeters, [7]), the results are reported elsewhere [21].

THE ELISE EXPERIMENT

Table 1 shows the main parameters of the ELISE test facility (see for more details Refs. [6,7,13,15]). Plasma operation of up to one hour is envisaged; but due to the technical limits of the IPP HV system, pulsed extraction only is possible.

The ELISE test facility is equipped with a half-size ITER RF source (1x0.9 m^2) with the same width but half the height of the ITER NBI source. Accordingly, the plasma is generated in four cylindrical drivers (instead of eight as for the ITER source) with an outer diameter of 300 mm each (see Figure 1). The RF power is coupled inductively into the plasma via a six-turn copper coil wound around an Al_2O_3 insulator; the latter is protected from plasma sputtering by an actively cooled copper Faraday screen. ELISE is equipped with two 180 kW RF generators, each of which drives a pair of two horizontal drivers in series, as it is the case for the ITER NBI sources. In order to avoid asymmetries of the RF magnetic field in the driver, each driver is embedded in a copper RF shield (see Figure 1). The drivers are operated in vacuum; they are enclosed by the so-called dome with its vacuum — about 10^{-6} mbar — being separated from the source and beam-line vacuum. The latter is maintained by two 2200 l/s turbo pumps and by two large cryopumps with a pumping speed of 300000 l/s

TABLE 1. Parameters of the ELISE test facility

Isotope	H, D (15h beam time/y)
Extraction area	1000 cm^2
Apertures	640, ø14 mm, 2x4 groups
Source size	1.0 x 0.9 m^2
Total Voltage	$\leq$ 60 kV
Extraction Voltage	$\leq$ 15 kV
Acc. Current	$\leq$ 25 A
RF Power	2x180 kW
Pulse length	
Plasma	3600 s
Extraction	10 s every 150 – 180 s

each; the base pressure is around 10^{-7} mbar and increases to about 10^{-4} mbar during plasma operation. With the given conductance of the ELISE grid assembly of 14 m^3/s for hydrogen and 10 m^3/s for deuterium, a gas flow per driver of 1 Pa m^3/s H_2 and 0.7 Pa m^3/s D_2, respectively, for the required filling pressure of 0.3 Pa is needed.

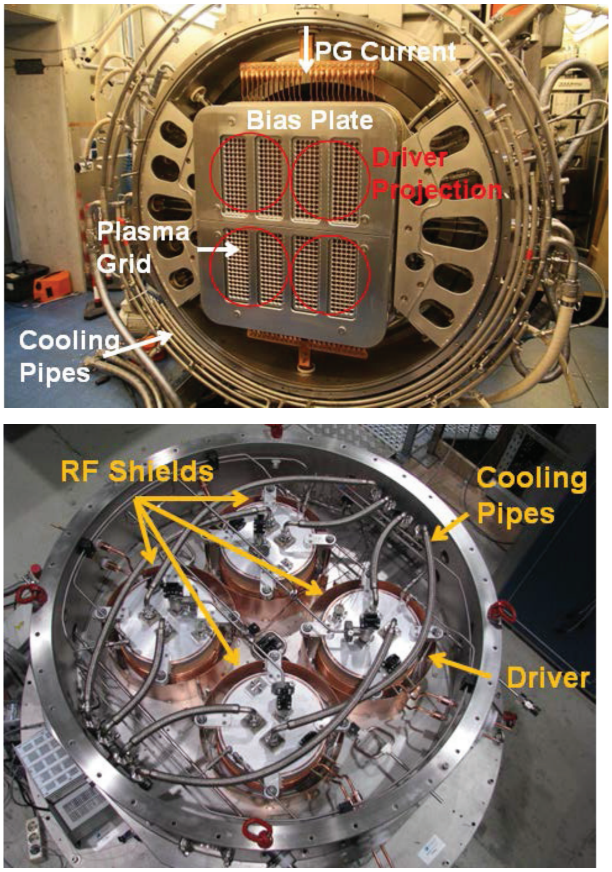

Figure 1: Details of the ELISE test facility. Top: View onto the extraction system with plasma grid, bias plate and PG current feedthrough. Bottom: View into the driver containment ('dome') with the four drivers surrounded by the RF shields.

The ELISE extraction system is designed for acceleration of negative hydrogen ions of up to 60 kV. It consists of three grids: the plasma grid (PG) which separates the plasma from the beam region, the extraction grid (EG), where the co-extracted electrons are filtered out of the beam by the embedded magnets, and the grounded grid (GG). Each grid has 640 extraction apertures with a diameter of 14 mm (PG and GG) and 11 mm (EG), respectively, and consists of two individual segments in a vertical arrangement, i.e. a top and a bottom segment. The apertures are arranged in eight beamlet groups (four in each segment; each group contains 5x16 beamlets. The ions are accelerated to a calorimeter located at a distance about 3.5 m from the GG. The source is at a high negative potential with a maximum voltage of 60 kV. The electrical currents flowing onto the grids, as well as the current flowing back to the HV power supply, are measured individually by means of current transducers. Both extraction grid segments are insulated against each other and against their grid holder boxes, so that the current flowing from each grid can be measured individually. In order to protect the extraction grid segments from thermal overloads by the impinging co-extracted electrons (and ions in some cases) — calculations [22] show that the power densities can reach values of up to 32 MW/m^2 on a small area —, the total impinging power is limited by a dedicated interlock in the ELISE control system. The maximum power of an ELISE EG segment was designed to 200 kW [22]; the operational limit, however, is presently still lower (125 kW per segment at the end of the third experimental period) in order to minimize the risk of damages.

Sufficient electron suppression can be achieved by a combination of biasing the plasma grid positively with respect to the source body and by a magnetic filter field across the source [18]. The plasma grid bias is supported by a so-called bias plate which is electrically connected with the source body and surrounds each of the eight aperture groups in a distance of a few centimeters (see Figure 1). The magnetic filter field is created by a current running through the plasma grid [23]. The presently installed power supply can deliver 5.3 kA at maximum, corresponding to a horizontal magnetic field of about 5 mT in the center of the plasma grid [24]. The current path in the plasma grid and the resulting magnetic filter field direction is presently so that — from the experience with the small prototype source — a possible **ExB** drift of the electrons on the plasma side should be upwards. In contrast to the filter field created with permanent magnets — as it is the case at the small prototype source — the field direction is reversed at the downstream side of the plasma grid with respect to the upstream side, so that negative charges are deflected downwards in the extraction system, as seen on the calorimeter (see Ref. [21] for details).

ELISE is equipped with two cesium dispenser ovens [25] at the sides of the source. For both ovens, a relative evaporation rate can be measured with a surface ionization detector placed at the nozzle, but the calibration has to be done for each oven individually after the dispenser is totally empty. A first assessment of the Cs consumption has been made and is reported elsewhere [26].

FIRST CS CONDITIONING

As mentioned above, ITER relevant extracted negative hydrogen ion currents at a filling pressure 0.3 Pa with a sufficient low electron current can be presently only achieved by using the surface H^- production process. The experience with the IPP prototype source showed that the necessary reduction of the work function of the plasma grid by inserting Cs into the source is a rather slow process with time constants of hours to days [18,27]. This reduction of the PG work function is done by the so-called "Cs conditioning" where the source is operated with a certain pulse/pause ratio with a continuous and constant Cs influx; then the performance of the source improves from pulse to pulse gradually; i.e. the extracted current density increases and the amount of co-extracted electrons decreases simultaneously. The underlying processes are not fully understood, but most probably the Cs is redistributed slowly in the source during both the vacuum and the plasma phases together with a cleaning effect of the Cs layer at the plasma grid by the plasma itself [27].

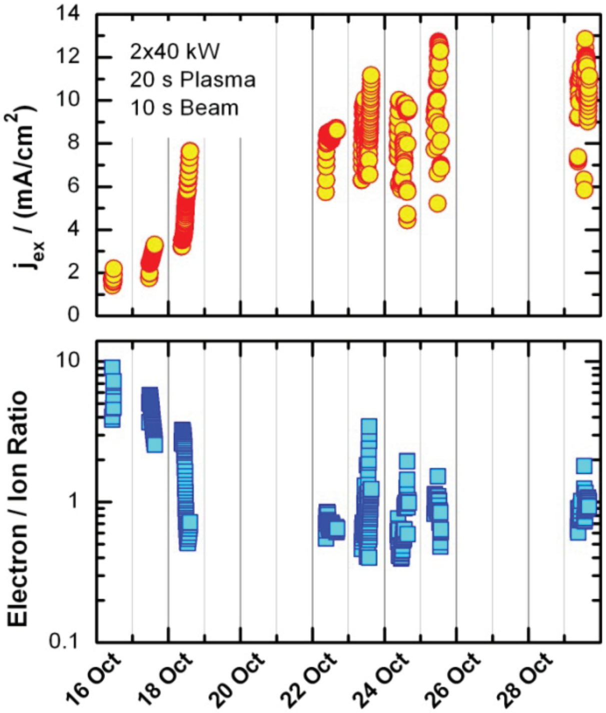

Figure 2: Performance progress of ELISE during the first days of Cs operation in October 2013. Cs operation started at the 17th. Top: extracted current density. Bottom: Ratio of co-extracted electrons to ions.

Figure 2 shows the progress of this Cs conditioning for ELISE during the first seven days of cesium operation (for more details see Refs. [26,28]). This was done at ELISE in hydrogen in order to avoid the additional radiation measures connected with deuterium operation; furthermore, this Cs conditioning is much easier due to the much lower amount of co-extracted electrons compared to deuterium (see below). The parameters are as following: (1) RF power 40 kW per generator, (2) source filling pressure 0.7 Pa, (3) extraction voltage 4.5 kV in order to keep the amount of co-extracted electrons low. These parameters have been successively adjusted, i.e. lower source pressure and higher extraction voltage, during the progress of the conditioning when the co-extracted electron current decreases. (4) Source temperature of 38 °C, plasma grid and bias plate temperature of 125 °C, the latter being the technical limit of the respective tempering circuit during the experiments reported here. (5) Cs evaporation rates of some mg/h (see also [29]), and (6) Bias current of 55 – 60 A, and (7) a PG current of 3.5 kA at start, later the PG current could be reduced to 2.2 kA (see below). It can be seen in Figure 2, that the source conditioned rather quickly with an electron/ion ratio of well below 1 and a rather large extracted ion current with respect to the low RF power.

After these first operational days with the exploitation of the basic features of the performance, the pulse length was increased subsequently to a value of around 400 s. Figure 3 shows all the performed hydrogen pulses in a performance plot, i.e. the achieved extracted negative hydrogen ion current density vs. the ratio of the co-extracted electrons to negative ions. Indicated are also the

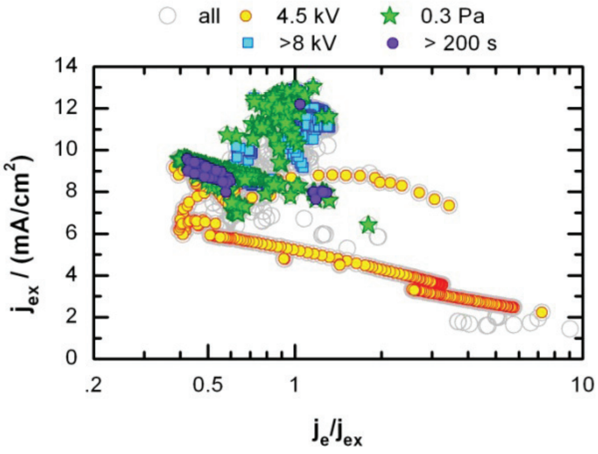

Figure 3: Performance of ELISE with Cs in hydrogen for low RF power operation. Indicated are also the pulses with at least one ITER relevant parameter (perveance at 4.5 kV extraction voltage, more than 8 kV extraction voltage, 0.3 Pa filling pressure and pulse lengths of more than 200 s).

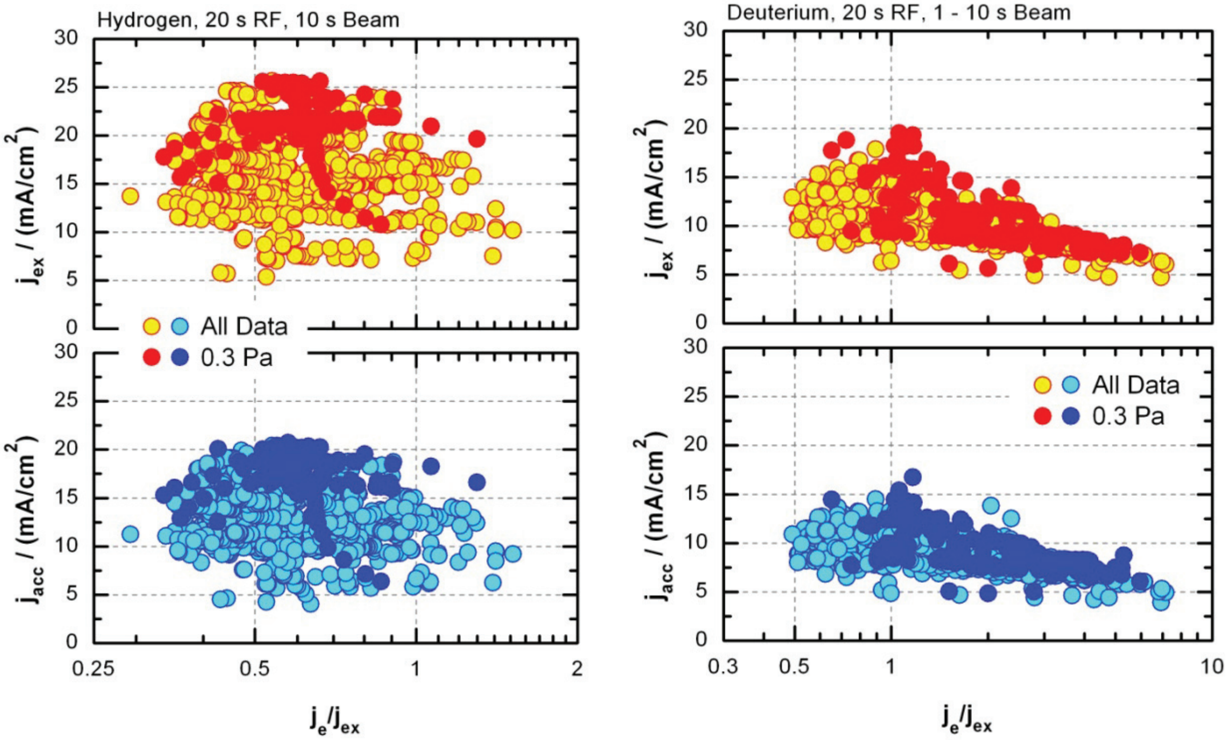

Figure 4: Performance of all the beam pulses in the third experimental phase for hydrogen (left) and deuterium (right).

pulses with at least one ITER relevant parameter of perveance (4.5 kV extraction voltage, see below), extraction voltage (> 8kV), filling pressure (0.3 Pa) and pulse length (> 200 s).

The highest current density is achieved with an extraction voltage of 9.5 kV, but due to the low RF power and thus a relatively low negative ion current density, the source operates here far away from the perveance optimum, i.e. with large beam divergence. The negative ion beam formation at the plasma boundary is space-charge driven (for details see Ref. [30]) and can be described by the Child-Langmuir law. The main parameter driving the beam quality is the perveance Π, defined by

$$\Pi = \frac{I_{ex}}{U_{ex}^{3/2}}, \tag{1}$$

with I_{ex} being the extracted total current and U_{ex} the extraction voltage.

The ELISE grid system was designed to have the beam divergence minimized at the required current density for an extraction voltage of about 9.5 kV, as it is the case for the ITER NBI accelerator. Due to the low RF power operation reported in the above figures, the normalized perveance is rather low, so that some of the quoted 'electron current' may be caused by ions impinging the extraction grid due to the bad optics. At the perveance optimum which is here at 4 – 5 kV extraction voltage, the electron/ion ratio can be kept well below one. Even values around/below 0.5 have been achieved at 0.3 Pa and for long pulses. The most striking feature is that these results have been achieved for a rather low magnetic filter field (see also below), about halve the value which was expected from the extrapolation of the results from the magnetic filter field parameters of the small prototype RF source [31].Here an integrated magnetic filter field from the source back plate to the plasma grid of about 1 mTm was necessary for sufficient electron suppression in hydrogen, corresponding to about 4.5 – 5 kA of plasma grid current in ELISE.

HIGH RF POWER OPERATION

For the third operational period which is reported in this section, the RF power was increased to values of about 110 kW per generator, i.e. 220 kW in total. This number is still well below the maximum power available. Figure 4

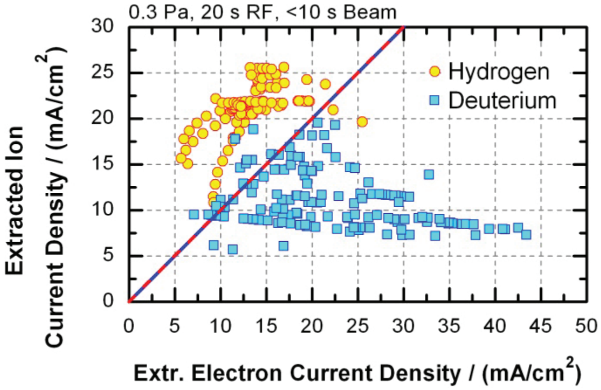

Figure 5: Extracted ion current density vs. extracted electron current density for hydrogen and deuterium, respectively for all pulses with 0.3 Pa filling pressure. The line indicates the required ratio of both currents of one.

shows the performance of all the pulses performed so far in this experimental period, both for hydrogen and deuterium. Additionally, the figure shows also the dependence of the accelerated current density on the ratio of the co-extracted electrons to extracted negative ions. The accelerated negative ion current density is calculated from the measured power at the calorimeter [21] assuming that all impinging particles (hydrogen neutrals and ions) have the full energy. As this is not the case due to stripping, the number given is a lower limit. Generally, more than 80% of the extracted ion current can be found at the calorimeter.

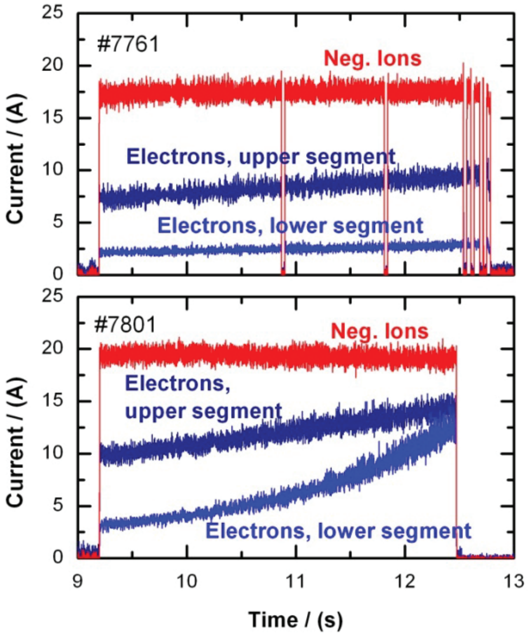

Figure 6: Extracted ion and electron currents for the two best pulses in deuterium. Both pulses have been terminated earlier than envisaged: #7761 by the maximum number of allowed HV breakdowns (seven), #7801 by the extraction grid segment power limit (125 kW). Filling pressure 0.3 Pa, RF power 2x90 kW for #7761, 2x105 kW for #7801, respectively, extraction voltage 9 kV.

The main features of these performance plots are rather similar. As already known from the operation of the IPP prototype source [32], there are two dedicated areas in this kind of performance plot. At the start of the Cs operation, with mainly volume production of negative ions, the extracted negative hydrogen ion current density is rather low and the amount of co-extracted electrons large. With subsequent Cs conditioning, i.e. increasing performance, the extracted ion current density increases and the amount of co-extracted electrons decreases. After achieving some optimum value (here at an ratio of co-extracted electrons to extracted ions of about 0.5 in hydrogen and about one in deuterium, respectively), a further reduction of the amount of co-extracted electrons can only be achieved by changing some operational parameters. Those are mainly an increase of the filter field current and hence the magnetic filter field strength, an increase of the PG bias, but also a decrease of the extraction voltage. All these measures decrease also the extracted ion current density. Due to various changes in the operational parameters performed during these experimental campaigns no distinguished correlation between j_{ex} (or j_{acc}) and j_e/j_{ex} can be seen in Figure 4. The best performance for different Cs conditions, however, is reflected by the upper envelope of the data points.

There is a large difference of these plots for both isotopes w.r.t. to the amount of co-extracted electrons: the electron/ion ratio is not only generally lower in hydrogen than in deuterium, but also the spreading is much less pronounced. In hydrogen, the range of the electron/ion ratio is between 0.3 and 1.5, i.e. a factor of 5, whereas the range in deuterium is from 0.5 to 7, i.e. a factor of 14. Figure 5 shows the comparison of the correlation of the extracted ion current density with the extracted electron current density for hydrogen and deuterium for all pulses with the required source filling pressure of 0.3 Pa. The range of the electron current — factor 5 in hydrogen, factor 14 in deuterium — is the same as for the electron/ion ratio, indicating that the main problem in deuterium is indeed the total number of co-extracted electrons. The large difference in the amount of co-extracted electrons between hydrogen and deuterium is even more remarkable, as the source was well conditioned in hydrogen before switching to deuterium. This large difference in the amount of the co-extracted electrons between hydrogen and deuterium is

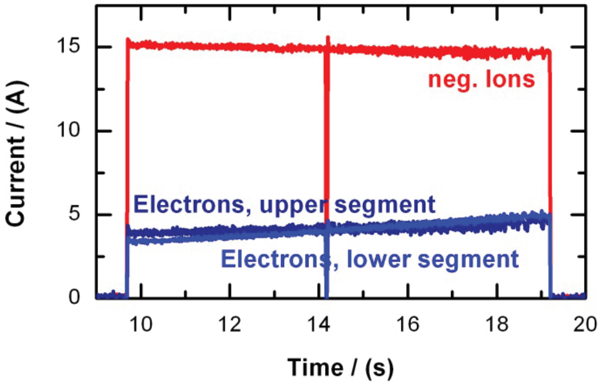

Figure 7: Extracted ion and electron currents for a 9.5 s hydrogen pulse at 0.23 Pa filling pressure. An HV breakdown occurred at 14.2 s. RF power 2x70 kW, extraction voltage 5.3 kV.

presently not fully understood; it might be correlated with a higher dissociation and ionization degree in deuterium plasmas [33].

In order to limit the power on the extraction grid the filter field current had to be increased in deuterium to values of 3 to 4 kA, which reduces also the extracted ion current density (see also the next section). The best performance was achieved in hydrogen at the required filling pressure of 0.3 Pa, also with a high reproducibility. This is still not the case in deuterium, where only a few pulses could be performed at 0.3 Pa for 10 s beam-on time due to the high non-stability of the co-extracted electron currents.

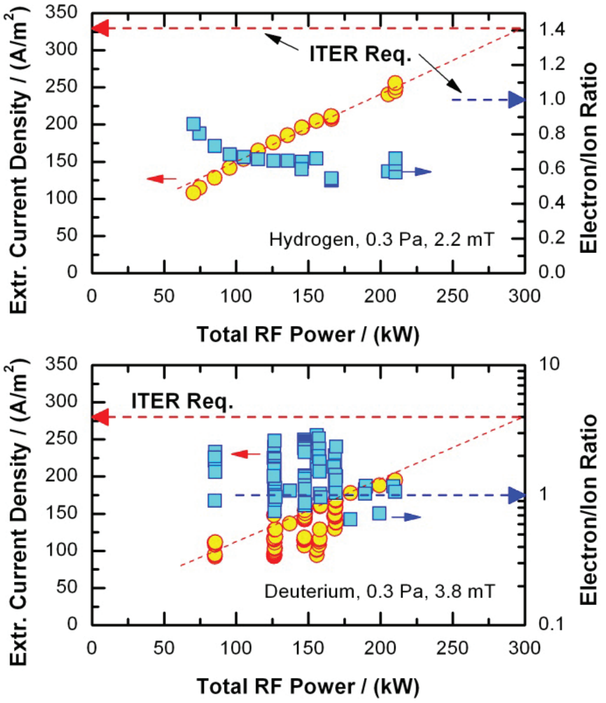

Figure 8: Extrapolation of the RF power to the required extracted negative hydrogen ion current densities, for hydrogen (top) and deuterium (bottom), respectively.

The best pulses in deuterium, however, have still a lower stability than in hydrogen. This is indicated in Figure 6, where the extracted currents — ion current and the currents on both extraction grid segments separately — for the two deuterium pulses with the highest performance are shown. The two pulses have been terminated not regularly leading to a beam-on time (about 3 s only) much shorter than technically possible (10 s),: pulse #7761 was terminated by the maximum number of HV breakdowns allowed (presently seven, most probably caused by too much Cs within the grid stack), pulse #7801 was terminated by the limit of the power at the extraction grid (for this pulse 125 kW per segment). It can also be seen, that the dynamic is much larger in the current measured at the lower extraction grid segment. If this different behavior of the electron currents for the upper and the lower segment is correlated with the magnetic filter field direction is an open point and will be investigated in the future by changing the current path in the plasma grid.

The rather stable electron currents in pulse #7761 indicate that the required ITER parameters can be most probably achieved, as this stable operation was obtained by a dedicated rather lengthy Cs conditioning procedure with long pauses of up to 10 min between the beam pulses (see for more details [34]) with a continuous and constant Cs influx. If there would be sufficient time also for grid HV conditioning, pulses with even better performance could be achieved. For the next pulse (#7762), the RF power was increased to 2x100 kW, leading to an increase of the extraction ion current to 188 A/m^2, but this pulse was terminated even earlier (at about 1 s) due to HV breakdowns again. The problem of this deterioration of the HV holding capability of the grids by absorbed Cs when the amount of evaporated Cs gets to large might be caused by a different Cs oven nozzle geometry with respect to the IPP prototype source. Due to this HV deterioration, however, an increase of the Cs flux for deuterium with respect to hydrogen by a factor of about two, which was done at the prototype source [26], is presently not possible at ELISE.

The reasons for the high instability of the electron currents in deuterium operation are presently not quite well understood. Deuterium operation in this third experimental campaign might suffer from the amount of Cs that has been released into the source during the long hydrogen phase before. This Cs may build reservoirs that can now be accessed with deuterium due to the different plasma transport and maybe increased sputtering due to the lower

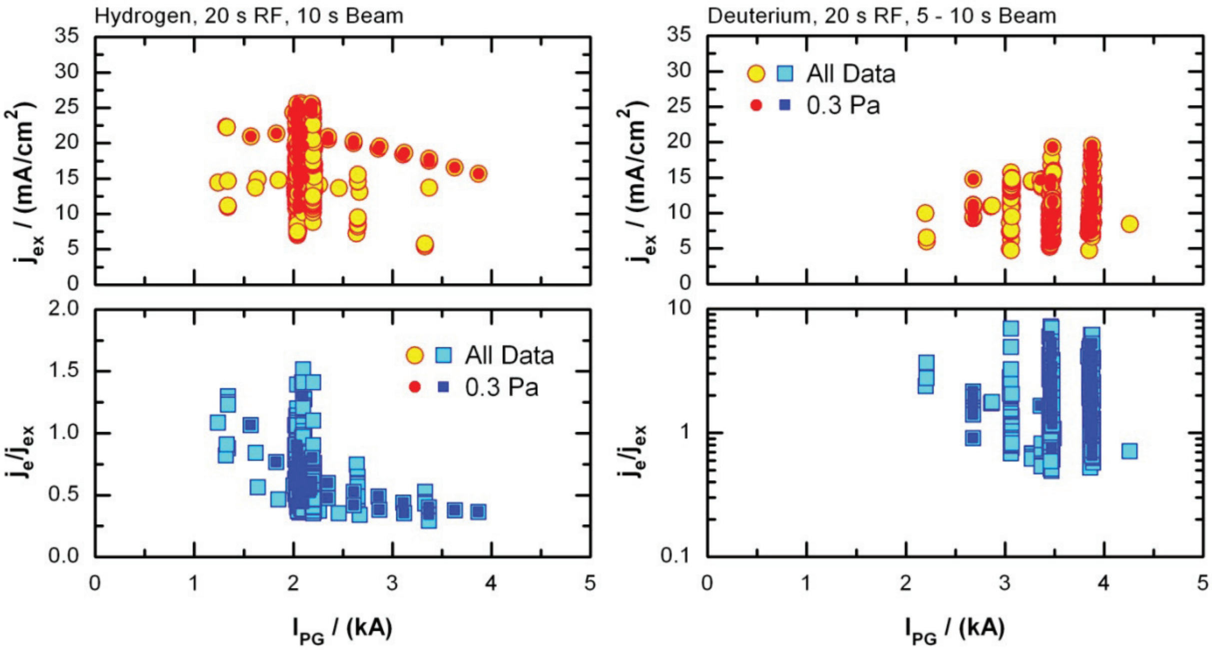

Figure 9: Dependence of the source performance on the plasma grid current in hydrogen (left) and deuterium (right) for all data in the third experimental campaign.

threshold energy. An indication is the fact that stable operation (and parameter scans) could not be performed in the third experimental campaign at 0.3 Pa even a low RF power of 2x40 kW, in contrast to the deuterium operation in the second experimental campaign [28]. Also the necessary filter field current is now much larger for sufficient electron suppression (3.6 – 4 kA, instead of 2.8 — 3.2 kA). A start of deuterium operation with a clean source could clarify whether the operation suffers from the previous Cs campaigns or whether there is a principle problem for deuterium. Another possibility for the high instability of the electron currents in deuterium might be that the source operates at non-optimized PG bias (see also [26]) or at non-optimized source, PG and bias plate temperatures, as the same settings are used both for hydrogen and deuterium. Fixed Langmuir probe measurements at the source edge are presently in preparation for a first estimation of possible differences of the plasma potential. However, the instability is not related to the gas flow of the source: hydrogen pulses at 0.23 Pa having the same gas flow as deuterium pulses at 0.3 Pa showed much more stable electron currents. An example is shown in Figure 7: there is a much smaller increase of both electron currents compared to deuterium; furthermore, there is even almost no difference of the currents of both extraction grid segments.

Figure 8 shows finally the extrapolation of the RF power needed for the achievement of the required extracted current densities. Both for hydrogen and deuterium, the required values should be achieved at a RF power of about 300 kW in total, i.e. about 75 kW per driver. This is less (about 75%) than the planned installed RF power at the ITER NBI system. The main challenge in deuterium however, especially at these high power levels and for pulses of several 100 s, will be the stability of the amount of the co-extracted electrons for the upcoming experiments at ELISE.

FILTER FIELD DEPENDENCE

Figure 9 shows the dependence of the source performance on the PG filter field current for all hydrogen and deuterium pulses in the third experimental campaign. A similar strong dependence of the amount of co-extracted electrons on the filter field can be seen with some saturation above a certain PG filter field current, especially in hydrogen. Due to the stability problems of the electrons currents (see Figure 6), the database for deuterium is rather limited and an optimization of the magnetic filter field strength — together with the PG bias — is still outstanding. As already mentioned above, the filter field needed for sufficient electron suppression is much less for both isotopes than it was extrapolated from the experience with the small IPP prototype source, where the magnetic filter field is generated by permanent magnets [31]. The reason for this lower field might be caused by the different geometry of the bias plate for the large ion source or by the different 3D geometry of the filter field when the filter field is generated by the PG current [24] — e.g. a lack of magnetic mirrors at the plasma edge or less steep gradients from the driver exit to the plasma grid, — or a combination of both (see also [26]). It should be mentioned for the further extrapolation of the magnetic filter field to the even larger ITER source, that the 3D structure of the magnetic filter field in ELISE is somewhat different from that in SPIDER and in MITICA due to different design of the plasma grid and a different arrangement of the return conductors. In ELISE, a plasma grid current of 5 kA corresponds to a horizontal field in the center of the source of 4.7 mT and an integrated field from the driver exit to the plasma grid of about 1 mTm [24]. Scaling of the ELISE results should therefore be done with the respective field components instead of the plasma grid current.

In hydrogen, the extracted ion current density shows some dependence on the filter field current, similar to the findings for the small IPP prototype source [31]. The largest current density was obtained at 2.2 kA of PG current, corresponding to a filter field strength of 2.08 mT in front of the PG center, so that the majority of pulses have been done at that PG current. An increase of the filter field strength to 3.3-3.8 mT — being perhaps necessary at MITICA in order to have the same field for hydrogen and deuterium — results in a loss of about 30% of negative ions that could be most probably compensated by a larger RF power. In deuterium, no clear trends can be seen here, as most of the pulses are limited by the EG power limit and a dedicated optimization by a scan of the PG current was not possible. Hence, the apparent increase of the extracted current density with increasing PG current is mainly caused by an increase of other operational parameters like RF power and extraction voltage.

CONCLUSIONS

The first experimental phases of ELISE with Cs — at low RF power as well as short pulse, high RF power operation — show rather encouraging results with respect to the ITER requirements. Especially in hydrogen operation, current densities of 25 mA/cm^2 at the required source filling pressure of 0.3 Pa with a ratio of co-extracted electrons to ions of 0.5-0.6 could be achieved at moderate RF power for the maximum possible beam pulse length of 10 seconds. In deuterium operation, a temporal instability of the co-extracted electron current limited the pulse length to about 3 seconds. For both isotopes, however, an extrapolation of required RF power with the extracted current density indicates that 300 kW, i.e. 75 kW per driver might be sufficient for achieving the required ITER current densities. The instability of the electron currents, however, will be the main challenge for long pulse RF operation in deuterium.

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REFERENCES

[1] HEMSWORTH, R. et al. **Nuclear Fusion**, v. 49, p. 045006, 2009.
URL: <doi:10.1088/0029-5515/49/4/045006>.
[2] SCHUNKE, B. et al. Proceedings of the 24th IAEA Fusion Energy Conference. 2012. p. ITR/P1-03.
URL: <http://www-naweb.iaea.org/napc/physics/FEC/FEC2012/papers/227_ITRP103.pdf>.
[3] MASIELLO, A. et al. **Fusion Engineering and Design**, v. 84(7-11), p. 1276-1280, June 2009.
URL: <http://dx.doi.org/10.1016/j.fusengdes.2008.12.090>.
[4] MASIELLO, A. et al. Proceedings of the 24th IAEA Fusion Energy Conference. 2012. p. ITR/P1-04.
URL: <http://www-naweb.iaea.org/napc/physics/FEC/FEC2012/papers/361_ITRP104.pdf>.
[5] HEINEMANN, B. et al. **Fusion Engineering and Design**, v. 86(6-8), p. 768-771, 2011.
http://dx.doi.org/10.1016/j.fusengdes.2010.11.031.
[6] FRANZEN, P. et al. **Fusion Engineering and Design**, v. 88, p. 3132, 2013.
URL: <http://dx.doi.org/10.1016/j.fusengdes.2013.09.006>.
[7] NOCENTINI, R. et al. 25th Symposium on Fusion Engineering (SOFE 25). 2013. p. PID2814993.

[8] HEINEMANN, B. et al. **Fusion Engineering and Design**, v. 88, p. 512, 2013.
URL: <http://dx.doi.org/10.1016/j.fusengdes.2012.11.003>.

[9] SONATO, P. et al. Proceedings of the 23rd IAEA Fusion Energy Conference. 2010. p. ITR/P1-13.
URL: <http://www-pub.iaea.org/mtcd/meetings/PDFplus/2010/cn180/cn180_papers/itr_p1-13.pdf>.

[10] ROTTI, C. et al. Proceedings of the 24th IAEA Fusion Energy Conference. 2012. p. ITR/P5-43.
URL: <http://www-naweb.iaea.org/napc/physics/FEC/FEC2012/papers/599_ITRP543.pdf>.

[11] SONATO, P. et al. Proceedings of the 24th IAEA Fusion Energy Conference. San Diego, USA: IAEA. 2012. p. ITR/1-3.
URL: <http://www-naweb.iaea.org/napc/physics/FEC/FEC2012/papers/523_ITR13.pdf>.

[12] SONATO, P. et al. **Fusion Engineering and Design**, v. 84, n. 2-6, p. 269–274, 2009.
URL: <http://dx.doi.org/10.1016/j.fusengdes.2008.11.095>.

[13] WÜNDERLICH, D. et al. **Review of Scientific Instruments**, v. 84, p. 093102, 2013.
URL: <http://link.aip.org/link/doi/10.1063/1.4820806>.

[14] FANTZ, U.; FRANZEN, P.; WÜNDERLICH, D. **Chemical Physics**, v. 398, p. 7–16, 2012.
URL: <doi:10.1016/j.chemphys.2011.05.006>.

[15] FRANZEN, P. et al. **Plasma Physics and Controlled Fusion**, p. 025007, 2014.
URL: <http://dx.doi.org/10.1088/0741-3335/56/2/025007>.

[16] WÜNDERLICH, D. et al. **AIP Conference Proceedings**, n. 1515, p. 12, 2013.
URL: <http://dx.doi.org/10.1063/1.4792765.>.

[17] WÜNDERLICH, D. et al. **Plasma Physics and Controlled Fusion**, v. 54, p. 125002, 2012.
URL: <http://dx.doi.org/10.1088/0741-3335/54/12/125002>.

[18] SPETH, E. et al. **Nuclear Fusion**, v. 46, p. S220, 2006.
URL: <http://www.iop.org/EJ/abstract/0029-5515/46/6/S03>.

[19] FRANZEN, P. et al. **AIP Conference Proceedings**, v. 1097, p. 451, 2009.
URL: <http://link.aip.org/link/?APCPCS/1097/451/1>.

[20] FANTZ, U. et al. **Nuclear Fusion**, v. 49, p. 125007, 2009.
URL: <doi:10.1088/0029-5515/49/12/125007>.

[21] NOCENTINI, R., 2014. this conference.

[22] NOCENTINI, R. et al. **Fusion Engineering and Design**, v. 86, p. 916, 2011.
doi:10.1016/j.fusengdes.2011.01.147.

[23] NOCENTINI, R. et al. **Fusion Engineering and Design**, v. 84, p. 2131-2135, 2009.
URL: <doi:10.1016/j.fusengdes.2009.02.015>.

[24] FRÖSCHLE, M. et al. **Fusion Engineering and Design**, v. 88, p. 1015, 2013.
URL: <http://dx.doi.org/10.1016/j.fusengdes.2013.01.024>.

[25] FANTZ, U.; FRIEDL, R.; FRÖSCHLE, M. **Rev. Sci. Instrum.**, v. 83, p. 123305, 2012.
URL: <http://dx.doi.org/10.1063/1.4771967>.

[26] FANTZ, U.; FRANZEN, P., 2014. this conference.

[27] FANTZ, U.; WIMMER, C. **Review of Scientific Instruments**, v. 83, p. 02B110, 2011.
http://dx.doi.org/10.1063/1.3670347.

[28] FRANZEN, P. et al. **Nuclear Fusion**, 2014. submitted.

[29] FRÖSCHLE, M.; FRANZEN, P. **this conference**, 2014. this conference.

[30] FRANZEN, P. et al. **Nuclear Fusion**, v. 51, p. 073035, 2011.
URL: <http://dx.doi.org/10.1088/0029-5515/51/7/073035>.

[31] FRANZEN, P. et al. **Plasma Physics and Controlled Fusion**, v. 53, p. 115006, 2011.
URL: <http://dx.doi.org/10.1088/0741-3335/53/11/115006>.

[32] FRANZEN, P. et al. **Nuclear Fusion**, v. 47, p. 264-270, 2007.
URL: <http://dx.doi.org/10.1088/0029-5515/47/4/004>.

[33] FANTZ, U.; SCHIESKO, L.; WÜNDERLICH, D. **AIP Conference Proceedings**, v. 1515, p. 187, 2013.
URL: <http://dx.doi.org/10.1063/1.4792785>.

[34] FRANZEN, P. to be published.