Achievement of ITER-relevant accelerated negative hydrogen ion current densities over 1000 s at the test facility ELISE

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The neutral beam heating system for the future international fusion experiment ITER will be based on RF driven ion sources delivering a large (≈1×2 m) and homogeneous negative hydrogen or deuterium ion beam of several ten Amperes over up to one hour. Such beams have never been produced up to now and a dedicated R&D process is ongoing for more than two decades. An important intermediate step is the size scaling test facility ELISE (Extraction from a Large Ion Source Experiment) with its half-ITER size ion source. Recently, ELISE has fulfilled its first main aim, demonstrating in hydrogen ITER-relevant accelerated negative ion current densities over 1000 s, at the required filling pressure of 0.3 Pa, electron-ion ratio below one and beam homogeneity better than 90 %. The measures identified as essential for achieving such pulses are the introduction of external permanent magnets and internal potential rods as well as a dedicated caesium conditioning technique.

The two injectors of the ITER neutral beam heating system will deliver a total power of 33 MW to the fusion plasma [1]. Central part of the systems is a large area (1×2 m^2) source for negative hydrogen or deuterium ions, 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. For keeping low the losses of negative ions by stripping reactions with the background gas in the extraction system, the source has to be operated at a filling pressure of 0.3 Pa or less. Assuming the same stripping fraction of 30 % for both isotopes, 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. The ratio of co-extracted electrons to extracted ions has to be smaller than one in order to keep the heat load in the extraction system at a tolerable level. For a proper beam transport, the homogeneity of the accelerated beam, composed of 1280 beamlets, has to better than 90 %. Up to now, these parameters have not been achieved simultaneously. Although ITER relevant ion current densities have been demonstrated at smaller test facilities [3], this was done for short pulses, i.e. a beam duration of a few seconds only.

A few seconds is also the typical pulse length possible at nominal heating power in NBI systems based on negative ions operated at LHD [4] and JT-60U [5]. For reduced power, pulses up to several ten seconds have been demonstrated. In preparation for the NBI system of JT-60SA pulses of up to 60 s have been obtained with an accelerated current density of 190 A/m^2, but only for a small extraction area (9 apertures) [6].

The ELISE test facility is an integral part of a R&D roadmap defined by the European domestic agency F4E for the construction of the ITER neutral beam heating systems [7, 8]. Main aim of ELISE [3] with its half-ITER-size ion source

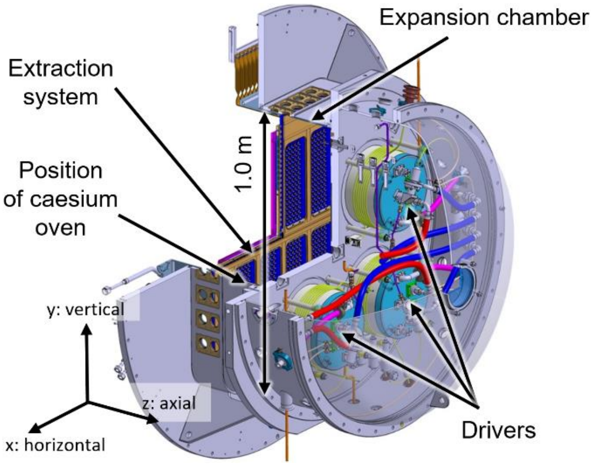

Figure 1: Schematic view of the ELISE ion source. The position of one of the caesium ovens at the left vertical side wall is indicated, the second oven is located at the right source wall.

(1×1 m^2, 640 apertures with a diameter of 14 mm each, extraction area: 0.1 m^2) is to demonstrate that the ITER requirements regarding the extracted current density, the electron-ion ratio, the filling pressure and the pulse length can be fulfilled in hydrogen and in deuterium. The gained operational experience is crucial to support the commissioning and operation of the SPIDER and MITICA test facilities at the European Neutral Beam Test Facility PRIMA [9].

Figure 1 shows a schematic view of the ELISE ion source. Shown are three of the four cylindrical RF drivers where a low-pressure, low-temperature plasma is generated by inductive RF coupling (f=1 MHz, maximum power: 75 kW/driver) and the expansion chamber. Additionally indicated is the three-grid, multi-aperture extraction system. While steady state plasma operation is possible, due to technical limits of the available HV power supply only pulsed extraction is possible: one extraction blip of about 10 s each ≈150 s. Long pulse operation at ELISE consequently means long plasma pulses (up to one hour), comprising several extraction blips. Additionally defined by the HV power supply are limits for the total potential (sum of extraction and acceleration potential, 60 kV) and the accelerated current (≈30 A).

A magnetic filter field is generated by a current, I_{PG}, flowing vertically through the plasma facing grid, the plasma grid (PG). The main component of this magnetic filter is parallel to the PG and in horizontal direction. The filter field reduces the electron density and temperature close to the PG [10] and as a result, the amount of co-extracted electrons as well as the destruction rate of negative ions by electron stripping are reduced. Additionally, the filter field plays an important role in the transport of negative ions generated at the PG surface to the extraction apertures [11]. A positive bias potential applied to the PG with respect to the source body (typically ≈20 V) additionally can reduce the co-extracted electron current. The co-extracted electrons are deflected onto the surface of the second grid. All grids consist of two individual segments in a vertical arrangement, i.e. a top and a bottom segment. The two segments of the second grid are insulated against each other against each other so that the electron current on these segments can be measured individually.

Negative hydrogen ions are generated predominately by conversion of hydrogen atoms impinging the caesiated low work function surface of the PG [12]. Caesium is evaporated into the source by means of two caesium ovens [13]. The position of one of these two ovens at the left side wall of the source is indicated in Figure 1. Evaporation occurs towards the back-plate of the expansion chamber. Caesium is re-distributed over the source walls and the PG, mainly during the plasma pulses [14]. For fulfilling the ITER requirements, caesium has to be evaporated and re-distributed during a caesium conditioning phase in a way that ensures a homogeneous, stable and low enough work function of the large area PG surface during long pulses with high RF power. Due to the highly reactive and volatile character of caesium, in combination with plasma asymmetries caused by a vertical plasma drift [10], this is a challenging task.

The long pulse performance of ELISE, i.e. the maximum achievable negative ion current density, usually is limited by an increase in the co-extracted electrons, which is probably due to a (locally) degrading PG work function. Reasons for an increasing work function can be the adsorption of impurities (hydrogen, oxygen, …) to the PG surface or the removal of caesium. The co-extracted electron current can increase dramatically (depending on the source parameters by a factor of up to ten in a few seconds) while the simultaneous decrease of the extracted negative ion current is less pronounced. A safety interlock system causes a premature end of the pulse when the power dumped by these electrons onto the segments of the second grid, i.e. the co-extracted electron current times the extraction potential, is higher than 125 kW. This limit is well below the design limit for the two grid segments (200 kW) in order to take into account for possible non-homogeneities of the deposited power. The amount of 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.

Thus, the main challenge is to define physical measures that reduce, stabilize and symmetrize the co-extracted electrons. The pulses presented in this letter were done after modifying the strength and topology of the magnetic and electric fields present in the source volume and thus the vertical plasma drift. This was achieved by introducing external permanent magnets [15] and internal potential rods [16]. Results of two non-compensated Langmuir pin probes located close to the PG (in the top and the bottom segment of the ion source) indicate that the top/bottom plasma density ratio close to the PG is significantly reduced; for hydrogen pulses by a factor of about two to almost perfect top/bottom homogeneity [17]. Consequently, a more symmetric transport of caesium to and from the PG is expected. Additionally applied is a newly developed caesium conditioning technique for long pulses that consists of increasing the caesium amount in the ion source above the optimum for short pluses. Both the more symmetric plasma and the increased caesium amount should prevent possible local depletion of the caesium layer on the PG surface.

Figure 2 shows the very first long hydrogen pulse performed at ELISE with an accelerated negative ion current density j_{acc} exceeding that required for the ITER heating neutral beam injectors, an extracted electron to extracted ion ratio that meets the requirements for those injectors, and at p_{fill}=0.3 Pa, for over 1000 s. Shown are j_{acc}, the extracted ion current density j_{ex}, the total co-extracted electron current density j_e and its top/bottom ratio $S(j_e)$, defined by the ratio of the currents measured on the two segments of the second grid. The extraction potential was 10.6 kV (concurring with the ≈10 kV of the ITER system [1]), the RF power 74.5 kW/driver, which is at the limit of the used RF generator but much less than the ≈100 kW/driver available for the ITER sources. The filter field generated by I_{PG} is 1.6 mT near the PG centre and the external magnets add about 0.4 mT, resulting in a total magnetic field of 2.0 mT close to the PG centre. The bias potential applied to the PG is regulated such that the bias current is 35 A. The potential rods were electrically connected to the PG, i.e. they increase the biased surface. The results shown in the left part of Figure 2 represent the average of the signals over the second half of the individual extraction blips.

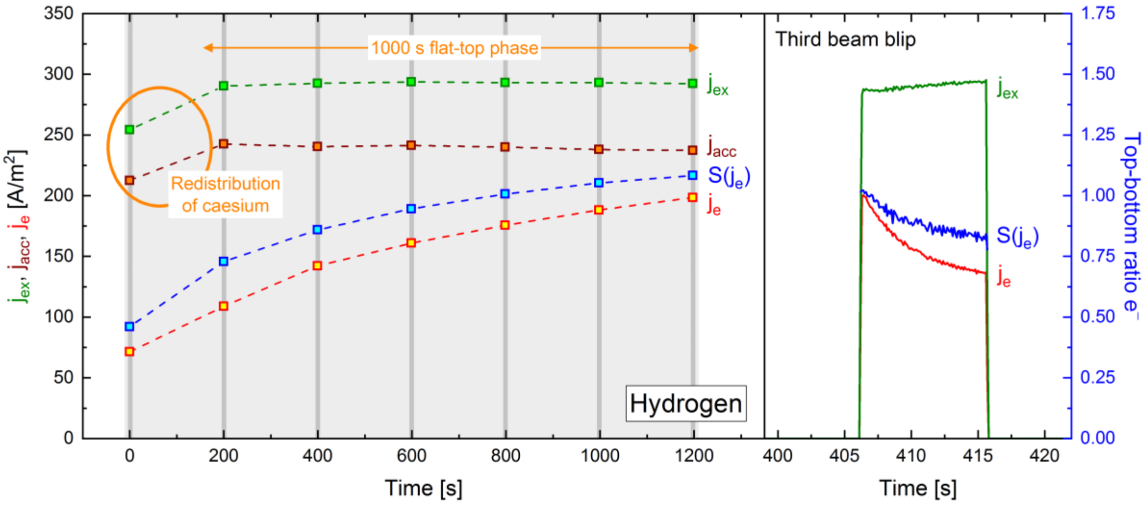

Figure 2: The best stable long pulse (with seven extraction blips) for p_{fill}=0.3 Pa in hydrogen at ELISE up to now: j_{ex}>290 A/m^2, j_{acc}>237 A/m^2, electron-ion ratio <0.7. Shown on the right side of the figure are the time traces for the third extraction blip. The area shaded in light grey indicates the plasma-on time, the dark grey areas indicate the duration of the extraction blips.

A significant suppression of j_{ex} and j_{acc} during the first extraction blip with respect to the following blips is observed. With the second extraction blip, the 1000 s long ITER-relevant phase of the pulse begins: the extracted and accelerated current densities are almost constant (lowest value: 290 A/m^2 and 237 A/m^2, respectively). About 90 % of the ITER requirement for j_{ex} are reached and the requirement for j_{acc} has been exceeded. The fact that the two target values for the current densities are not reached simultaneously is explained by the different fraction of negative ion destruction by stripping in the beamline of ELISE (below 5 % [18]) and ITER (30 %).

The reduction of j_{ex} and j_{acc} during the first extraction blip is caused by a high amount of caesium present in the plasma due to the applied long pulse conditioning technique. The caesium density is reduced by re-distribution during the first few hundred seconds of the plasma pulse. Since this phase of the pulse also includes an extraction blip, the release of caesium from the source back plate by back-streaming positive ions generated in the extraction system by interaction of fast negative ions with the background gas [19] may play an additional role. The high caesium density causes a reduction in the atomic hydrogen density, as indicated by optical emission spectroscopy (OES): the emission of the molecular Fulcher band ($d^3 \rightarrow a^3$) and the atomic Balmer H_α line ($n=3 \rightarrow n'=2$) in the four drivers is measured with an absolutely calibrated low-resolution spectrometer (336 pm/pix. at λ=600 nm). While the molecular emission during the first and the second extraction blip is identical, the Balmer emission increases by about 25 % (this factor is almost identical for H_α, H_β and H_γ). The identical molecular radiation indicates comparable electron temperature, electron density and molecular density for the first and the second extraction blip, thus a comparable rate of atomic hydrogen production by electron collision dissociation of H_2. However, the atomic emission indicates a strong increase of the atomic hydrogen density in the driver (thus also of the atomic flux impinging the PG and consequently the negative ion production rate) that can be explained by a decreased rate for atomic hydrogen destruction by gettering of hydrogen atoms by caesium atoms.

Compared to pulses without the external permanent magnets, the internal potential rods and the long pulse caesium conditioning technique, the top/bottom symmetry of the co-extracted electron current density is improved and its temporal increase is significantly reduced: although j_e increases steadily, the electron-ion ratio (0.7 for the last extraction blip) is well below the ITER requirement. With increasing co-extracted electrons they symmetrize: the top/bottom ratio $S(j_e)$ increases from 0.5 to 1.1 during the pulse, which means that for high power dumped onto the second grid this power is more homogeneously distributed. This facilitates keeping the power dumped on both segments of the second grid below the individual power limits of the safety interlock system.

The right part of Figure 2 shows time traces of j_{ex}, j_e and $S(j_e)$ for the third extraction blip: the extracted ion current increases slightly and the co-extracted electrons decrease. This means that caesium conditioning takes place within the extraction blip, caused by caesium released from the source back plate by back-streaming ions.

In the described status of ELISE it is possible to perform reproducible long hydrogen pulses without any caesium re-conditioning phase, i.e. it is not necessary to perform in-between a series of short pulses in order to regenerate the low work function PG surface. This behaviour is in contrast to previous experience, see e.g. [20]. Shown in Figure 3 are j_{ex}, j_{acc} and j_e (again averaged over the second half of the extraction blips) for a series of five pulses with a 1000 s flattop phase of the negative ion current density. For all these pulses similar source parameters have been used (exception: the third pulse was done for an increased filling pressure, p_{fill}=0.4 Pa) and the pulses show a similar behaviour. During the second pulse the first extraction 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.

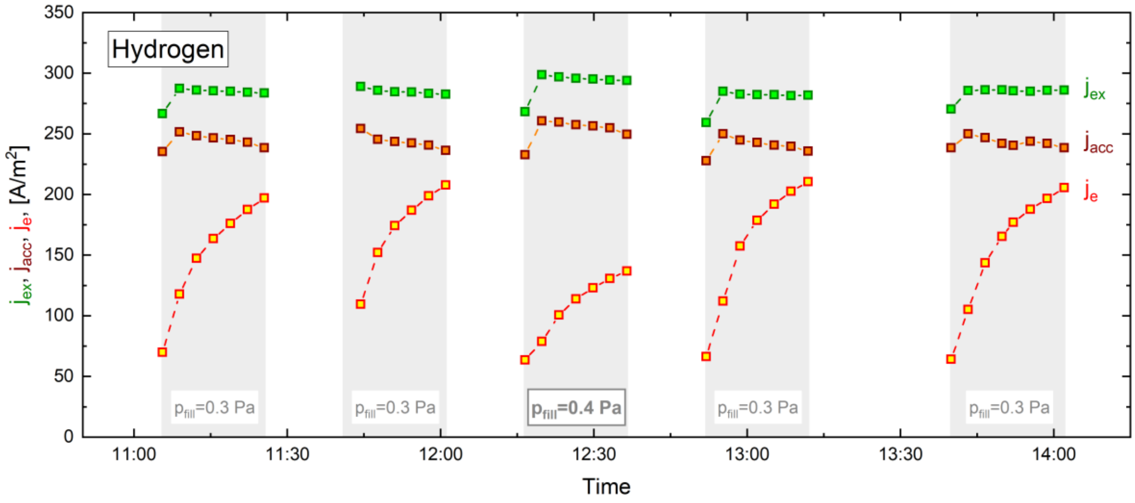

Figure 3: Reproducible high-power 1000 s pulses at ELISE. Identical source parameters have been used, with the exception of the third pulse with p_{fill}=0.4 Pa instead of 0.3 Pa. The areas shaded in grey indicate the plasma-on time.

The caesium consumption is a critical parameter for the ITER NBI system and it is desirable to reduce it (e.g. by using an improved caesium management) as much as possible. During the present ELISE campaign the caesium evaporation rate was determined by surface ionization detectors (SID) measuring the caesium flux at the oven nozzles [13]. The evaluation of the SID results is based on a calibration factor depending on the geometry of the nozzle and the SID and that can be determined only after completely depleting the caesium reservoirs of the ovens. Using the calibration for a slightly different geometry gives an upper limit of the evaporation rate of 3.0 mg/h and 1.7 mg/h for the two ovens. Although this is higher than reported previously for ELISE short pulse operation in deuterium [21], it is lower than the values used for estimating the caesium consumption of the ITER NBI system (10 mg/h [22]).

Crucial parameters for the beam transport in ITER are the beam divergence and homogeneity; target parameters are 7 mrad, i.e. 0.4 °and 90 %, respectively. Due to a different design of the acceleration system, the lowest divergence obtained at ELISE up to now, measured using Doppler shift spectroscopy [23] along a vertical line of sight (about 1 °) is higher than the ITER target. During the present campaign, an even higher divergence (about 2.7 °) was observed. Reasons are that the normalized perveance during these pulses was ≈0.18, which is below the perveance optimum [19] and that the ratio 3.8 of acceleration to extraction potential is lower than the optimum value (between 5 and 6). The maximum ratio of acceleration to extraction potential possible at ELISE for the used extraction potential of 10.6 kV is 4.7. Experiments using this ratio are planned for the next experimental campaign.

The ITER requirement for the beam uniformity (better than 90 %) is defined based on single beamlets. However, at ELISE no diagnostic is available that can resolve single beamlets. Instead, the beam homogeneity is evaluated globally by IR calorimetry of the diagnostic calorimeter, located in 3.5 m distance to the extraction system. Figure 4 shows the power density on the calorimeter for the second blip of the long pulse shown in Figure 2. The power density map is the result of the overlap of all 640 single beamlets. The beam originating from the top and bottom segment of the extraction system can be distinguished. The total (extraction and acceleration) potential was 51 kV, resulting in a beam power of ≈1.2 MW. The global top/bottom uniformity of the beam power (defined as the ratio of the power deposited by the top and the bottom segment of the beam onto the calorimeter)

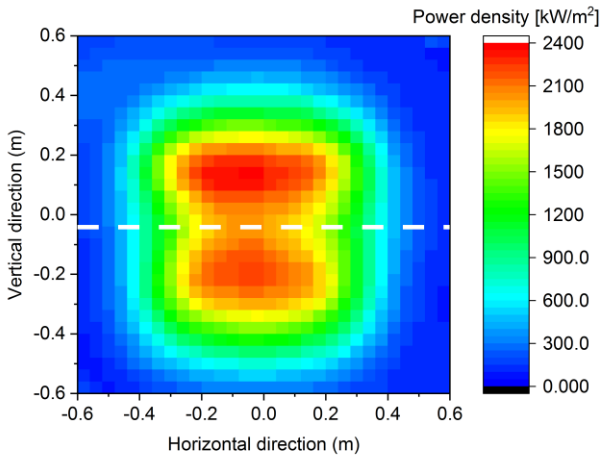

Figure 4: Power density measured by IR calorimetry on the surface of the diagnostic calorimeter for the second extraction blip of the long pulse shown in Figure 2. The horizontal dashed white line indicates the vertical centre of the beam, shifted downwards by ≈5 cm. The global top/bottom homogeneity is close to 100 %.

is determined from the IR image using a fitting procedure, taking into account the downward deflection (≈5 cm) of the beam caused by the magnetic filter [3]. The global top/bottom uniformity is close to 100 % and thus better than the ITER requirement for the beam uniformity. The global uniformity decreases slightly to ≈90 % during the pulse, mainly caused by a decrease in the bottom part of the beam.

The present results of ELISE are a significant step toward operation of the ITER NBI system in hydrogen, i.e. during the first operational phase of ITER (up to 2035): for the first time ever, a large negative ion source for NBI delivered a high long pulse performance in hydrogen that is comparable to what can be achieved during short pulses. Beneficial with regard to everyday operation of the ITER NBI is also the fact that series of reproducible long high performance pulses can be done. The improved symmetry of the co-extracted electrons has the side effect of increasing the operational safety of the ITER NBI system where the co-extracted electrons are measured only globally and strong asymmetries that could damage locally the second grid cannot be detected.

The parameters of the present pulses in hydrogen are close to the technical limits of the system regarding the available RF power, the accelerated current and the power deposited onto the diagnostic calorimeter (designed for 1.2 MW resulting from 20 A negative deuterium ions accelerated to 60 kV). Approaching the target parameters also for operation in deuterium – which will be the next step – should bring the system less close to its technical limits. However, this will be a challenging task since in deuterium the absolute value of j_e and its instability react much stronger on parameter variations [3]. Additionally, j_e is higher as well as much more asymmetric and the required pulse length (one hour) is longer than in hydrogen. Valuable tools for counteracting these effects may be the ones identified for hydrogen within the scope of the present work, i.e. modifying the topology of the electric and magnetic fields in the ion source order to reduce the vertical asymmetry of the plasma and the co-extracted electrons.

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