Long Pulse Operation at ELISE: Approaching the ITER Parameters

D. Wünderlich[a)], R. Riedl, F. Bonomo, I. Mario, U. Fantz, B. Heinemann, W. Kraus and the NNBI team

Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany

[a)] Corresponding author: dirk.wuenderlich@ipp.mpg.de

Abstract. The ion sources used in the ITER NBI beam lines will deliver over one hour a current density of 200 A/m^2 negative deuterium ions, accelerated to 1 MeV or over 1000 s a current density of 230 A/m^2 negative hydrogen ions, accelerated to 870 keV. The ELISE ion source (0.9×1.0 m^2 with an extraction area of 0.1 m^2) has half the size of the ion source foreseen for ITER. Aim of the ELISE test facility is to demonstrate that such large RF driven negative ion sources can achieve the following parameters at a filling pressure of 0.3 Pa: extracted current densities of 286 A/m^2 in deuterium and 329 A/m^2 in hydrogen, a ratio of co-extracted electrons to extracted ions below one and a beam homogeneity better than 90 %. The pulse length should be one hour in deuterium and 1000 s in hydrogen.

Reliable and reproducible long pulse operation (up to one hour) with high RF power (up to 75 kW/driver) is possible after technical issues have been resolved stepwise. Experiments are now focused on the physics of approaching the requirements for the ITER NBI ion source. The most crucial factor limiting the source performance during long pulses with high RF power is a steady increase and a strong top-bottom asymmetry in the co-extracted electron current.

Measures for partially counteracting this increase and asymmetry are external permanent magnets strengthening the standard magnetic filter field, internal potential rods and a new caesium conditioning technique, the so-called caesium overconditioning. Combining these measures enabled performing reproducible high-performance 1200 s pulses in hydrogen. During such pulses, about 90 % of the ITER requirement for the extracted negative ion current density were achieved while exceeding the requirement for the accelerated current density.

INTRODUCTION

The neutral beam injection (NBI) system at ITER will consist of two beamlines, delivering a total beam power of 33 MW. It will be used for heating and current drive [1]. An essential part of the NBI beam line is the negative hydrogen ion source, capable of delivering over one hour a current density of 200 A/m^2 negative deuterium ions, accelerated to 1 MeV or over 1000 s a current density of 230 A/m^2 negative hydrogen ions, accelerated to 870 keV. Assuming for both isotopes a stripping fraction of 30 %, as calculated for deuterium in [2], the extracted ion current density should be 286 A/m^2 for deuterium and 329 A/m^2 for hydrogen.

In order to minimize the destruction rate of negative ions in the accelerator, the source has to be operated at a low filling pressure, p_{fill}=0.3 Pa. Additionally, to limit the power loads in the extraction system, the amount of co-extracted electrons has to be equal or smaller compared to the extracted negative ions. In order to ensure a good beam transmission, the uniformity of the extracted beam is required to be better than 90 %. Up to now, these parameters have not been achieved simultaneously.

ELISE (Extraction from a Large Ion Source Experiment) [3] is part of a R&D roadmap defined by the European domestic agency F4E for the construction of the neutral beam heating systems [4,5]. The half-ITER-size ion source of the ELISE test facility (0.9×1.0 m^2 with an extraction area of 0.1 m^2) is an intermediate step between the RF driven ITER prototype source (0.3×0.6 m^2 with an extraction area of typically $6\cdot10^{-3}$ m^2) [3] and the ion source for the ITER NBI system (1.0×2.0 m^2 with an extraction area of 0.2 m^2) [1]. The latter ion source will be tested at the SPIDER and MITICA test facilities at the neutral Beam Test Facility PRIMA in Padova [6].

Negative hydrogen (or deuterium) ions are produced predominately by the surface effect, i.e. the conversion of impinging hydrogen atoms at a metallic surface. The most relevant converter surface is the surface of the plasma grid (PG, the first grid of the multi-grid, multi-aperture extraction system). The work function of the PG is effectively reduced by coverage with a thin (several monolayers) layer of caesium. Caesium is evaporated by means of two (ELISE) or three (the ITER sources) caesium ovens, attached to the side walls or the back plate of the ion source, respectively. Due to the reduced work function, the conversion yield is high: depending on the energy of the atoms it can reach up to 26 % [7].

At ELISE reliable and reproducible long pulse operation (up to one hour) with high RF power (up to 75 kW/driver) is possible after resolving several technical issues. Focus of investigation is laid now mainly on caesium conditioning techniques and on additional measures for symmetrizing the plasma, the extracted beam and the co-extracted electrons.

THE ELISE TEST FACILITY

A schematic view of the ELISE ion source can be seen in Figure 1. The plasma is generated by inductive RF coupling into four cylindrical drivers (P_{RF}<75 kW/driver, delivered by two RF generators, f=1 MHz) and then expands toward the extraction system. ELISE is operated in pulsed extraction mode: plasma pulses are possible up to one hour, with short extraction phases, so-called beam blips (length: 9.5 s; the shortest possible time between two blips is ≈150 s, limited by the available HV power supply).

The source performance usually is limited – in particular in deuterium – by a steady increase and a strong top-bottom asymmetry in the co-extracted electron current while the extracted negative ion current is much more stable. The reason are changes in the work function of the caesiated PG surface 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 [8], or by a sufficient caesium flux onto the surface [9], respectively. The interplay of these effects makes it challenging to ensure a low, stable and homogeneous PG work function during long pulses (up to one hour) with high RF power [3]. To fulfil the ITER requirements for the NBI source, the caesium flux onto the PG should be sufficient to ensure a low work function at the PG that is homogeneous over the area of the PG and stable over pulses up to one hour.

A horizontal magnetic field – the so-called filter field – with a strength of a few mT (sufficient for magnetizing electrons but not the ions) plays a crucial role for the suppression of the co-extracted electron current and for the transport of negative hydrogen ions to the extraction apertures [10]. The magnetic filter is generated by a current, I_{PG}, flowing through the PG in vertical direction [11]. By varying I_{PG}, the strength of the filter field can be adjusted (up to 5.3 kA at maximum, equivalent to a field strength of ≈5 mT close to the PG). The filter field can be strengthened by external permanent magnets attached to the vertical sidewalls of the source [12].

The number of co-extracted electrons is reduced by a factor of up to ten (depending on the source parameters) by the magnetic filter. Reason is a low probability for cross-field transport of magnetized electrons. An additional reduction of the co-extracted electrons is obtained by a positive bias potential applied to the PG with respect to the source body and the so-called bias plate [3], see Figure 1.

The co-extracted electrons are magnetically deflected onto the surface of the extraction grid, i.e. the extraction grid is acting as an electron dump. If the power deposited onto this grid is too high, beam extraction is stopped by a safety interlock. A unique feature of ELISE is that separate current measurements are available for the top and bottom segment of the extraction grid, i.e. the asymmetry of the co-extracted electron current is measured. The design limit of power deposited onto the extraction grid is 200 kW per segment [13], the safety interlock takes effect at 125 kW/segment. Thus, a high co-extracted electron current can prevent increasing the extraction potential or the RF power in order to increase the extracted negative ion current. If the co-extracted electron current strongly increases during a pulse it can limit the length of the pulse. Typically, in deuterium plasmas the

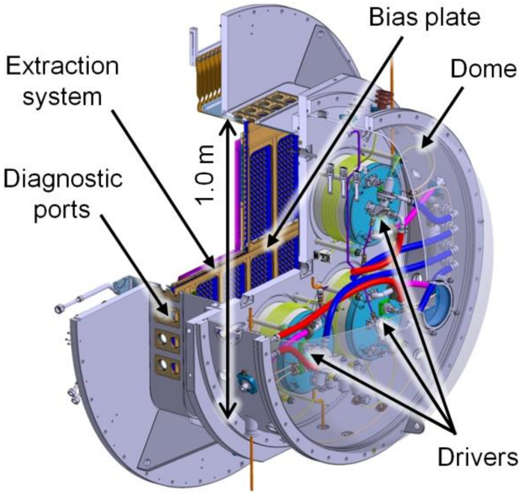

FIGURE 1. Schematic view of the ELISE ion source.

amount of co-extracted electrons is higher [14] and the temporal instability of the co-extracted electrons is more pronounced than in hydrogen [14].

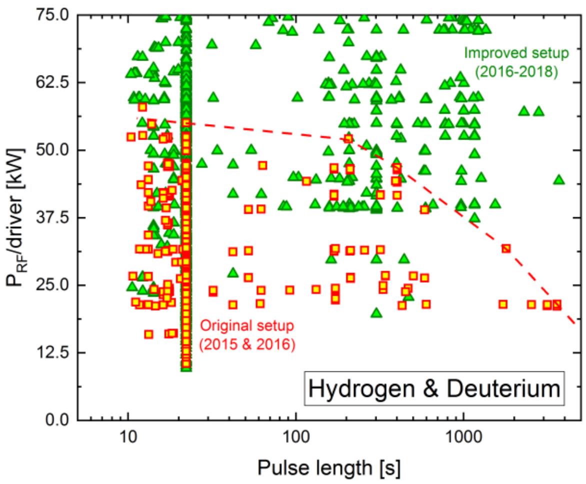

FIGURE 2. RF power per driver vs. pulse length for all ELISE pulses (in hydrogen and deuterium) since 2015 before and after performing the technical modifications enabling reliable long pulses with high RF power. The red line symbolizes the upper limit of the parameter space accessible with the original setup.

RELIABLE LONG PULSE OPERATION AT HIGH RF POWER

The following technical issues were solved stepwise in order to enable reliable long pulse operation at high RF power:

i) RF breakdowns in the driver region, occurring for P_{RF} above 40-60 kW/driver mainly caused by triple points (locations where a metal is in contact with a dielectric and the vacuum). After modifying the design of RF components in order to avoid triple points or to reduce the electric field at these locations, a significantly reduced probability for RF breakdowns is observed [15].

ii) heating of RF components. The water cooling system of the copper RF shields around each of the drivers was improved in order to avoid a strong heating-up (final temperature: more than 300 °C) during plasma pulses of more than several hundreds of seconds [15].

iii) RF matching issues and frequency flips. Initially used at ELISE as RF power supply were two self-excited tube based 180 kW oscillators. Even for optimized matching, for a filling pressure of 0.3 Pa the maximum power delivered by the tube-based generators into the plasma is between only 120 and 130 kW per generator (between 60 and 65 kW per driver). This value is too low for fulfilling the ITER requirements [16]. The tube-based generators have been replaced by two 150 kW solid-state RF amplifiers which can deliver up to their full nominal power into the plasma [17]. The now available 75 kW per driver, however, are still lower than the 100 kW/driver foreseen for ITER NBI [6].

Figure 2 shows the RF power per driver vs. the pulse length for the period between 2015 and 2018. In the original setup, the maximum power was about 55 kW per driver and for increasing pulse length, the possible power decreased. The dashed line acts as guide for the eye, indicating the parameter space accessible in the original setup. After introducing the design modifications described above, the available parameter space was significantly enlarged, as indicated by the green symbols.

Further investigations can now treat exclusively the physics relevant for long high performance pulses. Focus is laid on the homogeneity of the plasma and the extracted beam, in particular of the co-extracted electrons.

INTERNAL POTENTIAL RODS

The horizontal component of the filter field in front of the PG creates vertical plasma asymmetries, caused by cross **B** drifts [18,19]. For measuring these asymmetries, different plasma diagnostics are applied, e.g. optical emission spectroscopy (OES) at several horizontal lines of sight and non-compensated Langmuir pin probes (one in the top segment and bottom segment of the ion source). Because of plasma asymmetries, the extracted ion current and the co-extracted electron current can also be non-symmetric. The ion beam symmetry is measured, in 3.5 m distance to the extraction system, at the diagnostic calorimeter [20].

The vertical symmetry of plasma and the co-extracted electron current are decisive parameters for performing long pulses at high RF power. A symmetric plasma flux onto the PG correlates to a symmetric flux of caesium onto the grid and symmetric removal of caesium from the grid. This means that the homogeneity of the work function should be preserved during long pulses (not necessarily at a constant value). A symmetric co-extracted electron current prevents earlier activation of the safety interlock for the power deposited onto one of the extraction grid segments during long pulses.

Recently added to ELISE – besides the external permanent magnets – have been internal potential rods, shown in Figure 3, water-cooled vertical plates made of nickel-coated copper installed in between the groups of extraction apertures. Their vertical length is ≈48 cm and the axial extent ≈3 cm. Aim of the potential rods is to modify the

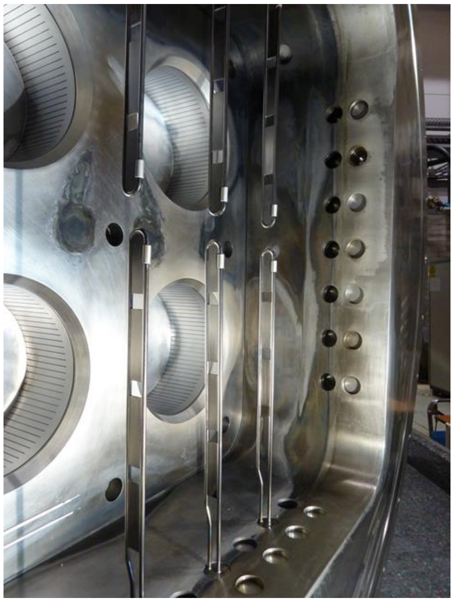

FIGURE 3. Internal potential rods used in ELISE. The rectangular openings in the rods are positioned at the location of the horizontal OES lines of sight.

plasma potential profile close to the PG and thus the plasma drift and to affect additionally the trajectories of the (magnetized) electrons. Observed is a reduction and stabilization of the co-extracted electrons. Additionally, in hydrogen pulses the top-bottom ratio of the plasma density (measured with the Langmuir pin probes) and in particular of the co-extracted electron current are shifted significantly down towards one, i.e. full symmetry.

Different potential settings of the rods with respect to the PG and the bias plate have been tested systematically for their impact on the stability of long pulses. The results obtained for the different settings are very similar, but the best setting identified so far is an electrical connection between the potential rods and the PG, i.e. the rods increase the area that is biased versus the source walls and the bias plate.

A negative side effect of the potential rods is that caesium conditioning takes longer: during the present campaign, conditioning for long pulses at high RF power needed 14 operational days with ≈700 pulses and a plasma-on time of ≈9 h. However, after a good caesiation status is achieved with the rods, this status is more stable than without the rods.

The reduced temporal increase in the co-extracted electrons together with the vertically more symmetric plasma density and co-extracted electrons caused by the potential rods and the permanent magnets enable long pulses at high RF power without exceeding the power limit of the two extraction grid segments.

CAESIUM CONDITIONING AND CAESIUM OVERCONDITIONING

For obtaining a high performance, a series of dedicated caesium conditioning pulses is necessary. During these pulses, caesium is redistributed to create suitable reservoirs inside the source, resulting in an improved subsequent source performance, i.e. an increased stability and/or higher extracted ion currents and/or lower co-extracted electron currents. Caesium conditioning usually is done using short pulses (20 s plasma, 9.5 s extraction) and is continued until the extracted negative ion current saturates at a level that is as high as possible and simultaneously the amount of co-extracted electrons is as low and stable as possible. The caesium oven is activated in the beginning of each operational day and shut-off in the evening.

Initial caesium conditioning, i.e. the transition from a caesium free source to a status in which negative ions are produced predominately by the surface process takes up to several days. Figure 4 shows the extracted negative ion current density vs. the electron-ion ratio for initial conditioning in deuterium done at a filling pressure of 0.6 Pa and without the potential rods [21]. These pulses have been done at reduced source parameters (as the RF power and the extraction potential) in order to stay below the safety limit of power deposited by the co-extracted electrons onto the extraction grid. After three days, the extracted negative ion current saturates. Due to the used reduced parameters, the finally reached source performance is significantly lower compared to the best possible values in deuterium.

At the beginning of each operational day, a re-conditioning phase of several pulses is needed in order to obtain again a good source performance. This re-conditioning phase lasts several pulses.

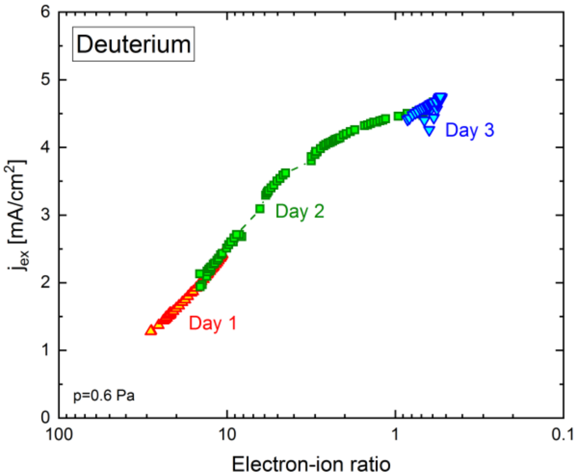

FIGURE 4. Extracted negative ion current density vs. the electro-ion ratio for the first three days of initial caesium conditioning in deuterium at p_{fill}=0.6 Pa.

For long pulses at high RF power, a new caesium conditioning technique, the so-called caesium overconditioning, is applied. Overconditioning is based on increasing the caesium evaporation and thus the caesium density in the ion source above the optimum for short pluses: for caesium densities above a certain limit, the extracted negative ion current density decreases again and the amount of co-extracted electrons can increase. Observed simultaneously is a decrease of the atomic Balmer line emission measured by OES in the drivers while the molecular Fulcher band emission stays unchanged. The reason is gettering of atomic hydrogen in the driver by caesium.

In hydrogen, overconditioning starts for a neutral caesium density significantly larger than $\approx 10^{14}$ m^{-3}, measured close to the PG during plasma pulses by Tunable Diode Laser Absorption Spectroscopy (TDLAS) [22]. Although additionally a large fraction of ionized caesium is present in the plasma, up to now no measurement technique for these caesium ions is available.

At the beginning of long pulses, however, caesium is re-distributed on a time scale of several hundred seconds in a way that results in a distinct stabilization of the co-extracted electrons compared to pulses without overconditioning and can result in an extremely stable negative ion current. On the same time scale, the Balmer emission increases to values measured without overconditioning. This caesium re-distribution at the beginning of the long pulse can be done during a plasma phase; alternatively a beam blip, releasing caesium from the back plate by the impact of back streaming positive ions generated in the extraction system, can reduce the needed time.

APPROACHING THE ITER PARAMETERS

Reliable long pulse operation at high RF power, together with the beneficial effect of the external permanent magnets, the internal potential rods and of caesium overconditioning enabled making the pulse shown in Figure 5, the best 1200 s hydrogen pulse at p_{fill}=0.3 Pa up to now. The used RF power is close to the maximum of the solid-state RF generators. Figure 5 shows the extracted current density j_{ex}, the accelerated current density j_{acc}, the co-extracted electron current density j_e and the top-bottom ratio $S(j_e)$ of the co-extracted electrons.

The first blip is used for reducing the time needed for caesium re-distribution. During the following blips, extremely stable j_{ex} and j_{acc} are almost constant over 1000 s (lowest value: 290 A/m^2 and 237 A/m^2, respectively). This means that ≈90 % of the ITER requirement for j_{ex} have been reached while the requirement for j_{acc} have been exceeded. The fact that the two target values for the currents are not reached simultaneously is explained by the different fraction of negative ion destruction by stripping in the beamline of ELISE (below 10 % [23]) and ITER (30 %). The performance is not limited by physical reasons but by the maximum power of the used solid state RF generators and the available HV power supply.

During the pulse shown in Figure 5 the co-extracted electron current increases steadily but the electron-ion ratio is well below the ITER requirement. It reaches 0.7 for the last beam blip. With increasing co-extracted electrons they symmetrize until $S(j_e)$ is about one the end of the pulse. This means that for high power dumped onto the second grid this power is homogeneously distributed (≈110 kW at the top segment, ≈100 kW at the bottom segment during the last beam blip). This is beneficial since it facilitates keeping the power dumped on both segments of the second grid below the power limit, 125 kW, of the safety interlock system. These results are of high relevance for the ITER sources where the co-extracted electrons are measured only globally, which means that strong asymmetries that could damage locally the second grid cannot be detected.

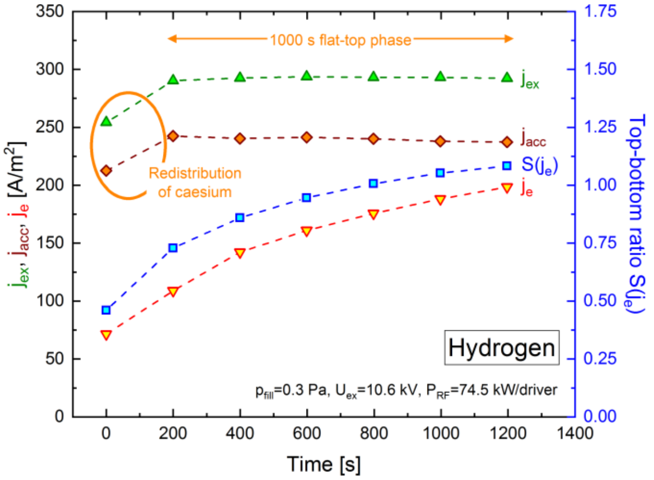

FIGURE 5. Extracted and accelerated negative ion current density, co-extracted electron current density and top-bottom ratio of the co-extracted electrons for the best long hydrogen pulse performed at ELISE up to now. The caesium re-distribution phase is followed by a 1000 s flattop phase of the extracted and accelerated current.

The spatial distribution of the power density of the negative ion beam measured by IR calorimetry of the diagnostic calorimeter during the second beam blip is shown in Figure 6. The total high voltage potential was 50.6 kV, resulting in a beam power of ≈1.2 MW, which is the design value of the diagnostic calorimeter (designed for 20 A negative deuterium ions accelerated to 60 kV).

The global top-bottom uniformity of the beam power is determined from the IR image using a fitting procedure, taking into account the downward deflection of the beam caused by the magnetic filter. The uniformity is close to 100 % and thus better than the ITER requirement for the beam uniformity (which is defined, however, based on the single beamlets). This uniformity decreases slightly to ≈90 % during the pulse, mainly caused by a decrease in the bottom part of the beam. The reason for this decrease is not known yet, but initial experiments [24] indicate that it may be possible to counteract by slightly increasing the RF power of the lower drivers during the pulse.

The beam divergence, measured by the vertical lines of sight of the beam emission spectroscopy system [20] is ≈2.7 °. This value is significantly higher compared to the ITER requirement (0.4 °) and even higher than the lowest obtained values at ELISE (≈1 °). The reason is the limitation to a maximum total high voltage of 60 kV which was not even fully exploited in the present experiments.

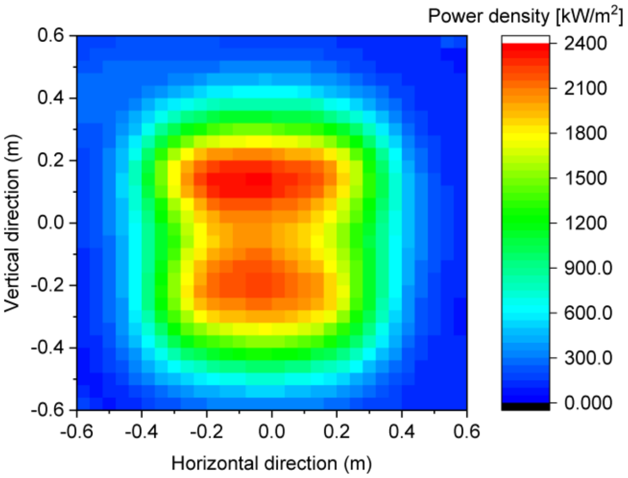

FIGURE 6. Power density measured by IR calorimetry on the surface of the diagnostic calorimeter for the second blip of the pulse shown in Figure 5. The global top-bottom uniformity is close to 100 %.

It is possible to do at p_{fill}=0.3 Pa series of reproducible 1200 s pulses at high performance. In between these pulses, no series of short caesium re-distribution pulses were necessary, just a break of about 15 minutes with continued caesium evaporation from the ovens. Figure 7 shows j_{ex}, j_{acc}, j_{e} and $S(j_{\text{e}})$ for such a series of pulses, done with similar source parameters and showing a similar behavior.

For all pulses – with the exception of the second one – a first beam blip is used in order to reduce the time needed for caesium re-distribution, resulting in lower extracted and accelerated ion currents measured for this blip. All pulses show the 1000 s flattop phase with very stable extracted negative ion currents. The electron-ion ratio is well below one. The symmetry of the co-extracted electrons improves during the pulses and reaches values around one for the later beam blips.

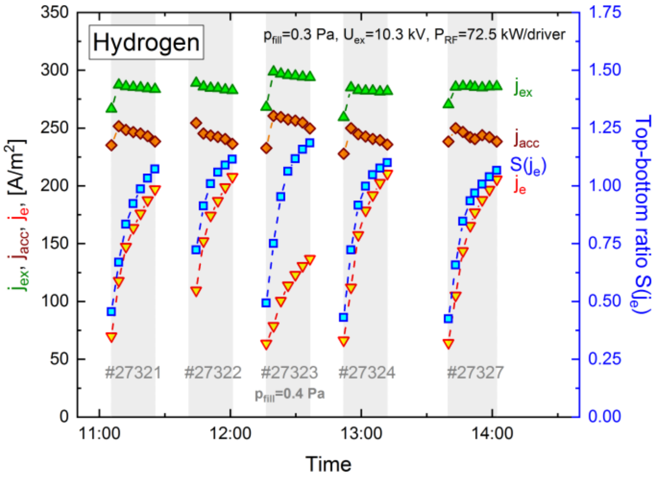

FIGURE 7. Extracted and accelerated negative ion current density, co-extracted electron current density and top-bottom ratio of the co-extracted electrons for a series of 1200 s pulses at high RF power. The areas shaded in grey represent the plasma-on time. Identical source parameters have been used, with the exception of pulse #27323 where p_{fill} was set to 0.4 Pa instead of 0.3 Pa.

During the second pulse the first blip was skipped with otherwise unchanged pulse timing, i.e. caesium re-distribution was done only by the plasma. The source performance obtained during this pulse is not significantly worse than for the other pulses.

The third pulse was done at an increased filling pressure (0.4 Pa instead of 0.3 Pa). The extracted ion current density is by about 10 A/m² higher than for p_{fill}=0.3 Pa and simultaneously the co-extracted electron current density is decreased by about 40% and the temporal increase is slightly suppressed. This result points out that operation at slightly increased filling pressure is significantly eased. While long high performance pulses in hydrogen at p_{fill}=0.3 Pa can be handled, in deuterium operation even a slight increase in the filling pressure would be beneficial.

CONCLUSIONS

Reliable and reproducible long pulse operation with high RF power is possible at ELISE after technical issues have been resolved stepwise.

The vertical asymmetries of the plasma and the co-extracted electron current are decisive parameters for performing long pulses at high RF power. Both symmetries are significantly affected by the recently introduced internal potential rods: the top-bottom ratio of plasma density and co-extracted electrons are shifted to significantly lower values. During long hydrogen pulses with high RF power, both ratios reach values close to one.

In combination with caesium overconditioning, it was possible to perform a 1200 s pulse at p_{fill}=0.3 Pa during that ≈90 % of the ITER target for the extracted current were reached and the requirement for the accelerated current density was exceeded. During a 1000 s flattop phase the extracted and accelerated negative ions are almost constant. The top-bottom beam homogeneity of the accelerated negative ions is close to 100 % at the beginning of the pulse and during the pulse it slightly decreases. It was possible to do series of such pulses in a very reproducible manner without the need of lengthy re-conditioning in between.

Due to the different stripping fractions in the beamlines of ELISE and ITER, a comparison of results obtained at ELISE with the target values is not straightforward, as evidenced by the fact that the present results are lower than the requirement for the extracted current while exceeding the one for the accelerated current. This should motivate the generation of a comprehensive set of calculated stripping fractions for ELISE, SPIDER and the ITER source, for hydrogen and deuterium separately. Such calculations – based on gas density profiles determined by a recent molecular flow code, e.g. AVOCADO, developed by RFX – would greatly enhance the comparability of the results achieved at the different test facilities.

Next step at ELISE will be to approach the ITER target also in deuterium. Topics will be the well-known isotope effect, i.e. higher co-extracted electron current and a stronger temporal increase in deuterium, but also the top-bottom ratio of the plasma density and the co-extracted electrons for long pulses at high RF power.

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