Size scaling of negative hydrogen ion sources for fusion

U. Fantz, P. Franzen, W. Kraus, L. Schiesko, C. Wimmer, and D. Wünderlich

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U. Fantz[a], P. Franzen, W. Kraus, L. Schiesko, C. Wimmer and D. Wünderlich

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

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

Abstract. The RF-driven negative hydrogen ion source (H⁻, D⁻) for the international fusion experiment ITER has a width of 0.9 m and a height of 1.9 m and is based on a ⅛ scale prototype source being in operation at the IPP test facilities BATMAN and MANITU for many years. Among the challenges to meet the required parameters in a caesiated source at a source pressure of 0.3 Pa or less is the challenge in size scaling of a factor of eight. As an intermediate step a ½ scale ITER source went into operation at the IPP test facility ELISE with the first plasma in February 2013. The experience and results gained so far at ELISE allowed a size scaling study from the prototype source towards the ITER relevant size at ELISE, in which operational issues, physical aspects and the source performance is addressed, highlighting differences as well as similarities. The most ITER relevant results are: low pressure operation down to 0.2 Pa is possible without problems; the magnetic filter field created by a current in the plasma grid is sufficient to reduce the electron temperature below the target value of 1 eV and to reduce together with the bias applied between the differently shaped bias plate and the plasma grid the amount of co-extracted electrons. An asymmetry of the co-extracted electron currents in the two grid segments is measured, varying strongly with filter field and bias. Contrary to the prototype source, a dedicated plasma drift in vertical direction is not observed. As in the prototype source, the performance in deuterium is limited by the amount of co-extracted electrons in short as well as in long pulse operation. Caesium conditioning is much harder in deuterium than in hydrogen for which fast and reproducible conditioning is achieved. First estimates reveal a caesium consumption comparable to the one in the prototype source despite the large size.

INTRODUCTION

Large and powerful ion sources for negative hydrogen ions (H⁻, D⁻) are mandatory for the neutral beam injection (NBI) system of the international fusion experiment ITER. The two beam lines for heating and current drive (HNB) are designed to inject 33 MW total power at a beam energy of 870 keV H^0 or 1 MeV D^0 into the ITER plasma for up to 3600 s [1]. In addition, a beam line dedicated for diagnostics of the ITER plasma (DNB) will be available injecting hydrogen particles at 100 keV with a power of 3.6 MW modulated at 5 Hz with a duty cycle of about 1/6 [2]. In order to fulfill these requirements the ion source has to deliver at a source pressure of 0.3 Pa negative ion currents of 66 A for hydrogen and 57 A for deuterium. The negative ions are created via the surface conversion process, i.e. the conversion of mainly atoms and positive ions at surfaces with a low work function, for which caesium is evaporated into the source. The ions are extracted from 1280 apertures with 14 mm diameter resulting in extracted current densities of 330 A/m² (H⁻) and 285 A/m² (D⁻) for the total extraction area of 0.2 m². The apertures are arranged in 16 beamlet groups in a 4×4 pattern, each group with 5×16 apertures. The 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 [3] using a frequency of 1 MHz and a total power of up to 800 kW from four RF generators. Further requirements concern the beam uniformity, where deviations in the extracted current densities of less than 10% are allowed and the amount of co-extracted electrons, which should be less or equal to the negative ions.

As these parameters have not yet been achieved simultaneously, also due to a lack of adequate test facilities, the European ITER domestic agency F4E has defined an R&D roadmap for the construction of the neutral beam heating systems [4]. Among the challenges is the size scaling of the ion source from the RF-driven prototype source [3] with a size of 1/ 8 of the ITER source towards the full size source. An important step herein is the new test facility ELISE (Extraction from a Large Ion Source Experiment) equipped with a ½ size ITER RF source designed as close as

possible to the ITER NBI source [5]. ELISE went into operation in November 2012 with the first plasma in February 2013 [6]. ELISE is intended to demonstrate large-scale extraction at ITER NBI parameters in terms of negative ion current densities, co-extracted electrons, and beam uniformity for long pulses. Furthermore ELISE allows gaining early experience of the performance and operation of such large RF driven ion sources and gives input for design, commissioning, and operating phases of the full-size sources at the upcoming test facilities and the ITER neutral beam injection systems. The European neutral beam test facility is being built in Padova, Italy and consists of the 100 kV ion source test facility SPIDER and the 1 MeV full power test facility MITICA, operational in 2015 and 2017 respectively [7]. As India is the Domestic Agency responsible for the DNB, India has also developed a dedicated roadmap: starting with the ⅛ ITER prototype source at the test facility ROBIN [8], which went into operation in 2011, an intermediate step using a ¼ ITER Source – the Twin source – towards a full size test facility [9] envisaged to be operational in 2015.

The RF-driven prototype source for ITER has been developed at the Max-Planck-Institut für Plasmaphysik (IPP), Garching and is operational since two decades at the short pulse test facility BATMAN [3]. BATMAN has achieved the ITER parameters with respect to extracted current densities at 0.3 Pa for 10 s RF pulses with 4 s beams [3]. The long pulse test facility MANITU was also equipped with the prototype source and demonstrated the first 3600 s beam extraction in hydrogen and in deuterium [10]. The size scaling experiment RADI was equipped with a source of approximately half the width and half the height of the ITER source but without extraction system. RADI was demonstrated the plasma homogeneity of such large RF sources [11]. As components are needed for the construction of ELISE, the IPP test facilities MANITU and RADI stopped operation in 2011 [12]. Several experimental campaigns have been carried at ELISE since the first plasma in February 2013; results on the first campaign are reported in [13] and a recent overview on the achievements is given in [14].

The present paper focuses on physical aspects, operational issues and the performance of these size scaling experiments, i.e. from the prototype source towards the ITER relevant size at ELISE addressing the following aspects: the magnetic filter field applied to reduce electron temperature and density, the biasing of the plasma grid applied to suppress the co-extracted electrons, consequences on plasma drifts, the RF efficiency, and the caesium conditioning, its distribution as well as the caesium consumption. Operation in deuterium will be compared to operation in hydrogen.

THE NEGATIVE ION SOURCE: SOURCE CONCEPT AND SIZE SCALING

In the IPP RF prototype source the plasma is generated in a cylindrical driver by inductive coupling using an RF generator with a frequency of 1 MHz and maximum power of 100 kW as indicated in Fig. 1.
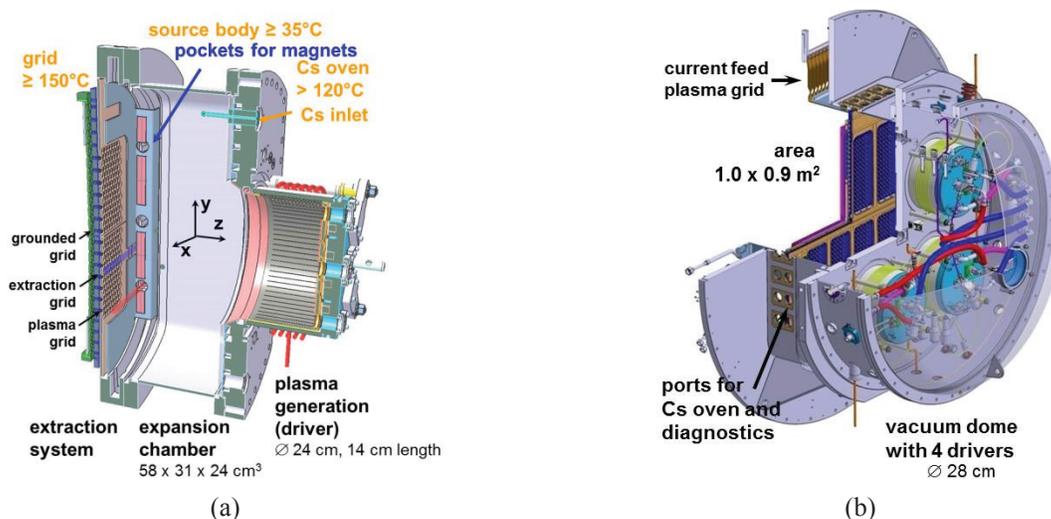

FIGURE 1. Cross sections of the ion sources: (a) prototype source (BATMAN, MANITU), (b) ½ size ITER source at ELISE.

The driver is equipped with a water-cooled Faraday screen to protect the alumina cylinder from the plasma. The plasma expands into the rectangular expansion chamber. A transverse magnetic filter field, produced by permanent magnets, with field strengths of about 7 mT in the source center ($x=y=0$) separates the expansion region from the extraction region. In the standard configuration the permanent magnets are embedded in pockets inside the source at an axial position of $z=3$ cm, whereas for dedicated studies of the filter field a flexible filter frame is used instead, positioned at $z=9$ cm or larger [15,16,17].The negative ions are created by conversion of mainly atoms and positive ions at the surfaces, at the first grid of the extraction system, the plasma grid [18]. A caesium oven is mounted at the back plate of the chamber; typical evaporation rates are 5–10 mg/h. 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 150°C, respectively. The source is at high negative potential (several tens of kV) and negative ions are extracted and accelerated towards the grounded grid. In order to prevent the co-extracted electrons to be fully accelerated, the second grid, the extraction grid, is equipped with permanent magnets creating a deflecting field perpendicular to the filter field. Extraction voltages of up to 11 kV are used. The aperture size, their arrangement and geometry follows the LAG system [17]; their diameter is 8 mm with conical shape. Besides the reduction of the electrons by the magnetic filter field, the amount of co-extracted electrons is actively reduced by a positive bias voltage applied between the plasma grid and the bias plate (see Fig. 1 and Fig. 2); the latter is connected to the source chamber, extending the source body potential closer to the grid (see [15] and references therein). The gas feed is located at the back plate of the driver; the pressure quoted here is the filling pressure, i.e. the pressure without plasma.

The prototype sources at the short pulse test facility BATMAN and the long pulse test facility MANITU are equipped with a grid system consisting of 126 apertures and 406 apertures, respectively, resulting in extraction areas of 63 cm^2 and 204 cm^2. The plasma grid is either made of molybdenum or coated with molybdenum for better caesium conditioning, whereas the Faraday shield and the back plate of the expansion chamber (in MANITU only) are coated to reduce sputtering by plasma particles in the driver and by backstreaming ions, respectively. At both test facilities the bias plate has limited active cooling or heating, which means their temperature rises continuously up to 150°C in long pulse operation [11].
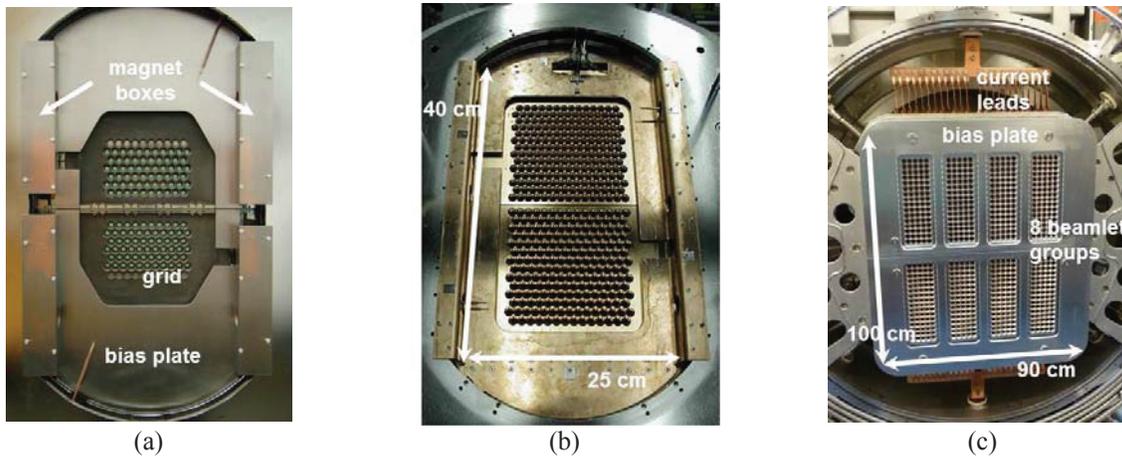

FIGURE 2. View onto the plasma grid: (a) prototype source at BATMAN, (b) prototype source at MANITU, (c) ½ size ITER source at ELISE

The modular concept is applied for the size scaling to the ITER source: instead of one driver illuminating a certain grid area, several drivers are used. The ion source at the RADI test facility with inner dimensions of 0.76×0.8 m^2, was equipped with four drivers of the same size as in the prototype source whereas for ELISE with a slightly larger size (0.87×1 m^2) the driver size was increased to 28.4 cm inner diameter [12]; their arrangement is indicated in Fig. 1. At the large sources each of the two RF generators has a maximum power of 180 kW and supplies two horizontal drivers connected in series. In contrast to the prototype source, the magnetic filter field in such large sources is created by a current of several kA flowing through the plasma grid (see Fig. 2(c) for the current leads).

The aim of the design of the ELISE source and extraction system was to be as close as possible to the ITER design. However, some modifications are carried out to allow better diagnostic access and to improve considerably the experimental flexibility [5,19]. The source vessel is in air (unlike in ITER) allowing for easy source modifications. The vessel hosts a high number of ports for plasma diagnostics close to the extraction system. The four drivers are built-in a dome such that the RF coils can be operated in vacuum (Fig. 1) like in ITER NBI. The extraction system is designed for acceleration of negative hydrogen ions of up to 60 kV. Each grid consists of two segments in a vertical arrangement, i.e. a top and a bottom segment. The extraction grid (EG) segments are insulated against each other so that the current of each grid can be measured individually. This gives the unique opportunity to investigate possible asymmetries in electron extraction [16]. The arrangement of the apertures, the beamlet groups and the bias plate is shown in Fig. 2(c). Plasma operation of up to 1 h is foreseen, but extraction is only possible in a pulsed mode (10 s every 150 s) due to the high voltage (HV) system available at IPP. A comparison of pulsed and continuous beam extraction from the long pulse plasma of the IPP prototype source at a long pulse test facility demonstrated that these scenarios are equivalent to each other [20].

Beside the size scaling, several changes are made for the large sources compared to the prototype source and for which the consequences on the source performance have to be explored in ELISE. One concerns the strength and 3D structure of the magnetic filter field created by the plasma grid (PG) current and the other the bias plate which extends also between the individual beamlet groups and changes thus the potential structure. As in the prototype source, the plasma grid and the bias plate are coated by molybdenum and the inner surfaces of the ELISE source are coated by nickel. For the evaporation of caesium two ovens are mounted at ELISE using dedicated ports in the expansion chamber. Further details on the ELISE test facility are given in Ref. [5,6,14] and references therein.

FROM THE PROTOTYPE SOURCE TO THE ITER RELEVANT SOURCE AT ELISE

Gas Flow and Low Pressure Operation

In the large source at ELISE the gas feed is evenly distributed to the back plate of the individual drivers. The measured gas conductance of the ELISE grid assembly is about 14 m^3/s. Due to some lateral conductance aside of the grid holder boxes the measured value is about 20% larger than calculated just using the aperture geometry. For a filling pressure of 0.3 Pa a gas flow of about 1 Pa m^3/s per driver is needed in hydrogen, which is a factor of three to four larger than in the prototype sources at BATMAN or MANITU with lower conductance of the grids.

In both sources, low source pressure operation with 0.3 Pa filling pressure and below is possible without any problems: 0.1 Pa was demonstrated at BATMAN [3], 0.2 Pa at ELISE [6] and in the plasma source RADI having a similar conductance as ELISE. However, filter field studies at the prototype source at BATMAN revealed that depending on the position of the magnetic filter field plasma sustainment became more difficult the closer the magnetic frame is located to the driver [15]. For the filter frame located at z=14 cm, stable plasma operation was possible only for pressures at or above 0.4 Pa. This suggests that penetration of the magnetic field into the driver plays a role, moreover also the 3D topology since at ELISE similar field strengths are present in the driver (Fig. 3).

In standard configuration, with the inner magnets (z=3 cm), operation at high RF power and low pressure showed a strong neutral depletion [21] such that also plasma sustainment became an issue. As in the large sources gas flow is much higher less neutral depletion can be expected.

Magnetic Filter Field

The filter field at the large ITER-relevant sources created by a current through the plasma grid forms a 3D magnetic field pattern which is completely different from that of prototype source where it is generated by permanent magnets. Figure 3 compares the axial profiles (along the central axis of a driver) of the field at ELISE at different PG currents with the one at the prototype source (for the 3D topology see Figs. 3 and 10 in [15]). In the present configuration with the return conductors between the drivers [6], the conversion factor between PG current and field strength at the centre of the plasma grid is 1mT/1.06kA. The adjustment of the PG current allows for changing the magnetic field strength without changing the 3D topology. As already demonstrated at RADI, the plasma emission in the ELISE drivers increases with increasing field strength due the hampered plasma flow out of the driver whereas it decreases close to the plasma grid due to the reduced transport across the magnetic filter [15].
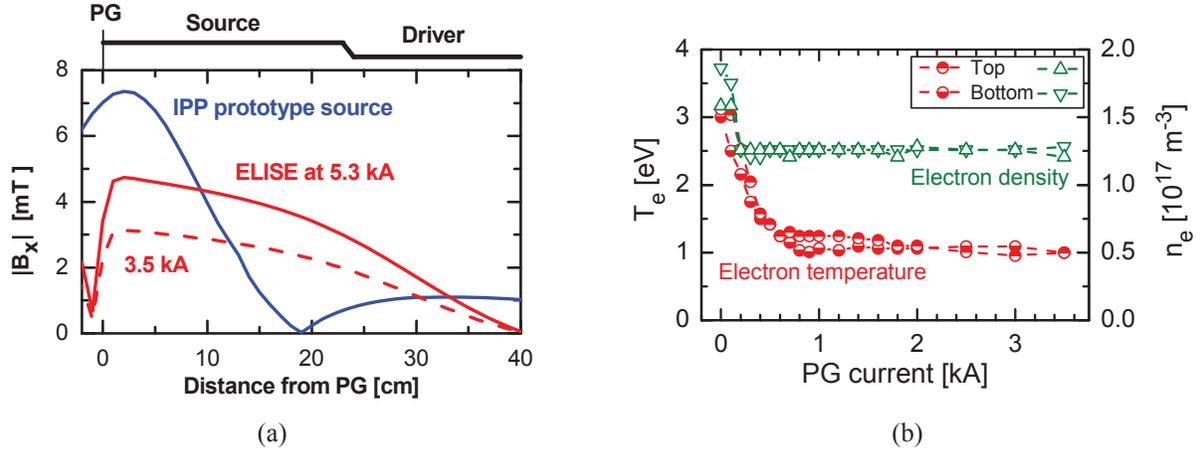
FIGURE 3. (a) Axial profile of the filter fields in the different sources. (b) Electron temperature and density as a function of the PG current in the ELISE source (20kW/driver).

The plasma parameters derived from emission spectroscopy with lines of sight (LOS) close to the plasma grid [23] are shown in Fig. 3 for one horizontal line of sight in the upper half and one in the lower half of the source. At about 0.6 kA PG current, the electron temperature is already reduced to the desired value of 1 eV and the electron density is reduced as well. The corresponding field strength of about 0.6 mT corresponds well to the field strength for which the electrons are magnetised in the source. These results are in accordance to what has been measured in the RADI source, whereas for the prototype source only values for the field strength peak of about 7 mT at different positions and without filter field are available resulting in temperatures of equal or less than 1 eV and 4–5 eV, respectively. Thus, the cooling effect is measured for lower field strengths suggesting already that less filter field is needed for reducing the destruction of negative ions by electrons and for reducing the co-extracted electrons sufficiently. Moreover, the agreement of the results from the two lines of sight implies that the plasma in front of the grid is vertically symmetric; using six vertical LOS the intensity of Balmer lines varies less than 40% [15]. In particular, a drift direction (cross B drifts) as seen in the prototype sources is not obvious (see below). The better uniformity of the large source in comparison to the prototype source is attributed to the four driver operation with mutual plasma overlap in the expansion chamber where the wall is close to the plasma in each direction.

Magnetic Filter Field and PG Bias

The combination of both, the magnetic filter field and the PG bias, are used to suppress the amount of co-electrons to a tolerable amount without decreasing the current of negative ions [3]. The bias applied between the plasma grid and the bias plate changes the plasma sheath and hence the electron fluxes to the apertures. In order to control the fluxes the bias current is the better control parameter as the use of the bias voltage requires an adjustment according to changes in the plasma potential caused, for example, by pressure changes or caesium seeding [17]. Figure 4 shows typical time traces of bias current and voltage with the extraction phase indicated by the drain current, i.e. the sum of the extracted current of electrons and negative ions. The bias current flows during the whole plasma phase. Due to the larger area, the bias current is larger as well at ELISE; due to similar plasma parameters, the bias voltages are comparable. The time trace of the bias voltage changes in both experiments at the beginning according to changes in the pressure and is sensitive on the extraction. In the prototype source the bias voltage increases with extraction which can be understood as a reaction to compensate the flux losses by extracting electrons. Surprisingly, the bias voltage decreases at ELISE during the beam phase which indicates differences in the potential structure close to the grid. This might be due to the different geometry of the bias plate (Fig. 2), i.e. a bias plate surrounding the beamlet groups. As plasma potential measurements might give more insight; they are planned for the next campaign.
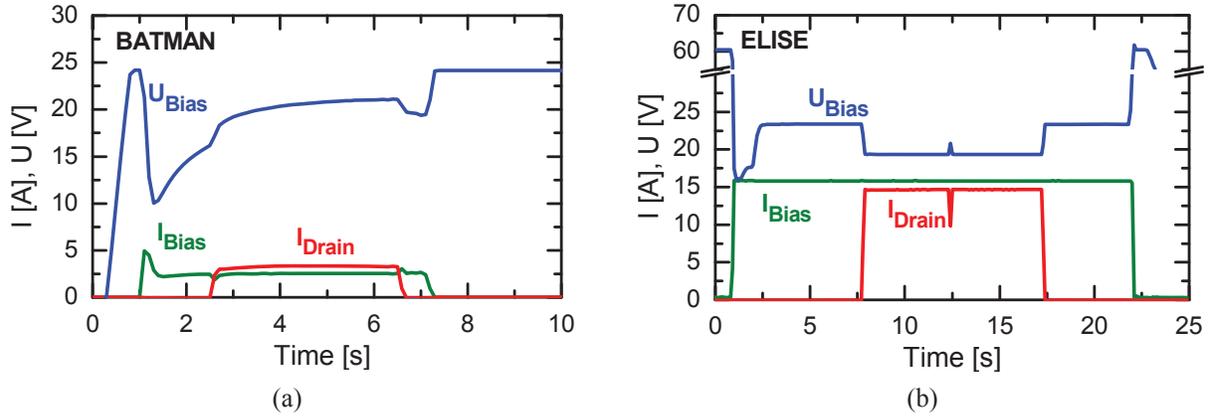
FIGURE 4. Typical time traces of bias current, bias voltage and drain current (electrons and ions) at (a) BATMAN (#40000: D_2, 70 kW, 0.4 Pa) and at (b) ELISE (#1935: H_2, 20kW/driver, 0.7 Pa).

The reduction of the co-extracted electrons by the increasing bias current and the influence on the extracted ions is shown in Fig. 5 for the prototype source at MANITU and for the ELISE source, for which also a variation of the PG current, i.e. the magnetic filter field strength, is given. As mentioned before, ELISE has the unique opportunity to measure the current of the co-extracted electrons in the two segments (top and bottom) separately. The figures show clearly an asymmetry in the electron suppression which depends on the combination of PG bias and field strength. This was observed for the first time in the non-caesiated campaign at ELISE in low power discharges [13]. As this asymmetry might be critical for ITER NBI using an integrated limit for the power load on the extraction grid based on measurements of the total electron current, it will be investigated in more detail in future.
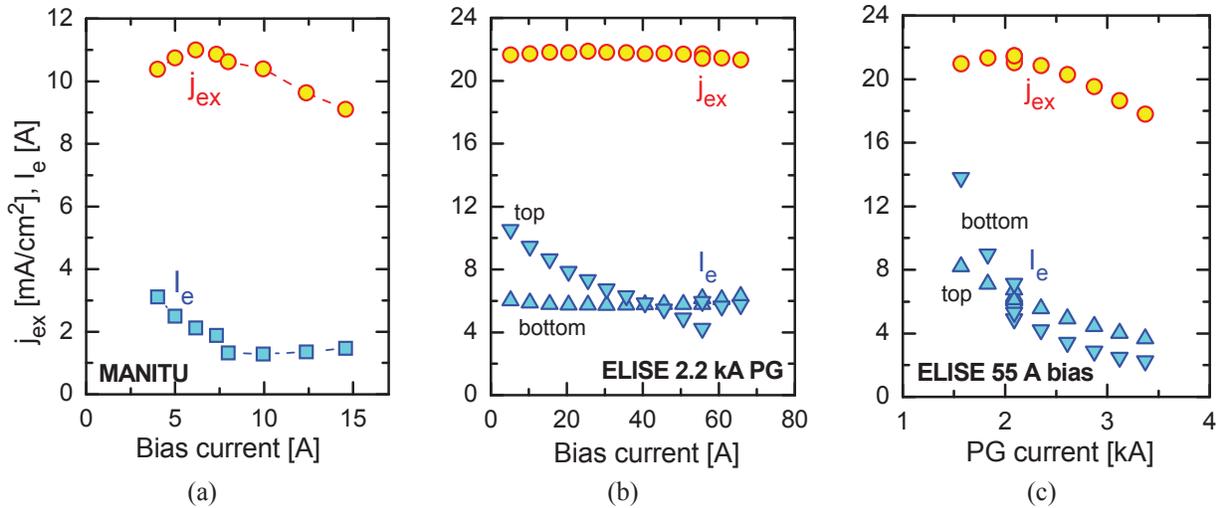

FIGURE 5. Dependence of the negative ion current density and the co-extracted electron current (caesiated hydrogen discharges with 50 kW/driver) on (a) the bias current at MANITU (0.4 Pa), (b) the bias current and (c) the plasma grid current at ELISE (0.3 Pa), where the electrons are measured separately in the upper and lower half of the extraction grid.

Detailed investigations in the prototype source showed the presence of plasma drifts in vertical direction due to the presence of the transverse filter field. Furthermore, the direction and strength of the drift measured by Langmuir probes and emission spectroscopy close the plasma grid depends on the position and strength of the magnets in interplay with bias voltage and with extraction voltage (see [15] and references therein). The beam uniformity,

however, studied at the prototype source by beam emission spectroscopy, revealed almost no correlations of the beam homogeneity with the plasma symmetry in front of the plasma grid [27]. As the negative ions are created mainly by the conversion of atoms at the grid [18] and as it is reasonable to assume a homogenous atomic flux towards the plasma the plasma asymmetry has, in first order, no consequence for the beam uniformity. A second order effect might come from the positive ions which are responsible for the space charge compensation.

In ELISE and at RADI pronounced plasma drifts are not observed; see Fig. 3 and Ref. [11] (Fig.9), respectively. First measurements on the beam uniformity by different beam diagnostic tools confirm also the absence of strong drifts (apart from the beam deflection in the accelerator) [14, 28]. Thus, the asymmetry of electron extraction is even more surprising and underlines the need of investigations – experimentally or by modelling.

Performance and RF Efficiency

The ITER parameters with respect to negative ion current density and the amount of co-extracted electrons at 0.3 Pa have been demonstrated in the prototype source at the short pulse test facility BATMAN (4 s beams)[3], whereas long pulse operation (1 hour beams) has been demonstrated at MANITU at reduced parameters [29], in both hydrogen and deuterium. It was shown that the source performance depends strongly on the Cs conditioning (see also below) and is often limited by the amount of co-extracted electrons, i.e. the power on the extraction grid. In particular, in long pulse operation the stability of co-extracted electrons became an issue. Furthermore, for electron suppression in deuterium the magnetic field has to be strengthened compared to hydrogen and the source has to be operated at reduced parameters (low RF power, reduced extraction voltage) to keep the ratio of electrons to ions below one which in turn also limits the achievable ion current.

The source performance achieved in the experimental campaigns carried out so far at the ELISE facility is reported in detail in [14]. Basically similar trends as in the prototype source are observed, however neither sufficient experience at high RF power nor in long pulse operation could be gained yet due to the limited experimental time.
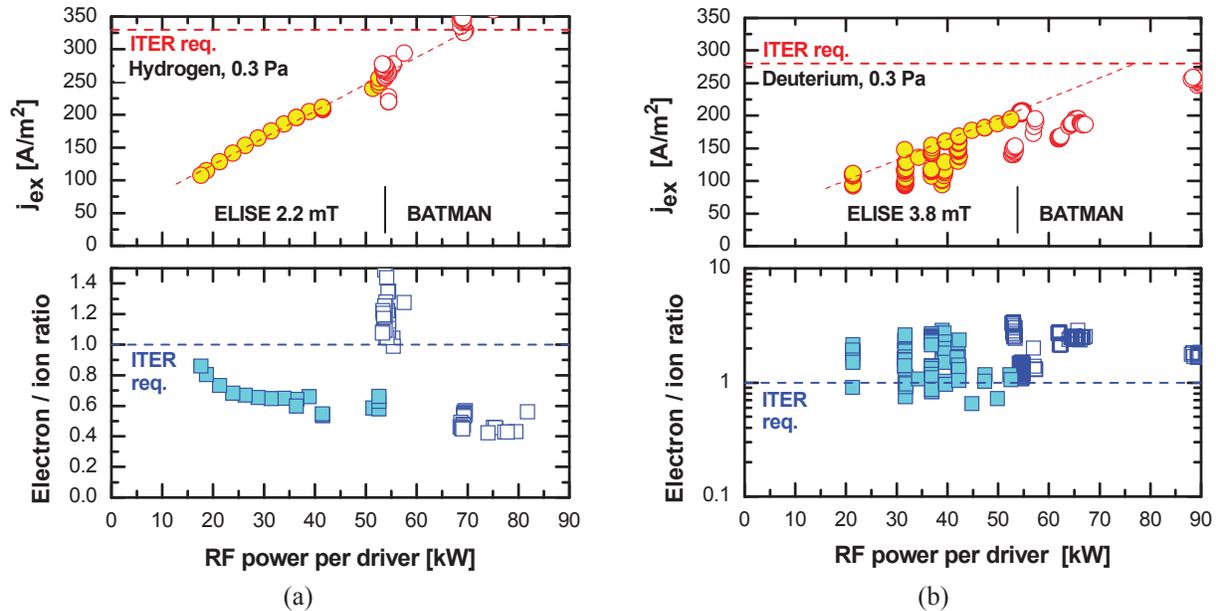

FIGURE 6. Comparison of the source performance at BATMAN (open symbols) and ELISE (closed symbols) in (a) hydrogen and (b) deuterium discharges at a pressure of 0.3 Pa and extraction voltages < 9.5 kV.

Figure 6 compares the source performance at BATMAN with the one at ELISE as a function of the RF power per driver. ELISE was operated with 20 s plasma including 10 s beams and the maximum RF power applied up to now is 55 kW/driver, i.e. 220 kW in total. For better comparison only data points with extraction voltages between

8.5 kV and 9.5 kW are plotted, which means the high performance achieved at BATMAN is not included as they have been obtained at higher voltages (up to 11 kV). As shown, operation in hydrogen with a low co-extracted electron current is no issue, neither in BATMAN nor in ELISE, whereas for deuterium the dynamics of the electron to ion ratio is much more pronounced and ratios below one are difficult to achieve. The current densities of negative ions show the same or even better RF efficiency in the large source as in the prototype source. In both hydrogen and deuterium, less filter field as expected is needed: only 2.2 mT and 3.3. mT are used at ELISE, whereas the peak value at BATMAN is 7 mT. Also the integral value along the axial direction from the PG to the driver exit is much lower: about 0.4 mTm (hydrogen) and 0.6 mTm (deuterium) in ELISE compared to 1–1.5 mTm in BATMAN [16].

From these quite encouraging results extrapolations of the measured ELISE data to the ITER value (horizontal line) are performed: a required RF power of about 70 kW to 80 kW per driver can be expected for the large source which is less than envisaged for the ITER NBI source.

Conditioning and Distribution of Caesium

The process of evaporating Cs into a source for achieving high negative ion current densities accompanied by a reduction of the co-extracted electrons is called Cs conditioning and depends on several parameters: the status of the source (cleaned source, i.e. without Cs layers at the surface, or a vented caesiated source and pumped down again, or daily/weekly conditioning), the amount of Cs evaporated, the surface temperatures, the vacuum conditions and the plasma-on time, to name most but not all of them as this is a very complex – and not fully understood – behavior. This applies also to the Cs distribution and re-distribution by the plasma which allows also operating at high performance without additional Cs evaporation under certain conditions.

Experiments at the prototype sources demonstrated a faster source conditioning when the base pressure of the source was reduced by a factor of two to $5 \cdot 10^{-7}$ mbar [23]; the condition process is shown in Fig. 7. Furthermore, the comparison of short and long pulse operation revealed that the total plasma-on time and the amount of Cs is decisive for the time needed for conditioning, as the plasma distributes very effectively Cs in the source and cleans the Cs layers from vacuum impurities [24].
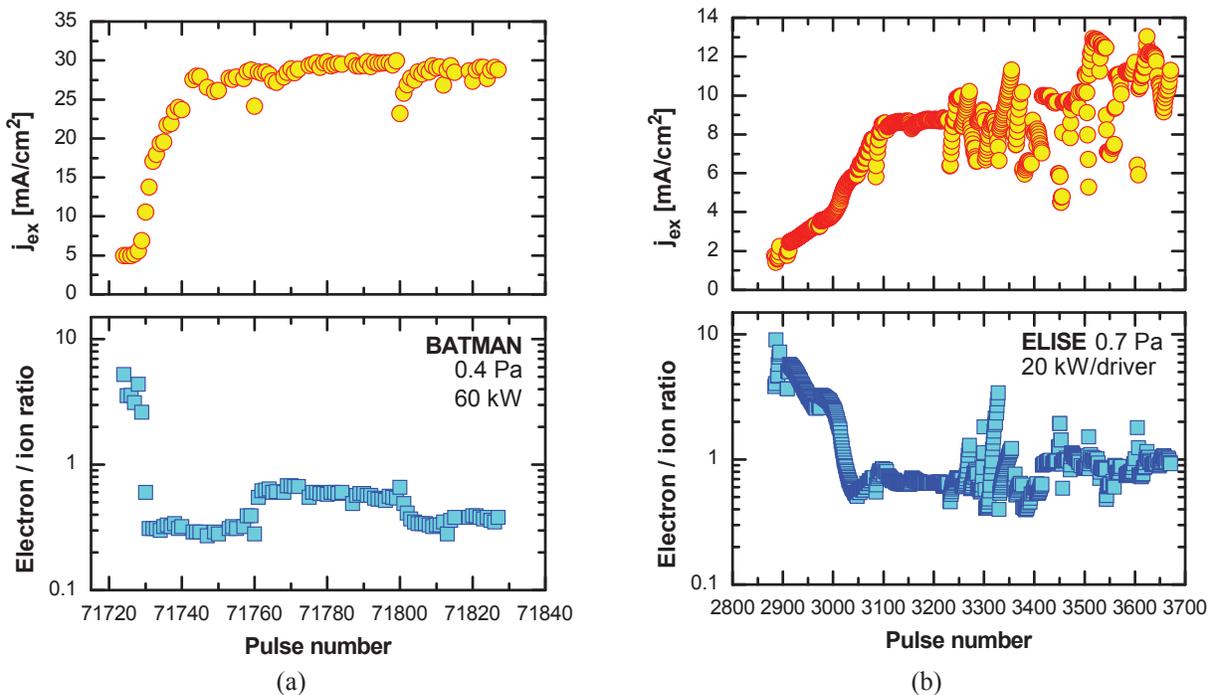

FIGURE 7. Source performance during caesium conditioning in hydrogen discharges at (a) BATMAN for re-conditioning after source opening and (b) at ELISE for the very first caesium conditioning in low power operation.

Figure 7(a) shows the first Cs conditioning at BATMAN within a few pulses (6 s plasma including 4 s beam, 180 s vacuum phase) for a source being vented before. Figure 7(b) shows the very first Cs conditioning of ELISE in the low RF power campaign at 0.7 Pa using two Cs ovens. Despite the differences of the source parameters as pressure and power per driver, ELISE conditioning (20 s plasma including 10 s beam) went rather quickly with a ratio of electrons to ions of less than one (see [14] for more details). Furthermore, the Cs distribution from the two ovens at the side walls of the ELISE source works as well as the distribution with an oven from the back plate as at BATMAN. This confirms once more, that the position of the oven is of no concern as the plasma effectively redistributes the Cs [25]. Limiting cases for the position and the direction of the nozzles are influences on the HV holding capability of the grids and on the driver operation. Due to the low base pressure of ELISE and the possibility to close the source valve during cryo-pump regeneration, daily condition was reduced in this low RF power phase to one or two discharges in hydrogen.

The Cs campaigns performed so far at ELISE revealed a reliable recipe for Cs conditioning in hydrogen in short pulses and for long pulse operation. In contrast, the situation is very much different for deuterium where the amount of the co-extracted electron current and its temporal stability is an issue. According to the experience at the prototype sources, for deuterium more caesium is required; this however was not possible so far at ELISE due to HV deterioration of the grids when too much Cs is introduced during the vacuum phase. Thus, the achievement of high performance in deuterium, in particular the reduction of the co-extracted electrons, for long pulses is the challenge for the next campaigns.

Caesium Consumption

The prototypes sources at BATMAN and at MANITU were equipped with an oven containing three Cs ampullas with 1 g Cs each as reservoir, which can be cracked individually [3]. The integral amount of cracked ampullas in one campaign and the oven-on time and its temperature allowed to derive a relation between oven temperature and evaporation rate such that for high performance operation typical evaporation rates of 5 –10 mg/h could be estimated [30]. With the change to the dispenser oven at BATMAN which is equipped with a surface ionization detector (SID) [25], the evaporation is measured directly; the calibration for the evaporation rate is performed by using the integral amount stored in the dispenser (1.2 g at the IPP sources). The previous values could be confirmed.

ELISE uses two of those dispenser ovens with SID with the same uncertainty in the calibration, meaning that the evaporation rates derived for ELISE have to be regarded as upper value. Evaporation rates of about 4 mg/h per oven for the hydrogen campaign are obtained for a plasma-on time of 22 hours with about 5 hours beam time. Compared to the prototype sources, evaporation rates are very similar despite the larger source volume, larger grid surface and larger volume-to-surface ratio. Although the size scaling parameter for the Cs consumption is not identified yet, the recent ELISE results indicate a lower Cs consumption.

CONCLUSIONS

The size scaling experiments, from the prototype source with an area of ⅛ of the ITER source to the ½ size source at ELISE, show very encouraging results for the ITER NBI systems. The magnetic filter field and the PG bias reveal the expected functioning: the decrease in electron temperature and density for optimization of the negative ion production and the suppression of the co-extracted electrons. Furthermore, less filter field is needed for sufficient electron suppression, in both hydrogen and deuterium. The plasma symmetry is much better than in the prototype source, i.e. the cross B drifts are much less pronounced which might be a consequence of the different 3D topology of the magnetic filter field and the bias and the same space to walls in all directions. Although the beam homogeneity is almost independent on the plasma uniformity, homogeneous plasma parameter in front of the grid are in any case beneficial, as fluxes of atoms and positive ions influence the formation of negative ions and the space charge compensation, respectively. The uniformity of co-extracted electrons could be measured for the first time at the ELISE test facility, revealing an asymmetry which depends strongly on the combination of filter field strength and bias. Concerning the caesium, the distribution by two caesium ovens at different locations than in the prototype source worked very well confirming the dominant role of re-distribution by the plasma. Cs conditioning went also rather fast; moreover the daily conditioning could be reduced to one or two discharges. The Cs consumption is less

than expected from scaling laws using either the area or the volume-to-surface ratio, which is beneficial for the Cs consumption at ITER. The source performance in terms of RF efficiency, i.e. achievable current densities of negative ions per RF power/driver, and the electron to ion ratio are well in line with values achieved at the prototype source. In long pulse operation, however, the stability of co-extracted electrons, i.e. the achievement of electron to ion ratios below one is an issue already known from the prototype source, in particular for deuterium.

In general, it can be stated that a large source size helps in many aspects, that Cs conditioning in deuterium is quite demanding, and that the co-extracted electrons still limit the achievable source performance. For the upcoming ELISE campaign high RF power operation at long pulses is the challenge, in particular for deuterium. For vertical scaling by a factor of two to the ITER NBI source, no crucial parameters are obtained; in contrary the experience showed that a larger volume-to-surface ratio is beneficial for the source performance.

ACKNOWLEDGMENTS

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