Operation of Large RF Sources for H^-: Lessons Learned at ELISE

U. Fantz [a)], D. Wünderlich, B. Heinemann, W. Kraus, R. Riedl and the NNBI Team

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

[a)]Corresponding author: ursel.fantz@ipp.mpg.de

Abstract. The goal of the ELISE test facility is to demonstrate that large RF-driven negative ion sources (1×1 m^2 source area with 360 kW installed RF power) can achieve the parameters required for the ITER beam sources in terms of current densities and beam homogeneity at a filling pressure of 0.3 Pa for pulse lengths of up to one hour. With the experience in operation of the test facility, the beam source inspection and maintenance as well as with the results of the achieved source performance so far, conclusions are drawn for commissioning and operation of the ITER beam sources. Addressed are critical technical RF issues, extrapolations to the required RF power, Cs consumption and Cs ovens, the need of adjusting the magnetic filter field strength as well as the temporal dynamic and spatial asymmetry of the co-extracted electron current. It is proposed to relax the low pressure limit to 0.4 Pa and to replace the fixed electron-to-ion ratio by a power density limit for the extraction grid. This would be highly beneficial for controlling the co-extracted electrons.

INTRODUCTION

One of the key components of the neutral beam injection (NBI) systems of the international fusion experiment ITER are large and powerful RF-driven ion sources for negative hydrogen ions (H^-, D^-) [1]. The beam source has to deliver stable extracted current densities of 285 A/m^2 D^- for one hour and 330 A/m^2 H^- for 1000 s at a source pressure of 0.3 Pa while keeping the ratio of co-extracted electrons to extracted ions always below one. The beam source has a rectangular shape with a width of 0.9 m and a height of 1.9 m and is based on the RF-driven concept [2] using a frequency of 1 MHz and a total power of up to 800 kW from four RF generators. With a total extraction area of 0.2 m^2, consisting of 1280 apertures with 14 mm diameter, the extracted currents are as high as 57 A D^- and 66 A H^-. Taking 30% stripping losses in the accelerator into account, an accelerated current of 40 A D^- and 46 A H^- has to be achieved. The beam homogeneity of this large beam needs to be better than 90%.

As these parameters have not yet been achieved simultaneously the European ITER domestic agency F4E has defined an R&D roadmap towards the NBI systems for ITER [3]. The test facility ELISE (Extraction from a Large Ion Source Experiment) represents an important step in the size scaling of RF sources from the prototype source (1/8 area) via the ½ size ITER source (ELISE) to the ITER sources. The latter will be commissioned and operated first at the European Neutral Beam Test Facility (NBTF) being currently under construction in Padua. The NBTF hosts a test facility for the full-size ITER source (SPIDER) and the prototype of the Heating Neutral Beam (HNB) for ITER (MITICA test facility) [4]. The same source will be used for ITER's Diagnostic Beam (DNB) which is under the responsibility of ITER-India [5].

Besides the goal to achieve the ITER parameters, the early start of ELISE had also the task to consolidate the design of beam source for which the ELISE design was kept as close as possible to the ITER design [6]. Furthermore, ELISE serves as a test bed to gain early experience with a large and modular RF-driven negative ion source. ELISE went into operation in November 2012 with the first plasma in February 2013 [7]. To demonstrate the performance of the beam source a stepwise approach has been chosen starting with short pulse operation (10 s beam during a 20 s plasma phase) at low RF power (20 kW/driver) towards long pulses which means plasma phases up to one hour with pulsed extraction at higher RF power. The experimental campaigns have been interrupted after 2 years by seven months maintenance phase accompanied by a thorough source inspection. The paper summarizes the experience gained regarding operation and maintenance so far and discusses consequences for operation of the ITER beam sources. Relevant technical issues of such large RF sources are addressed as well.

SIZE SCALING OF THE BEAM SOURCE

In the RF-driven prototype source the plasma is generated in a cylindrical driver by inductive coupling followed by expansion into a rectangular chamber (Fig. 1). The driver is powered by an RF generator with a frequency of 1 MHz and maximum power of 100 kW using a matching network in between. A high voltage transformer separates the ion source being on high potential from the RF generator connected to ground. The driver is equipped with a water-cooled Faraday screen to protect the alumina cylinder from the plasma. The prototype source is operational since two decades at the short pulse test facility BATMAN (beam pulse: 4 s) [3]. At the long pulse test facility MANTU pulses up to one hour have been demonstrated with this source [8]. The modular concept of using multiple drivers mounted to a large expansion chamber has been tested first at the size scaling plasma experiment RADI [9]. The source size was very similar to the size of the ELISE beam source but without extraction sytsem. From the four driver sources only a size scaling in vertical direction is required for the ITER sources as can be seen in Fig. 1. In the multiple driver concept the two horizontally arranged drivers are powered by one RF generator via a series circuit. Thus, two RF generators with a power of 180 kW each are connected to the ELISE source whereas the ITER sources are powered by four RF generators at 200 kW maximum each.

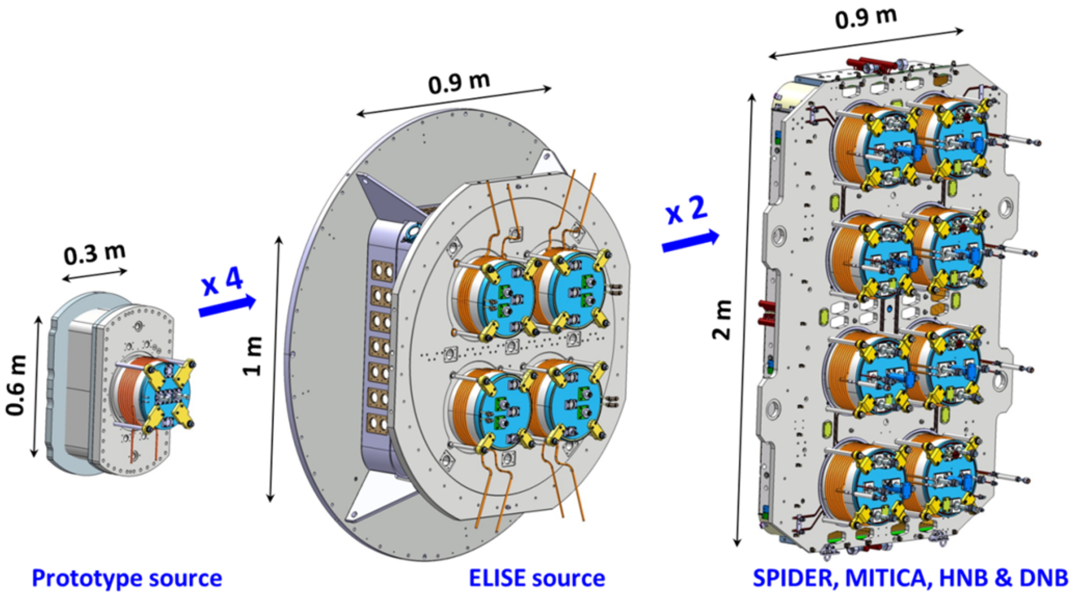


FIGURE 1. Size scaling of the RF-driven beam sources: from the prototype source (BATMAN, MANITU), via the ½ size ITER source at ELISE to the ITER size source.

The beam source at the ELISE test facility follows in principle the design of the ITER source with some modifications to allow better diagnostic access and to improve considerably the experimental flexibility [6,10]. The source vessel is in air allowing for easy source modifications but the four drivers are built-in a dome such that the RF coils can be operated in vacuum like at the ITER sources. The vessel hosts a high number of ports for plasma diagnostics close to the extraction system (Fig. 1). The extraction system is designed for acceleration of negative hydrogen ions of up to 60 kV. Due to the limitations in the available high voltage (HV) power supply, extraction is only possible in pulsed mode (10 s every 150 s), but the grids and the source is designed for continuous operation up to the desired value of one hour. The source is at high negative potential and negative ions are extracted and accelerated towards the grounded grid (GG), the third grid of the two stage extraction system. In order to prevent the co-extracted electrons to be fully accelerated, the second grid, the extraction grid (EG), is equipped with permanent magnets creating a deflecting field perpendicular to the filter field. Extraction voltages of up to 15 kV are possible.

The first grid, the plasma grid (PG) can be positively biased against the source (up to 60 V) for suppression of co-extracted electrons. A bias plate is installed above the grid and connected to the source chamber to enhance this effect [11]. Each grid consists of two segments in vertical arrangement. The segments of the extraction grid are insulated against each other so that their current is measured individually. This gives the unique opportunity to investigate possible asymmetries in electron extraction [12]. The arrangement of the 640 apertures follows the ITER design resulting in total of eight beamlet groups of 5x16 apertures. Each segment is hosting one row consisting of four beamlet groups. In order to avoid contamination of the ion source by copper, the plasma grid and the Faraday screens are coated with molybdenum whereas the inner surfaces of the ELISE source are coated by nickel.

In all the sources the negative ions are created via the surface conversion process, i.e. the conversion of mainly atoms at surfaces with a low work function, for which caesium is evaporated into the source. To improve the caesium distribution and to achieve reproducible conditions, the source body and the plasma grid are heated to temperatures equal to or higher than 35°C and 125°C, respectively. For the evaporation of caesium two ovens are mounted at ELISE using dedicated ports in the expansion chamber. At the ITER source the ovens will be mounted in the back plate of the ion source between the drivers.

In the large sources the magnetic filter field is created by a current of several kA flowing through the plasma grid. The maximum PG current will be 5 kA in the ITER source whereas for ELISE the design allows for currents up to 8 kA restricted to 5.3 kA maximum in the current setup. The return conductors are routed between the drivers at ELISE. The magnetic field is needed to cool the electrons from the driver down such that the destruction of negative ions is no longer dominated by electrons and to suppress the amount of co-extracted electrons.

The results obtained so far with ELISE in the different experimental campaigns can be found in [13-16] and references therein, with the latest results reported in [17].

LESSONS LEARNED FROM BEAM SOURCE OPERATION

RF Issues

The RF coupling to the plasma is reliable for RF power levels of up to ≈50 kW/driver. Increasing the RF power can be accompanied by breakdowns in the dome. This volume is pumped independently from the source to a pressure as low as 10^{-6} mbar. Once a breakdown occurs, the pressure in the dome increases instantaneously due to gas release, the RF power is deposited outside the driver and the internal plasma extinguishes. As the reason for the breakdowns was not obvious several countermeasures were taken: increasing as much as possible distances between coil connectors and feeds, thoroughly cleaning of the bottom feedthroughs for the RF current from dust (most likely produced by previous dome breakdowns and accumulated) and modifying their design in order to avoid triple points. Furthermore, DC voltage holding tests and simple 2D electric field analyses have been performed to better understand qualitatively the critical issues. A reduction of the field strength in the gap between coil and driver is possible by (i) increasing the gap or (ii) using Quartz (ε = 3.8) instead of Al_2O_3 (ε = 9.5) for small gaps [18]. Consequently, new driver cylinders are currently under manufacturing which combine both effects.

Another modification concerns the series connection of the two coils powered by one RF generator. In this configuration the same current is driven through both coils generating similar plasmas in both drivers. However, the RF voltage of both coils adds up to about 12 kV (typically 2 kV/turn). As they are electrically isolated from the source the RF voltage will float around the source potential in a self-adjusting way. In order to reduce the RF voltage with respect to the source potential two drivers have been switched in parallel to one generator [17,18]. The reduced inductance of the circuit has to be compensated by increasing the series capacitance (C2) from ≈1.5 nF to ≈5 nF. It was possible to apply up to 70 kW/driver without any breakdowns, but the matching by adjusting the variable capacitor of C2 is difficult and has a very narrow operation window, because of the low frequency stability of the RF generators which are self-excited oscillators. Thus, the increase of the RF power was also limited by either frequency flips or overcurrent in the RF generator.

The option to exchange the self-excited oscillators by solid state amplifiers was demonstrated at the test facility BATMAN with a prototype of a 75 kW amplifier [19]. Because of the higher RF efficiency (90% for the amplifier compared to 55% for the oscillator) water cooling is not necessary. The huge advantage however is the fixed frequency. Fig. 2 shows the matching curves: for the oscillator the frequency becomes unstable and frequency flips occur if cos φ is close to one, which corresponds to a good matching. For the solid state amplifier the matching is represented by the standing wave ratio (SWR; no reflected power SWR = 1) measured by a directional coupler. In collaboration with the company delivering the amplifier, automatic power control and frequency matching was developed and successfully tested at BATMAN. Based on these very promising results, high power RF amplifier have been purchased for the upgrade of one beam line at ASDEX Upgrade and for the beam lines at W7-X. One of the 150 kW amplifiers is currently in operation at BATMAN [20] and works very reliably.

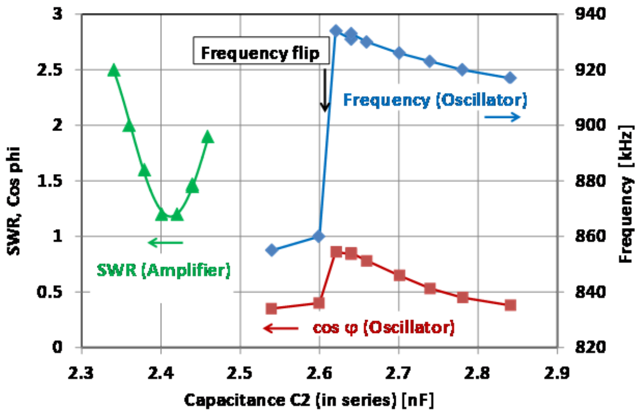


FIGURE 2. Matching curves for the two RF generators (green curve: solid state amplifier; red and blue curves: free oscillator) at the prototype source (BATMAN test facility).

Increase of the RF power at ELISE was also hampered by temperature runways for which improved cooling are provided now. One example to bring to notice is the cooling of the electromagnetic screen (EMS), which is installed around each driver to avoid mutual inductance between neighbored drivers. The EMS is heated by eddy currents of 1.4 % of the RF power. A new design of EMS has been developed and installed: the four support rods (per driver) have been replaced by actively cooled ones and the EMS is attached in four quadrants with good thermal contact to those rods. Heat conduction is further increased by increasing the EMS wall thickness from 1.5 mm to 4 mm [18].

Regarding the RF issues, it needs to be underlined that commissioning of SPIDER should be done with EMS to avoid damages to the Faraday screens via mutual coupling of the drivers as the ELISE configuration showed no damages (see below: source inspection) and as at RADI – where the damages occurred - a critical power level could not be identified. Regarding the use of solid state amplifiers, ELISE and / or MITICA would be test beds to qualify them for the ITER sources (the RF generators for SPIDER are already installed) as this increases the reliability of RF matching. Open issue are the breakdowns for the ITER sources; here SPIDER operation will give more insights.

Cs Consumption and (Re-) Distribution

The improved Cs ovens [21] are equipped with a Surface Ionization Detector (SID) at the nozzle for monitoring the evaporation. Furthermore, the design and operation of the ovens has been optimized such that the liquid reservoir is the cold spot reacting on temperature variation of 1°C. Those two modifications allow for fine control and adjustment of Cs evaporation. The ovens are used in both test facilities (BATMAN and ELISE) ([22] gives details on the mounting and the nozzle). At BATMAN the nozzle is directed towards the plasma grid. Estimations for the prototype source result in a reduced evaporation rate of about a factor of two (at least) compared to the previous ones which was between 5 – 10 mg/h. ELISE has a similar Cs consumption as the prototype source despite its larger size [11]. Furthermore, the valves allow for avoiding contamination of caesium during venting the source, thus re-conditioning requires also less Cs flow. A careful and dedicated Cs conditioning is needed for maintaining a good source performance in particular in long pulses [17].

The position of the ovens however is less relevant due to the fact that the plasma redistributes caesium very effectively. Although in vacuum phase strong asymmetry is measured in the Cs neutral density, the symmetric density with respect of the upper and lower half of the prototype source, is obtained during plasma [23].This is confirmed by resent results on source conditioning with one oven (top or bottom position) or both simultaneously [20]. Due to the low amount of Cs in the source at ELISE the Cs emission is below the detection limit of the installed spectroscopic system such that quantitative measurements cannot be performed. In order to allow for dedicated measurements laser absorption spectroscopy will be available in the next experimental campaign.

Fig. 3 shows the influence of the extraction of the time trace of the caesium emission measured with a diode using the appropriate interference filter. The increase during the beam blips is attributed to the back streaming positive ions created in the accelerator (the corresponding footprints are shown Fig. 8). Their energy is sufficient to sputter caesium from the back plate of the source being then redistributed by the plasma. In particular, in long pulse operation this influences the Cs dynamics in an uncontrollable manner. The consequence for operation with continuous extraction can be only revealed with a CW power supply which is not available for ELISE.

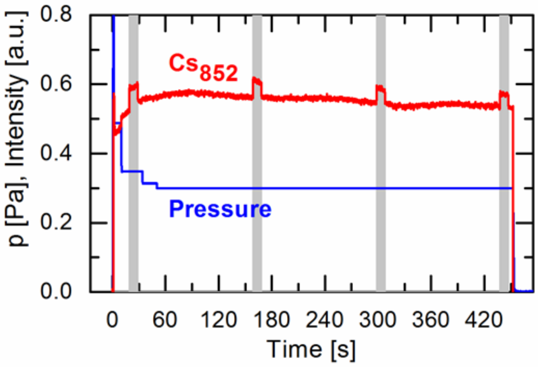


FIGURE 3. Pressure and emission of the 852 nm resonance line of neutral Cs in front of the grid at ELISE during a 450 s hydrogen discharge with pulsed extracted. The grey bars indicate timing and duration of the beam blips.

For the ITER sources the following statements can be drawn: (i) the caesium consumption can be expected to be lower than estimated, reducing then the maintenance interval for the Cs ovens and reducing the Cs contamination of the source provided fine adjustable and reliable ovens are used. (ii) The oven position is less relevant and (iii) the back streaming ions influence the Cs dynamics during plasma pulses. The consequences of the latter on the source performance during CW extraction are an open issue yet. It needs to be mentioned that the oven nozzle should be not directed toward the drivers as this can have consequences for the RF matching and not directly to the grid as this causes breakdowns between the grid if more caesium needs to be evaporated (as for example in deuterium) [17].

Magnetic Filter Field

The adjustment of the PG current allows for changing the magnetic field strength without changing the 3D topology. At about 0.6 kA PG current (about 0.6 mT in the PG centre), the electron temperature is already reduced to the desired value of 1 eV and the electron density is reduced as well to the values obtained in the prototype source (typically $1 - 2\times10^{17}$ m^{-3}) [11]. Furthermore, this field configuration does not cause such a strong plasma drift as it is known from the prototypes sources [11]. This is attributed to the different 3D topology of the field created by the PG current with which the field gradient in axial direction is much lowered.

The increase in the field strength reduces the amount of co-extracted electrons as shown in Fig. 4 for hydrogen and for deuterium discharges. The higher the field the better the co-extracted electrons are suppressed, however revealing also a lower limit. The optimum point to operate is always a compromise between electron suppression without reducing the extracted ions too much (grey shaded areas in Fig. 4). Clearly, higher fields are needed for deuterium. It should be kept in mind, that the interplay with the bias current is very important and the best operation point needs to be identified individually. In order to suppress the co-extracted electrons even more several configurations of additional permanent magnets attached to the lateral walls of the source have been tested [13,14]. With the additional magnets attached such that the field in the center of the source is strengthened the co-extracted electrons are suppressed further as shown in Fig.4, slightly on cost of the ions. Moreover, in long pulses the temporal stability of co-extracted electron current is improved [13]. Only in this configuration an one hour pulse could be achieved at 0.3 Pa in deuterium. The change of the extracted currents is less attributed to small increase of the field in the source center but to the change of the field topology in particular at the lateral walls.

The effect of the magnetic field on the beam homogeneity is measured via beam emission spectroscopy and via the diagnostic calorimeter [24]. The results of both show a vertical beam profile reflecting very well the two rows of beamlet groups with a slightly higher intensity in the upper half of the beam. With increasing magnetic field strength this asymmetry becomes more pronounced. The vertical position is shifted downwards by typically 4 cm indicating an increased beam shift (+-2 cm max.) with higher field strength. In a well caesiated source (uniform caesiation of the plasma grid) this beam shift is dominantly caused by the fringe field of the magnetic filter. Detailed analysis of the Doppler-shifted H_α peak reveals an inhomogeneity of about 3% in horizontal and about 7% in vertical direction (comparing the two rows of beamlet groups) in a well-conditioned source and at good perveance conditions.

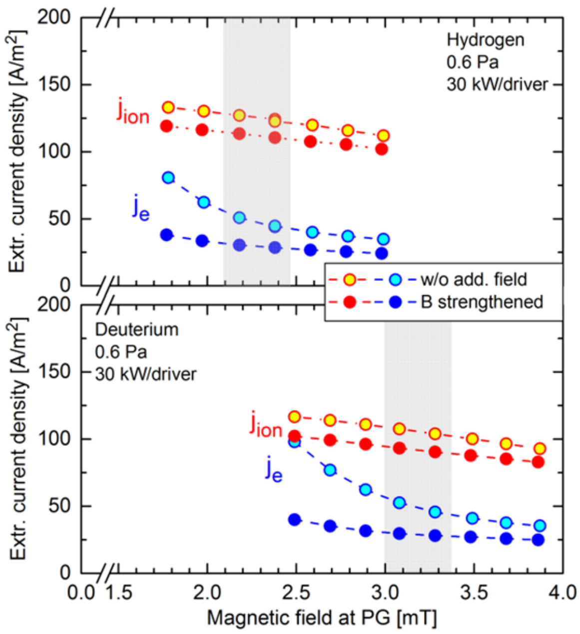
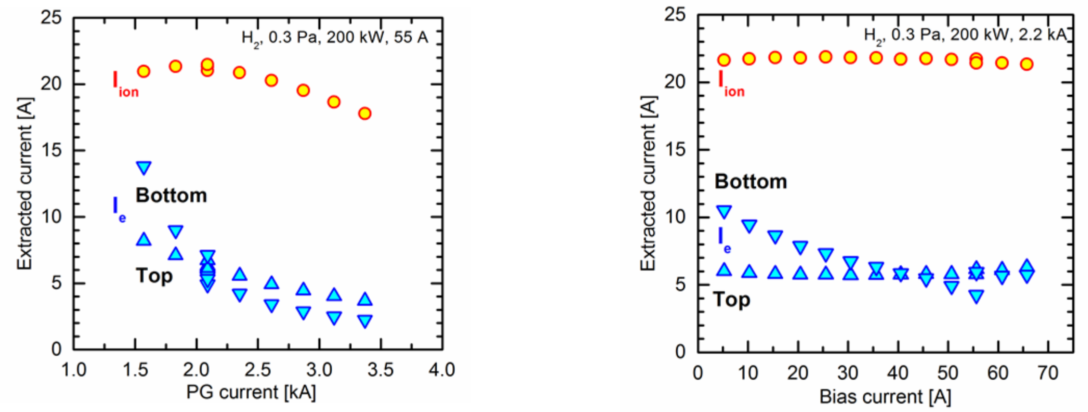


FIGURE 4. (a) Extracted ion and electron current densities as a function of the magnetic field generated by the PG current in standard configuration (w/o add. magnets) and with additional magnets at the lateral walls of the ELISE source (B strengthened).

In view of the ITER source for which 5 kA of PG current will be available one can conclude that the filter field topology as well as the strength is sufficient to achieve the desired cooling effect needed for reducing the destruction of negative ions by electrons in front of the PG. Further investigations on the field topology are underway at ELISE, for example it is planned to adopt the MITICA configuration. Nevertheless, it is recommended to keep the filter field strength adjustable (independent from the accelerator field) as this is required for finding the best operational point in view of electron suppression at tolerable reduction of the ion current which is of particular relevance for long pulse deuterium operation. The complex interplay with bias current and Cs conditioning strengthens the need for this requirement. Regarding the beam homogeneity a value above 90% seems to be achievable.

Co-extracted Electrons

The interplay of the magnetic field with the bias current and with the Cs conditioning, results not only in strong change of the amount of co-extracted electrons but also in an asymmetry of the electron currents [25]. Fig. 5 shows the extracted ion current density and the co-extracted electron current of the top segment and the bottom segment of the EG separately. Both currents decrease with increasing filter field, the current in the bottom segment however, decreases stronger. This is even more pronounced for the variation of the bias current. Although the electron-to-ion ratio is always below one, this demonstrates that the power load on one EG segment can be much stronger than on the other segment. The asymmetry depends also on the RF power. As the effect is not clarified yet, estimations or predictions for an expected asymmetry are not possible. The same is true for the temporal stability of the co-extracted electrons which however depends dominantly on the Cs conditioning and on the pressure [17]. The lower the pressure the more critical is the suppression and stability of the co-extracted electrons, in particular for the step from 0.4 Pa to 0.3 Pa [17].



(a) (b)

FIGURE 5. Extracted ion current density and co-extracted electron current of the top and bottom EG segment for a variation of (a) PG current and (b) bias current at ELISE in short pulse operation.

In view of the ITER sources it is proposed to define a power density limit for the extraction grid replacing the strict limit to keep the electron-to-ion ratio below one. This would simplify the Cs conditioning process in which the extraction voltage is changed as well. The detected asymmetry in the electron currents might be a more demanding issue for the ITER sources in which only the total electron current of all four segments are measured. Nevertheless, relaxing the pressure limit to 0.4 Pa would allow for a much better control of the electrons.

Stripping in the Accelerator

The pressure limit of 0.3 Pa is based on calculated stripping losses in the accelerator of 30%. At the test facility MANTU which was equipped with a cryopump system as ELISE is, the stripping losses for the used extraction system have been determined to be below 5% in the pressure range of 0.3 to 0.8 Pa at a tank pressure of 10^{-5} mbar [26]. One reason could be the much higher gas temperature measured in the source (1200 K) whereas the calculations are based on room temperature. This influences strongly the stripping losses in the first gap.

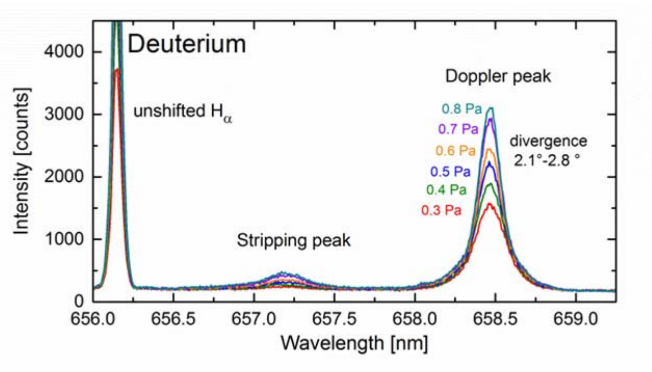


FIGURE 6. Beam emission spectra at ELISE (LOS 5) for several pressures in the ion source taken with 6 kV extraction voltage and 22 kV acceleration voltage (30 kW/driver, 4 kA PG current).

Fig. 6 shows beam emission spectra obtained at ELISE for a pressure variation using deuterium. The Doppler peak and the stripping peak increase clearly with pressure. The stripping peak is well separated from the other two peaks and can be straightforward analyzed. The stripping fraction is given in Fig. 7 showing results for hydrogen and deuterium at almost identical tank pressure. Similar to MANITU results, the stripping fraction is well below 10%. For both isotopes the same cross sections are used, which might be the reason for the higher stripping observed in D. At the ITER relevant pressure of 0.3 Pa the stripping fraction is 3% or below; taking into account some variation with the parameters it is reasonable to account for stripping losses of about 5% in the extraction and acceleration system of ELISE, i.e. the pre-accelerator of an ITER source.

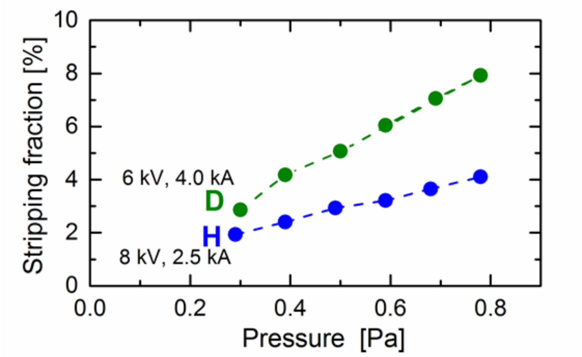


FIGURE 7. Stripping fraction as measured by BES (LOS 5) using 30kW/driver for hydrogen (U_{ex}= 8 kV, I_{PG} = 2.5 kA) and deuterium (U_{ex}= 6 kV, I_{PG} = 4 kA).

The analysis of the Doppler peak reveals a varying divergence of the beam of 2.1°- 2.8°. A more refined analysis however, reveals a broad component of about 7°, its portion strongly varying between a few percent up to 50% [27]. The reason for the broad component is unidentified at the moment and needs further investigations. It needs to be emphasized that in perveance matched conditions a divergence of about 1.5° can be obtained.

For the stripping losses 30% are taken into account for the whole accelerator of ITER NBI [1]. About 10% can be attributed to the stripping in the first acceleration stage, i.e. the pre-accelerator [28], which is higher to what is measured at ELISE. Thus, one might also think about to allow for a slightly higher source pressure, i.e. 0.4 Pa. An open issue is the broad component which requires further investigations to deduce consequences for ITER sources.

Source Performance

The linear extrapolations of the source performance from power levels up to 55 kW/driver in short-pulse mode at the filling pressure of 0.3 Pa showed that it can be expected to meet the required ion current densities at about 80 kW per driver [15] which is less than the power being installed for the ITER sources (100 kW/driver). The co-extracted electrons seem to be of no concern for hydrogen operation but for deuterium it is an issue to keep the amount of electrons below one already at this medium power levels.

The accessible RF power level in long pulse operation is hampered by the amount of co-extracted electrons as well, such that 1 h pulses have been carried out with 20 kW/driver only using reduced extraction voltages: 6 kV for hydrogen, 4 kV for deuterium. This underlines the challenge to meet the ITER target in deuterium at 0.3 Pa.

Due to the issues arisen with RF breakdowns and matching, and due to the temperature runaways only very limited experience in source operation at ELISE at high RF power is available at present. Hence, the validity of the linear extrapolation for the RF power needed to achieve the ITER target can be proven by experimental results. Furthermore, operation at high RF power levels for long pulses might require more caesium. These investigations have highest priority for gaining experience for ITER source operation.

LESSONS LEARNED FROM INSPECTION

A thorough inspection of the beam source after two years of operation showed that all components, and in particular the grids show no damages. Thus valuable experience is gained in the maintenance of this large source, although not having operated at full RF power."

Inspection of the Source

The Faraday screens are in very good condition; neither issues with the molybdenum coating nor melting traces have been obtained. The low caesium consumption resulted in a low caesium contamination of the inner surfaces of the expansion chamber with the footprint of grid pattern at the back plate caused by the back streaming positive ions. Using slightly wetted litmus paper, the pH index was determined to have a rough indication of the presence of Cs: on dark surfaces (side walls) pH values between 9 and 12 have been measured. On blank surfaces (grid pattern on the back plate) and on the surfaces of the Faraday screens and driver back plate a mostly neutral pH value (7) has been measured. The plasma-side of the plasma grid shows surprisingly neutral values. Only on the edges of the grid between the two grid segments a pH value between 8 and 9 has been measured. Higher pH values (up to 10) have been observed on the beam-side of the bias plate. Small probes were taken from several locations in the source and analyzed by EDX (energy dispersive X-ray spectroscopy) for elemental analysis. Besides Cs, molybdenum and nickel has been found at the surfaces being obviously redistributed as well during plasma (beam) operation and deposited downstream in the extraction system even in deeply shadowed regions. Traces of bismuth and indium have been found, presumably from the usage of Cs-dispenser in the first experimental campaigns [16]. These impurities might have influenced the Cs conditioning process of the source.

Inspection of the Grid System

The close inspection of the grids revealed some unexpected features (Fig. 8). The backside of the plasma grid, initially coated with molybdenum, showed copper deposition in and around the beamlet groups. On the copper EG each aperture is surrounded by dark rings which might lead to the conclusion that Cs diffuses from the ion source through the PG apertures onto the EG accompanied by a removal by negative ions with poor beam optics. The EDX analysis of scraped off pieces identified molybdenum, nickel and caesium. The GG showed copper sputtering around the apertures most likely caused by working not always at perveance optimized conditions or a beam halo. Deposition of copper was also detected on the grid holder boxes with some removal in areas which might be explained by a beam halo or re-ionized particles.

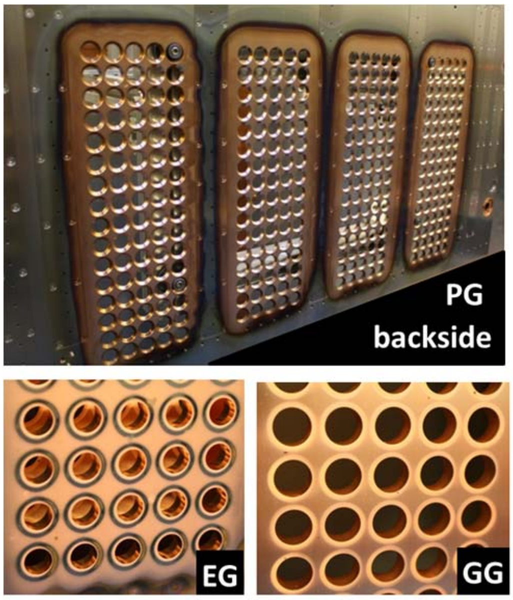


FIGURE 8. View onto the plasma grid from the backside and onto the extraction grid and grounded grid from the source side.

Summarizing, unexpected strong effects of copper sputtering are observed. Caesium, molybdenum and nickel from the ion source are transported into the grid system. Detailed explanations and consequences for the ITER sources are an open issue which needs future attention. Nevertheless, it is recommended to coat (at least) the EG with molybdenum as well.

CONCLUSIONS

With the experience gained so far with operation of the test facility ELISE (and those from BATMAN, MANITU and RADI), conclusions are drawn for commissioning and operation of the ITER beam sources. Among them are critical technical RF issues such as RF matching and breakdowns which might hamper the operation at high RF power. With testing powerful solid-state based RF amplifiers at BATMAN the ground is prepared to consider such RF generators for being tested with two driver operation at ELISE or at MITICA to achieve reliable matching. The caesium consumption can be expected to be lower than estimated, reducing the maintenance interval for the Cs ovens and reducing Cs contamination of the source. The position of the Cs ovens is of no concern. Regarding the magnetic filter it can be stated that the field structure and the PG current provided is sufficient to achieve the desired plasma cooling effect. It is recommended to keep the filter field strength adjustable (independent from the accelerator field) as this is required for finding the best operational point in view of electron suppression at tolerable reduction of the ion current which is of particular relevance for long pulse deuterium operation. Concerning the co-extracted electrons, a power density limit should replace the strict limit to keep the electron-to-ion ratio below one which would also simplify the Cs conditioning process. The asymmetry observed in the co-extracted electron currents is an opened point to be followed. Relaxing the pressure limit to 0.4 Pa, would easy the situation for the co-extracted electrons as well and is advantageous for the RF coupling. The low stripping losses measured at ELISE support this proposal.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The work at ELISE was supported by a contract from Fusion for Energy (F4E-2009-0PE-32-01), represented by Antonio Masiello. The opinions expressed herein are those of the authors only and do not represent the Fusion for Energy's official position.

REFERENCES

1. R. Hemsworth *et al.*, Nucl. Fusion **49,** 045006 (2009).
2. E. Speth *et al.*, Nucl. Fusion **46,** S220–S238 (2006).
3. A. Masiello *et al.*, Fusion Eng. Des. **86**, 860 (2011).
4. V. Toigo *et al.*, Nucl. Fusion **55**, 083025 (2015).
5. B. Schunke, D. Bora, R. Hemsworth and A. Tanga, AIP Conf. Proc. **1097**, 480 (2009).
6. B. Heinemann *et al.*, Fusion Eng. Des. **84,** 915 (2009).
7. P. Franzen *et al.*, Fus. Eng. Des. **88,** 3132–3140 (2013).
8. W. Kraus, *et al.*, Rev. Sci. Instrum. **79**, 02C108-1–3 (2008).
9. U. Fantz *et al.*, Rev. Sci. Instrum. **79**, 02A511–6 (2008).
10. R. Nocentini *et al.*, IEEE Trans. Plasma Sci. 42, 616–623 (2014).
11. U. Fantz *et al.*, AIP Conf. Proc. **1655**, 040001 (2015).
12. P. Franzen *et al.*, Plasma Phys. Control. Fusion **53,** 115006 (14pp) (2011).
13. D. Wünderlich *et al.*, Plasma Phys. Control. Fusion, submitted in 2016.
14. W. Kraus *et al.*, Rev. Sci. Instrum. **87**, 02B315 (2016).
15. U. Fantz *et al.*, Rev. Sci. Instrum. **87**, 02B307 (2016).
16. P. Franzen *et al.*, Nucl. Fusion **55**, 053005 (15pp) (2015).
17. D. Wünderlich *et al.*, Contribution to the NIBS conference 2016, submitted to AIP Conf. Proc.
18. B. Heinemann *et al.*, Contribution to the SOFT conference 2016, to be submitted to Fus. Eng. Des.
19. W. Kraus *et al.*, Fusion Eng. Des. **91**, 16-20 (2015).
20. C. Wimmer *et al.*, Contribution to the NIBS conference 2016, submitted to AIP Conf. Proc.
21. U. Fantz, R. Friedl, and M. Fröschle, Rev. Sci. Instrum. **83**, 123305-1–5 (2012).
22. A. Mimo *et al.*, Contribution to the NIBS conference 2016, submitted to AIP Conf. Proc.
23. C. Wimmer *et al.*,. AIP Conf. Proc. **1515**, 246 (2013).
24. B. Heinemann *et al.*, to be submitted to New J. Phys.
25. P. Franzen *et al.*, Plasma Phys. Control. Fusion **56**, 025007 (12pp) (2014).
26. P. Franzen, U. Fantz and the NNBI Team, AIP Conf. Proc.**1390**, 310 (2011).
27. M. Barbisan *et al.*, Contribution to the NIBS conference 2016, submitted to AIP Conf. Proc.
28. A. Krylov and R. Hemsworth, Fusion Eng. Des. **81**, 2239 (2006).