Towards Powerful Negative Ion Beams at the Test Facility ELISE for the ITER and DEMO NBI Systems

U Fantz[1,2], C Hopf[1], D Wünderlich[1], R Friedl[2], M Fröschle[1], B Heinemann[1], W Kraus[1], U Kurutz[1,2], R Riedl[1], R Nocentini[1], L Schiesko[1]
[1]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
[2]AG Experimentelle Plasmaphysik, Universität Augsburg, Universitätsstr. 1, 86159 Augsburg, Germany

E-mail: ursel.fantz@ipp.mpg.de

Abstract. The test facility ELISE represents an important step in the European R&D roadmap towards the neutral beam injection (NBI) systems at ITER. ELISE provides early experience with operation of large radio frequency (RF) driven negative hydrogen ion sources. Starting with first plasma pulses in March 2013, ELISE has meanwhile demonstrated stable 1 h plasma discharges with repetitive 10 s beam extraction pulses every 3 min in hydrogen and deuterium at the ITER required pressure of 0.3 Pa. Stable ion currents of 9.3 A and 5.8 A have been extracted using only one quarter of the available RF power and reducing the extraction voltage in order to control the co-extracted electrons. The best hydrogen pulse for the required 1000 s for hydrogen gave an extracted current of 21.4 A and resulted in an accelerated current of 17.9 A, using only 53 kW per driver. Linear scaling towards full RF power (90 kW/driver) predicts that the target value of the negative ion current (H^-: 33 A extracted, 23 A accelerated; D^-: 28 A extracted and 20 A accelerated) can be achieved or even exceeded. Issues in long pulse operation are the caesium dynamics and the stability of the co-extracted electron current, for which the caesium management and the magnetic field configuration are promising tools for optimisation. Operation at high RF power for long pulses has highest priority for the next experimental campaign. In parallel or in a later stage, ELISE could serve as a test bed for studies on a DEMO NBI system. Examples are concepts concerning RF efficiency, operation with largely reduced caesium consumption or with caesium alternatives, and neutralization of the accelerated ion beam by a laser neutralizer in order to improve efficiency and reliability of NBI systems. Lab scale experiments on these topics are carried out presently in parallel with ELISE operation.

1. Introduction

The neutral beam injection system for heating and current drive for ITER and the one foreseen as candidate for DEMO rely on the generation, acceleration and neutralisation of negative hydrogen ions [1,2]. The requirements for the beam source for ITER are clearly defined, whereas the requirements for DEMO are under discussion as they will strongly depend on the DEMO scenario [3]. Compared with ITER the wall-plug efficiency and the RAMI requirements (reliability, availability, maintainability, inspectability) are of uttermost importance. One of the approaches towards a DEMO NBI system is based on an ITER-like system for which the specifications of the source are comparable with the ones for the ITER beam source. More advanced concepts pose the challenge to operate the source at even lower pressure to reduce the stripping losses in the beam line. The geometry of the source is driven by the neutraliser concept and still an open point in both cases.

The requirements at ITER, and consequently also those at DEMO, for the operational parameters of ion source and accelerator are very challenging and exceed by far those at the existing devices JT-60U [4], JT-60SA [5] and LHD [6]. For ITER, currents of 57 A D^- have to be extracted from one source to achieve an accelerated current of 40 A at 1 MeV in deuterium [1], where the stripping losses in the accelerator are expected to be 30%. As the current densities of negative ions that have routinely been achieved up to now by negative ion sources are in the range of 200 A/m^2, the ITER ion source area has to be rather large with dimensions of 1.9×0.9 m^2 and an extraction area of 0.2 m^2. In contrast to the arc sources used at existing devices, the beam source is based on the RF-driven concept [7] using a frequency of 1 MHz and a total power of up to 800 kW from four RF generators. Besides the requirement 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, the ratio of co-extracted electrons to extracted ions is to be kept below one. The latter is driven by the demand to keep the heat load on the second grid of the extraction system, the extraction grid on which the electrons are dumped, at a tolerable level. The beam is extracted from 1280 apertures with 14 mm diameter and accelerated within a five-stage accelerator system. This large beam needs to have a homogeneity better than 90% with a divergence of better than 7 mrad in order to be transported adequately to the fusion device.

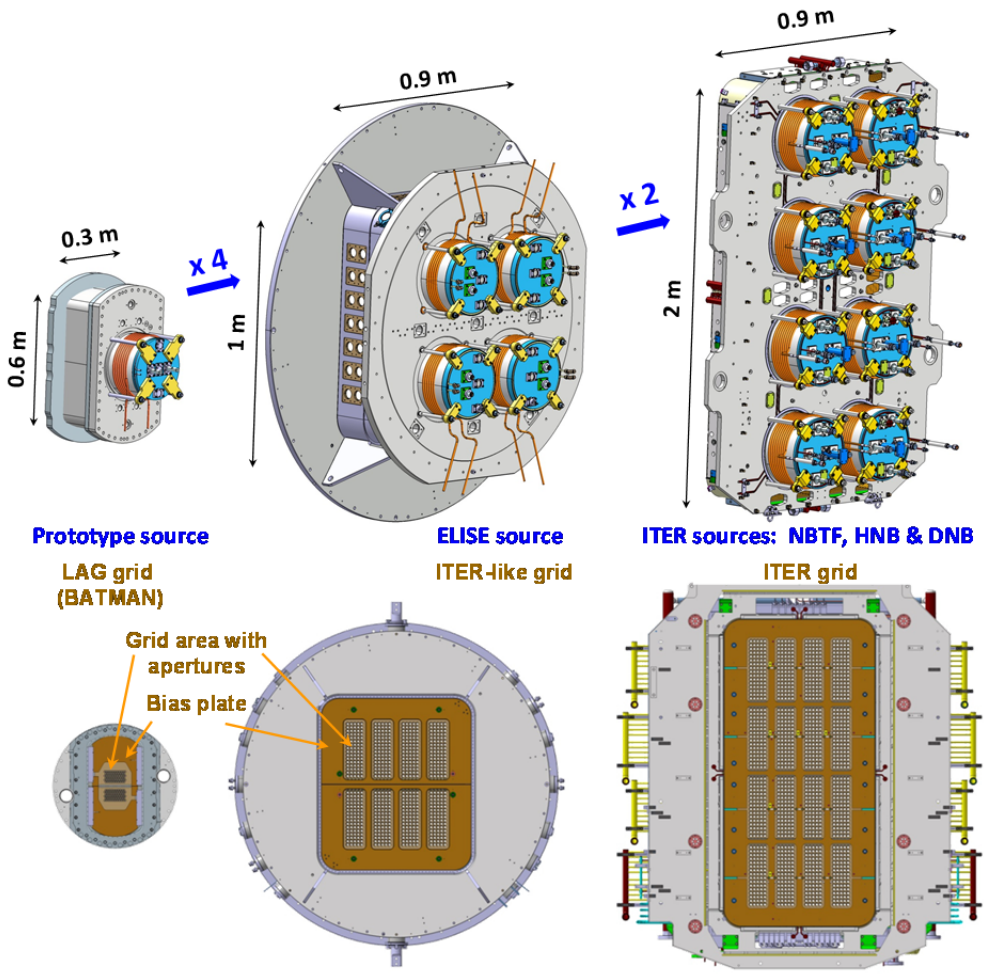

Figure 1. Modular concept of the RF-driven beam sources: from the prototype source via the ½ size ITER source at ELISE to the ITER sources together with the corresponding view onto the first grid of the extraction system, the plasma grid, with the surrounding bias plate.

As these parameters have not yet been achieved simultaneously, the European ITER domestic agency F4E has defined an R&D roadmap for the NBI systems on ITER [8]. The test facility ELISE (Extraction from a Large Ion Source Experiment) with its half-size ITER source represents an important step in the size scaling of RF sources between the prototype source (1/8 area, developed at IPP for many years and still in operation at the short pulse test facility BATMAN [7]) and the full-size

ITER source. The size scaling of the ion source uses the modular concept where several cylindrical drivers are mounted on an expansion chamber as illustrated in Figure 1. The prototype source consists of one driver with 245 mm inner diameter for plasma generation. The plasma expands towards the grid and illuminates the grid area on which negative ions are formed and then extracted. Figure 1 shows a view onto the grid surrounded by the bias plate for the three sources. The bias plate is connected electrically to the source body. The plasma grid is positively biased against it, which helps reducing the amount of co-extracted electrons. The grid system at BATMAN (called LAG grid), consists of two groups of apertures with 63 apertures each (8 mm diameter) resulting in an extraction area of 63 cm^2 [7]. ELISE uses the same grid pattern as the ITER beam sources, having one row with 4 beamlet groups arranged in each grid segment. One beamlet group consists of 16×5 apertures with 14 mm diameter. Four or eight drivers with 284 mm inner diameter (wall thickness 8 mm) are used to illuminate two or four segments by the plasma, respectively.

The ITER source will be commissioned and operated first at the European Neutral Beam Test Facility (NBTF) which is currently under construction in Padua. The NBTF hosts a test facility for the full-size ITER source (SPIDER) and one for the complete prototype of the Heating Neutral Beam (HNB) for ITER (MITICA) [9]. An almost identical source will be used for ITER's Diagnostic Beam (DNB) which is under the responsibility of ITER-India [10].

ELISE is set up at IPP Garching and provides early experience with the performance and operation of large RF-driven negative hydrogen ion sources with plasma illumination of a source area of 1.0×0.9 m^2 and an extraction area of 0.1 m^2 using 640 apertures corresponding to the full width but only half height of the ITER source. Consequently, the test facility aims at demonstrating large-scale extraction and acceleration of negative hydrogen ions (H^-, D^-) for long pulses of up to one hour with ion currents of half the value required for the ITER beam line.

2. The ELISE Test Facility

Figure 2 shows a vertical cross section through the ELISE test facility and gives the characteristic parameters and target values. The ELISE source and extraction system was designed to be as close as possible to the ITER design with some modifications aimed at improving the experimental flexibility and to provide better access for source and beam diagnostics (see [11-13] for details). Unlike at ITER, the source vessel is in air allowing easy source access and modifications, but the four drivers are enclosed in a vacuum containment, called dome, such that the RF drivers are operated in vacuum like at ITER.

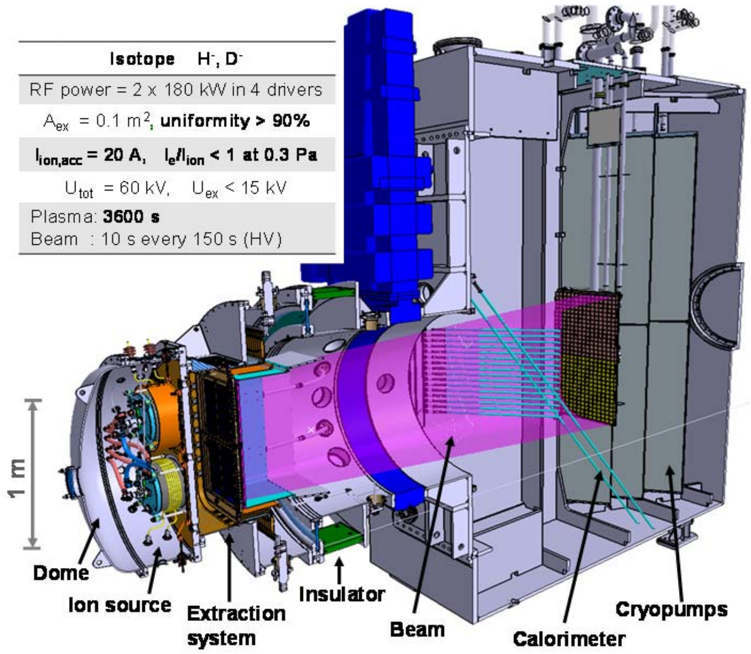

Figure 2. Vertical cross section of the ELISE test facility with the main parameters and target values (bold letters).

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. The extraction system is designed for an extraction voltage in the first stage of up to 15 kV and a total acceleration over both stages of up to 60 kV. Due to 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 are designed for continuous operation. In order to prevent the co-extracted electrons from being fully accelerated, the second grid, the extraction grid (EG), is equipped with permanent magnets that create the deflecting field. 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 asymmetries in electron extraction [14]. Although these segments are designed to withstand a heat load of 200 kW/segment an interlock is set to 125 kW for each segment for safety reasons. At the ITER sources the segments are not insulated against each other and the global value for the heat load on the extraction grid is 600 kW which corresponds to 150 kW/segment. The first grid is the plasma grid (PG) and can be biased with respect to source body and bias plate. Typically, the bias current is fixed (in the order of some ten amperes) and the bias voltage self-adjusts to values around the plasma potential [14].

The plasma is generated via inductive coupling using a six-turn copper coil wound around each of the four cylindrical drivers (Al_2O_3 insulator). These are mounted on the back plate of the main chamber (Figure 1) into which the plasma expands and illuminates the full area of the grid system. Two drivers are switched in series to one RF generator (self-excited oscillator) with a maximum power of 180 kW and a frequency of 1 MHz. Electromagnetic screens (EMS), i.e. copper rings, around each driver prevent mutual influence of the RF fields. The matching of the load to the generator is achieved by a combination of a series and a parallel capacitor, the latter being remotely tunable in order to react to possible changes of the load during a pulse.

In order to achieve the required current densities of negative hydrogen ions at the low pressure of 0.3 Pa the negative ions are created via the surface conversion process, i.e. the conversion of hydrogen neutral atoms (dominant share) and positive hydrogen ions at surfaces with a low work function. A low surface work function is achieved by caesium evaporation into the source for which two ovens are mounted at ELISE using dedicated ports in the side wall of the expansion chamber. Each oven is equipped with a surface ionization detector at the nozzle in order to monitor the relative evaporation rate [15]; typical evaporation rates are in the range of mg/h per oven.

The ion source is made from stainless steel with an electro deposited copper layer (1 mm) to distribute and conduct local heat loads towards the cooling channels. In order to avoid contamination of the ion source by copper due to sputtering and the subsequent formation of Cs compounds with copper, the plasma grid and the Faraday screens are coated with a 3 µm molybdenum layer whereas the inner surfaces of the ELISE source are coated with nickel. As in the ITER sources, the source body and plasma grid are temperature controlled to avoid sticking of caesium on cold spots and to improve the caesium redistribution. Typically wall temperatures between 35°C (ITER value) and 50°C are used. For the current experiments the plasma grid temperature is set to 120°C, but the grid is designed to be operated up to 200°C. It should also be noted that the back plate of the ion source is exposed to back-streaming positive ions formed in the accelerator by beam–gas interaction, leaving a footprint of the grid pattern at the back plate. This local sputtering has two important consequences: (i) it limits the life-time of the source, for which reason the molybdenum coating for the ITER beam sources is 3 mm thick and (ii) it leads to an influence of beam extraction on the caesium distribution.

A magnetic filter field is needed to reduce the electron temperature from about 10 eV in the driver down to about 1 eV close to the PG such that the destruction of negative ions is no longer dominated by collisions with electrons. Furthermore, the magnetic filter field is a parameter to reduce the co-extracted electron current. In contrast to the small prototype sources where permanent magnets can be used to create field strengths of about 7 mT close to the grid (horizontally and vertically centered) the filter field is created by a current of several kA flowing through the PG. At ELISE the grid design allows for currents up to 8 kA limited by the present power supplies to 5.3 kA. This corresponds to a maximum field strength of 5 mT at the PG.

ELISE is equipped with several diagnostic techniques, mainly optical emission spectroscopy and pin probes using ports close to the extraction system [16]. A set of beam diagnostic tools provides information about the large ion beam: a tungsten wire calorimeter for qualitative online monitoring of the beam during operation and the beam emission spectroscopy with 20 lines of sight with a dedicated diagnostic calorimeter for quantitative measurement of parameters such as divergence and uniformity [13]. Due to the available extraction and acceleration voltages, ELISE operates mostly in the underperveant range resulting typically in divergences of about 3°. In the perveance minimum divergences down to 1° are achieved using a total voltage of 35 kV [17].

3. Towards Parameters of ITER's Ion Sources

3.1. Short Pulse Operation

ELISE went into routine operation in February 2013. The first experimental campaigns were dedicated to the source performance in short pulses (20 s plasma with 10 s beam) allowing a comparison with the performance of the prototype source at the test facility BATMAN [7]. Until recently, the maximum RF power at ELISE was limited to 55 kW/driver. By solving several RF problems (see section 3.2.) higher RF power levels became feasible and the first results available for hydrogen are plotted in Figure 3. All data shown in Figure 3 are taken at extraction voltages between 8.5 kV and 9.5 kV. For BATMAN only high RF power results are shown in Figure 3.

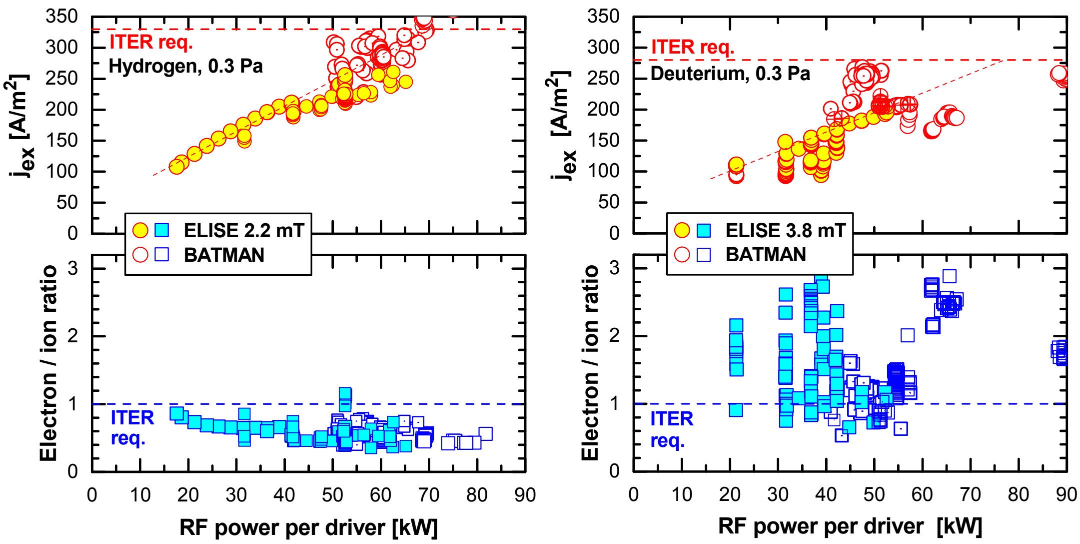

Figure 3. Extrapolation of the source performance of the ELISE source (closed symbols) and the prototype source (BATMAN, open symbols) to the required ITER beam source parameters.

For both hydrogen and deuterium, a required RF power of about 80 kW per driver can be extrapolated which is less than the installed power for the ITER source (100 kW/driver). In hydrogen, operation with a low co-extracted electron current is not an issue, neither on BATMAN nor on ELISE, whereas in deuterium ratios below one are difficult to achieve. Less filter field than expected is needed at ELISE: only 2.2 mT (hydrogen) and 3.8 mT (deuterium) are used, whereas the peak value at BATMAN is 7 mT with respect to the PG center. Concerning the filter field effect on plasma cooling, the electron temperature is already reduced to the desired value of 1 eV at about 0.6 kA PG current (about 0.6 mT) and the electron density is reduced as well to the values obtained in the prototype source (typically $1 - 2\times10^{17}$ m^{-3}). Furthermore, this field configuration does not cause such a strong plasma drift as it is known from the prototype sources, which is attributed to the different 3D topology of the field created by the PG current due to which the field gradient in axial direction is lowered.

3.2. Long Pulses and Limiting Factors

Extension of the pulse length is often limited by the absolute value and the dynamics of the co-extracted electron current which strongly depends on the dynamics of the caesium, i.e. evaporation, distribution and deterioration of caesium by interaction with impurities from the background gas in the vacuum phase as well as on the redistribution and cleaning effect of caesium layers during plasma phases ([18] and references therein).

The dynamics of the Cs signal and the current densities is illustrated in Figure 4 for a 1200 s pulse at 0.3 Pa in hydrogen. During this time seven beam blips with an interval of about 180 s are accommodated. The extracted ion current density of 220 A/m^2 averaged over the seven beam blips corresponding to 21.7 A ion current is very stable with deviations of less than 5%. In contrast, the sum of the co-extracted electron currents measured for each segment individually increases from beam blip to beam blip and reveals a time dependence within the beam blips. Moreover, an asymmetry is observed for the two EG segments, changing during the pulse as well. Dedicated experiments show that the asymmetry depends on the interplay of the magnetic filter field with bias and the state of Cs conditioning [14]. The caesium signal obtained with a photodiode in front of the grid is very stable during the plasma phase, but reacts clearly to beam extraction. The enhancement of the Cs signal is attributed to back-streaming positive ions which are created in the accelerator by collisions of negative ions and electrons with the hydrogen gas and accelerated back into the source. Their energy is sufficient to sputter caesium from the back plate of the source which is then redistributed by the plasma. Whether this changes the plasma parameters with consequences for the electron currents or whether it has direct influence on the electron fluxes towards the grid and thus on the plasma parameters at fixed bias voltage is not clear at this point. Dedicated investigations showed that only small variations are measured in the plasma parameters and the ion current is almost stable, whereas a strong change of the co-extracted electron current is observed [19]. This can be understood from the fact that the plasma in front of the grid is electronegative [17], i.e. the negative ions dominate over the electrons. At the meniscus, i. e. the potential surface from which the particles are extracted, the density of electrons is the square root of the mass ratio lower than the density of negative ions at an extracted electron-to-ion ratio of one (assuming the identical kinetic energy for both particle species). Consequently, the electrons are the minority species and hence much more sensitive to parameter variations than the negative ions.

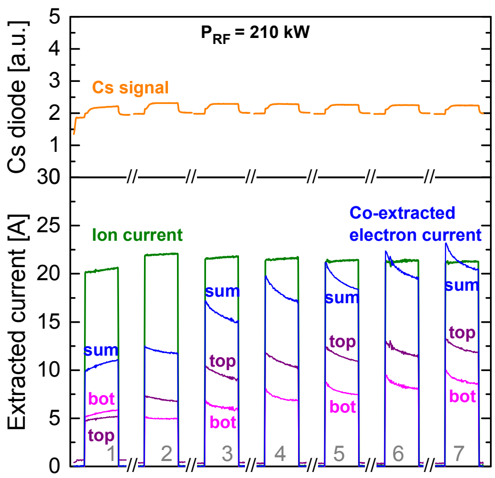

Figure 4. Signal of a Cs diode with a line of sight in front of the grid and the extracted currents of a 1200 s hydrogen pulse at the RF power of about 50 kW kW/driver (210 kW in total) with seven beam blips (9.5 s each). The co-extracted electron currents measured at the top and the bottom segment are plotted individually as well as their sum. (Same hydrogen pulse as shown in Figure 5).

The high co-extracted electron current and its unpredictable dynamics in long pulses prevents an increase of the RF power as this would unavoidably increase the problem further. Figure 5 shows the extracted currents for the best pulses achieved in hydrogen and deuterium for the required duration of 1000 s and one hour, respectively. For hydrogen, the pulse is identical to the one shown in Figure 4. The extracted ion current of 21.7 A (average) used about 50 kW/driver (total RF power of 210 kW) and an extraction voltage of 9.5 kV. A bias current of 55 A and a PG current of 1.5 kA have been used to suppress the electrons without reducing the ion current. The accelerated current measured by water calorimetry is 17.9 A, which means more than 80% are found on the calorimeter, which is the typical value at good perveance for ELISE [20]. The ITER targets regarding the extracted and accelerated currents at ELISE are 33 A and 23 A respectively, showing that the losses in the ELISE test facility are lower than those expected for the full beam line. The analysis of the beam emission spectroscopy shows a beam divergence of about 3–3.5° depending on the line of sight (acceleration voltage: 28 kV); the stripping fraction has been measured to be 3% at maximum.

In order to demonstrate a one hour pulse in hydrogen (not shown here), the RF power and extraction voltage was reduced to 20 kW/driver and 6 kV respectively (20 A bias, 2.8 kA PG current), resulting in an extracted current of 9.3 A on average. For the one hour pulse in deuterium shown in Figure 5 the extraction voltage had to be reduced further (4.5 kV) and the PG current and bias current had to be increased to 4 kA and 40 A respectively. With those parameters an averaged current of 5.8 A could be extracted. The target value at full power and extraction voltage around 10 kV would be 24.3 A, which seems to be feasible assuming a less than linear scaling with RF power (factor 4) and extraction voltage (factor 2). The experience gained from all long pulse experiments so far has shown that the maximum achievable ion current is quite stable (within 5%) and limited by the amount of co-extracted electrons which underlines the need to control the electrons in a better way.

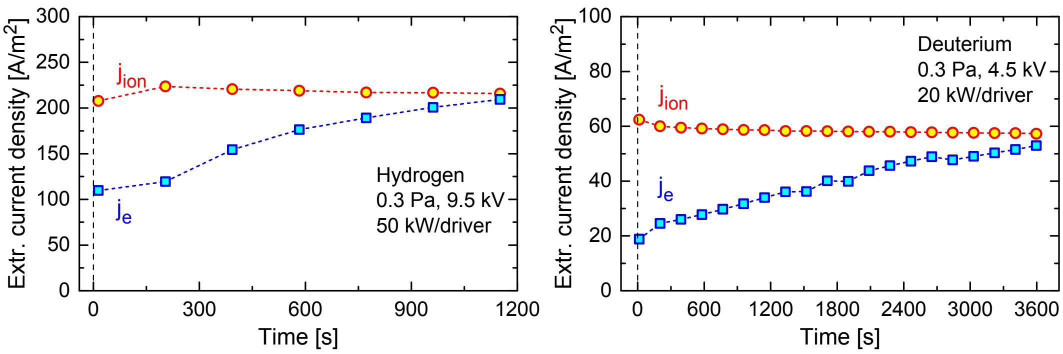

Figure 5. Best pulses at ITER parameters: 1000 s hydrogen and 1 hour deuterium with an electron-to-ion ratio below one at using an extraction voltage of 9.5 kV and 4.5 kV, respectively.

A promising tool to reduce and to control the co-extracted electrons is the magnetic filter field strength and its 3D topology. As the filter field is generated by the PG current its value can be changed easily without changing the topology. By increasing the field strength the amount of co-extracted electrons is reduced but ultimately stagnates. Concerning the isotopes, generally higher magnetic fields are needed for deuterium than for hydrogen. Due to the interplay with the bias current the best operational point needs to be identified individually. The optimum point to operate is a compromise between electron suppression without reducing the extracted ions too much. Attaching additional permanent magnets to the lateral walls of the source does not very much change the field strength at the grid but changes the 3D topology. Figure 6 shows the reduction of the co-extraction electron current induced by attaching the magnets such that the field in front of the PG is slightly enhanced. A strong dependence of the electron reduction on the pressure is observed for both, hydrogen and deuterium, being close to 50% at the required pressure of 0.3 Pa. However, this is correlated with about 10% reduction of the ion current as well. Additionally, the temporal stability of the co-extracted electron current is improved in long pulses [17,21]. Only in this configuration could one hour deuterium pulses be achieved at 0.3 Pa.

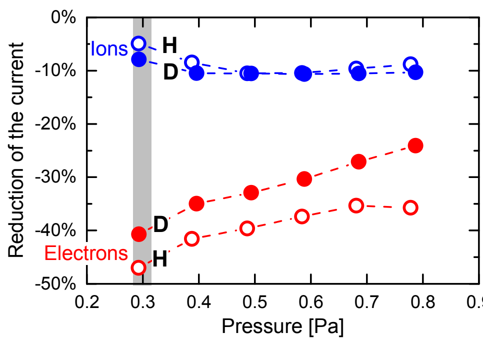

Figure 6. Reduction of the extracted currents in hydrogen and in deuterium by attaching additional permanent magnets at the lateral walls of ELISE. The filter field was set to 2.4 mT (hydrogen) and 3.8 mT (deuterium) at a RF power of 30 kW/driver.

The Cs conditioning of the source, i.e. providing a Cs layer to the PG for stable long pulse operation, is another task that needs further attention. The maximum Cs evaporation rates from the two ovens are adjusted such that the plasma in the driver is not influenced by Cs as this reduces the effective RF coupling and thus the power coupled to the plasma. Another limitation comes from Cs leaking through the grid in the plasma-off phases as this causes breakdown between the grids. The Cs reservoir in the source is built up during the vacuum phases and then redistributed by the plasma and additionally released by the back-streaming positive ions in the extraction phases. In order to prevent a degradation of the pure bulk Cs layer at the PG, a steady flux of Cs is required at present due to the presence of the residual gas in the vacuum phases at the base pressure of about 10^{-6}–10^{-7} mbar in the source. In laboratory experiments it has been found that the plasma recovers the work function of a degraded Cs layer [22]. On the other hand, sputtered particles from the interior of the source (Cu, Ni, Mo) will degrade the work function of Cs.

An inspection of the source after two years of operation showed low caesium contamination of the inner surfaces of the expansion chamber with the footprint of grid pattern visible at the back plate, caused by the back-streaming positive ions. The presence of Cs was analyzed by using wetted litmus paper: on the side walls Cs was identified by the increased pH value. The plasma-side of the plasma grid, the grid pattern at the back plate caused by the back-streaming ions, and the surfaces of the Faraday screens and driver back plate revealed a neutral pH value, indicating that Cs is not accumulated at these surfaces. A remarkably high Cs accumulation (pH values up to 10) was observed on the beam-side of the bias plate. For elemental analysis small probes were taken from several locations in the source and analyzed by EDX (energy dispersive X-ray spectroscopy). Besides Cs, molybdenum and nickel was found at the surfaces, being obviously redistributed during plasma (beam) operation. These impurities might have influenced the Cs conditioning process of the source. The beam-side 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 indicate that Cs from the ion source diffuses through the PG apertures onto the EG being partly cleared by negative ions with poor beam optics. The EDX analysis of scraped off pieces identified molybdenum, nickel and caesium. This leads to the conclusion that caesium, molybdenum and nickel from the ion source are transported into the grid system. The GG showed copper sputtering around the apertures, most likely caused by working not always at optimum perveance or by a beam halo. Deposition of copper was also detected on the grid holder boxes with some clean areas which might be explained by a beam halo or re-ionized particles [23].

3.3. Present Status

Table 1 summarizes ITER's requirements (extraction voltage of about 10 kV) for the beam sources and the best results obtained with the prototype source at the short pulse test facility BATMAN as well as the long pulse test facility MANITU (described in [7]) and at ELISE. It should be kept in mind that, due to the half-size scaling, only half the ITER currents have to be achieved at ELISE.

Table 1. ITER requirements and achievements performed at the prototype sources and at the ELISE source. All data points are taken at 0.3 Pa.

		ITER requirements		IPP prototype (BATMAN* and MANITU⁺)				IPP (ELISE) Half-size source			
Species		H^-	D^-	H^-		D^-		H^-		D^-	
Pulse length	s	1000	3600	4.5*	1000⁺	4.5*	3600⁺	9.5	**1000**	9.5	**3600**
Extracted current density	A/m²	329	286	339	151.6	319	89.1	261	**217.2**	177	**58.5**
Extracted current	A	66	56	2.4	3.2	2.0	1.2	25.7	**21.4**	17.4	**5.8**
Accelerated current	A	46	40	1.3	2.7	1.4	0.9	21.9	**17.9**	15.2	**5.2**
Electron-ion-ratio		<1	<1	0.43	1.13	0.99	1.17	0.73	**0.97**	0.74	**0.92**
RF power/driver	kW	100	100	90	47	76	43	63	**53**	47	**21**
Extraction Voltage	kV	10	10	9.5	6	10.5	6	10	**10**	10	**4.5**

The ITER parameters with respect to extracted current density and electron-ion-ratio are met in the prototype source and even exceeded for short pulses. In the ELISE source, the RF power had to be reduced to keep the electron-to-ion-ratio below one as already discussed in Section 3.1. Regarding the long pulse performance, not only the RF power had to be reduced but also the extraction voltage. The comparison of the results achieved at ELISE so far with those obtained in the prototype source (MANITU) shows that for hydrogen a better performance is achieved whereas for deuterium the situation seems to be much worse. However, it should be noted that the majority of pulses in ELISE have been performed using hydrogen for extensive electron reduction studies. This has the advantage of not being limited by the neutron budget which has to be considered for deuterium operation.

In order to meet the ITER requirements, highest priority will be given to increase the RF power with an optimization of the magnetic filter field configuration. Besides the limitation given by the co-extracted electrons the long pulse experiments have also been hampered by intolerable temperature raises and RF breakdowns in the dome (Figure 2). Insufficient cooling of the electromagnetic screens was identified as the cause for the temperature rise in the dome. Consequently an improved cooling system was attached. Results of dedicated dome breakdown investigations (mainly videos from the dome camera and inspection of the driver region after operation) indicate that the RF feedthroughs and the coil windings play a role in the onset of the dome breakdowns due to the presence of triple points. In order to mitigate the risk of breakdowns in the RF feedthroughs, their design was modified, optimizing the geometry of the triple points and thus decreasing the electric fields. Calculations of the electric field in the initial design of the feedthroughs showed that more than 1 MV/m was reached. In a small gap between the RF line and the insulator a maximum value of 4.3 MV/m was found. By moving the triple point with deepening the drilling and filling a small hole in the insulator with epoxy, the calculated maximum field strength was reduced by almost 50 %. During inspection some small particles, mainly dust, were found inside the feedthroughs additionally. Most probably these particles have been produced during previous dome breakdowns. The increasing dome breakdown probability observed during the operation may have been caused also by the accumulation of particles in the feedthroughs. Thus, in parallel with modifying their geometry, the feedthroughs were thoroughly cleaned. Regarding the RF coils, the breakdown traces indicated a “several point” contact of the coils to the driver. In these points of contact triple points are formed with unfavourable acute angles between metal and insulator, which locally increase the electric field strength. At these triple points stronger electron emission can take place, which can trigger dome breakdowns. ANSYS calculations showed that a reduction of the field strength is possible by (i) using quartz as driver material with a lower permittivity (ε=3.8) than Al_2O_3 (ε=9.5) for small gaps or (ii) increasing the gap between driver cylinder and coil. Thus, new driver cylinders were manufactured that combine both effects: quartz cylinders with identical inner diameter but reduced wall thickness (6 mm instead the previous 8 mm) to provide a 2 mm gap between coil and driver cylinder. The position of the coil is assured via six silicone combs positioned between cylinder and coil and is therefore kept in the same distance to the plasma. The lower pair of drivers was replaced by this configuration. In order to check another configuration simultaneously, the upper pair of drivers uses additionally Teflon™ coated copper coils. A similar concept has been successfully used at the prototype sources. The drivers at the ITER sources should be adapted in a later stage to the best configuration identified at ELISE. Subsequent experiments showed that the mitigation measures for RF breakdown have been very successful: the upper limit of P_{RF} is not defined by dome breakdowns anymore but only by the co-extracted electrons.

Regarding the beam characteristics, the detailed analysis of the Doppler-shifted H_α peak measured by beam emission spectroscopy reveals an inhomogeneity of less than 5% in horizontal and less than 10% in vertical direction (comparing the two rows of beamlet groups) in a well-conditioned source and at good perveance conditions. ELISE is typically operated with a beam divergence between 1.5° and 2° [20] and varies at optimum perveance and a total voltage of 35 kV from 0.9° to 1.5° over the 20 lines of sight of the beam emission spectroscopy. Recent investigations on the line profile of the Doppler-shifted peak revealed the presence of a broad component [23]. The contribution to the total line profile varies with the parameters, mainly the bias voltage and the magnetic filter field, and can reach values up to 40%; the divergence of this broad component is about 5°. This might correlate with the observed sputter traces around the apertures of the grounded grid and at the side walls of the grid holder boxes [23]. The origin of this broad component is not clear. Systematic experimental investigations accompanied by beam modelling are underway.

Towards achieving the ITER parameters, operation at high RF power and suppression of the co-extracted electrons are key, in particular for deuterium. Emphasis will be laid on the heat load on the EG, i.e. allowing the maximum tolerable power load to the segments and understanding the asymmetry of co-extracted electrons in the grid segments. The latter is of uttermost relevance as the ITER beam sources allow only measurements over the total grid area. The beam homogeneity at optimum perveance will also be addressed making use of the improved analysis of the beam emission spectroscopy and the infrared calorimetry together with the modelling of the beam extraction and beam transport with the BBC-NI code [24].

4. Relevance for DEMO NBI systems

Within EUROfusion, the 'European Consortium for the Development of Fusion Energy', a conceptual design of the beam source for DEMO is being developed [3,25] in the Work Package Heating and Current Drive (WPHCD) under the Power Plant Physics and Technology (PPPT) activities to fulfill in the best way the requirements on a neutral beam injector for the DEMO fusion reactor [26]. The requirements placed on the ion source are close to the ones for ITER. In principle, the source module is based on the modular RF source concept whereas the route of having a large expansion chamber powered by multiple drivers is followed as well as the route of having individual smaller sources (up to 20) [25]. Besides the RAMI issues which need to be fulfilled by all components of the machine, specific R&D topics for the ion source have been identified as well [27] and are part of the WPHCD R&D work programme. For an advanced concept of an NBI system the wall-plug efficiency is of uttermost relevance for which the development of a laser neutralizer is identified as key [25]. Many European laboratories contribute with their expertise to the research needed in these areas. The following focusses on some of the issues addressed by IPP with different small scale test facilities at present, preceding future tests at ELISE. Besides the uniquely high experimental flexibility at ELISE, the permission to operate in deuterium and the wealth of experience gained renders this test facility particularly important for developments towards a negative ion source for DEMO NBI.

4.1. RF- efficiency and reliability

In order to improve the efficiency of the RF system and its reliability, state-of-the-art solid state RF generators (amplifier) were tested successfully at the test facility BATMAN equipped with the prototype source, i.e. one driver [28]. Compared with the so far used self-excited oscillators, which are also foreseen to be used at the ITER sources, their electrical efficiency is higher than 90% instead of 50-60% and they do not need water cooling. Due to their original purpose being series produced for radio transmitters they are highly reliable and available at different power levels, typically in 50 to 100 kW units. Another huge advantage is their operation at fixed frequency which eases stable matching and thus stable coupling to the plasma load. Figure 7 shows the matching curves for the oscillator and the amplifier. For the oscillator the frequency becomes unstable for cos φ close to one and a frequency flip occurs, resulting in poor matching. For the amplifier the matching is represented by the standing wave ratio (SWR; no reflected power corresponds to SWR = 1) measured by a directional coupler. Together with industry automatic frequency matching and coupled power feedback control was implemented as well. This prototype with a maximum power of 75 kW works very reliably.

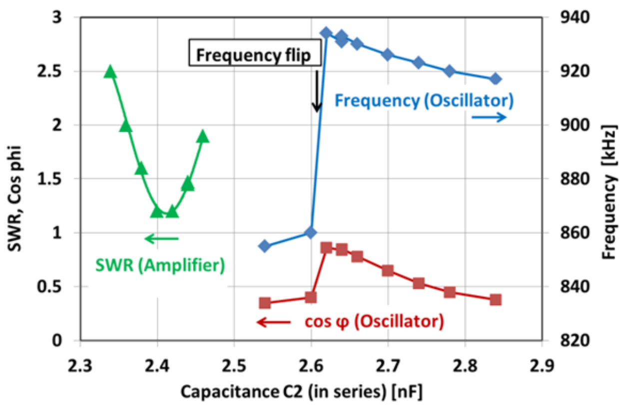

Figure 7. RF matching curves using either the self-oscillator or the amplifier (solid state RF generator) at the BATMAN test facility.

Together with the switch to a larger driver in the shape of a racetrack, a 150 kW solid state generator was also tested at BATMAN [29]. The racetrack shaped plasma source is the model that is in use to generate positive ions at the neutral beam line at ASDEX Upgrade for about 20 years now. Thus, the technology and its reliability are well proven. The volume of such a driver is increased by a factor of five compared with the standard cylinder at BATMAN. Power levels of up to 120 kW have been applied to the racetrack driver. The power was limited by the increasing amount of copper sputtered from the side walls of the expansion chamber which has the same cross section as the racetrack driver and is thus directly hit by the plasmas particles flowing out of the driver. In order to avoiding copper sputtering in future the expansion chamber is currently being coated with molybdenum. Nevertheless, reliable source operation with the amplifier could be demonstrated in this configuration as well. Presently, two amplifiers with 150 kW each are prepared for connection to the ELISE test facility in order to demonstrate their reliability in a series connection of two drivers and to fully qualify them for their potential use in future modular RF-driven ion sources.

The ultimate reason behind testing a racetrack driver is the idea to replace two cylindrical drivers of a large source that are connected to one RF generator via a series circuit by one large driver. This would markedly reduce RF problems such as breakdowns and matching problems and thus improve source reliability. ELISE could serve as a test bed for such investigations. The two possible configurations are illustrated in Figure 8. The horizontal configuration has the advantage that possible vertical asymmetries in the plasma caused by a plasma drift can be adjusted by the power level of the RF generators. Overall, the modular principle of the RF ion source and the flexibility of the shape of the drivers are advantageous for developing a source concept for DEMO NBI.

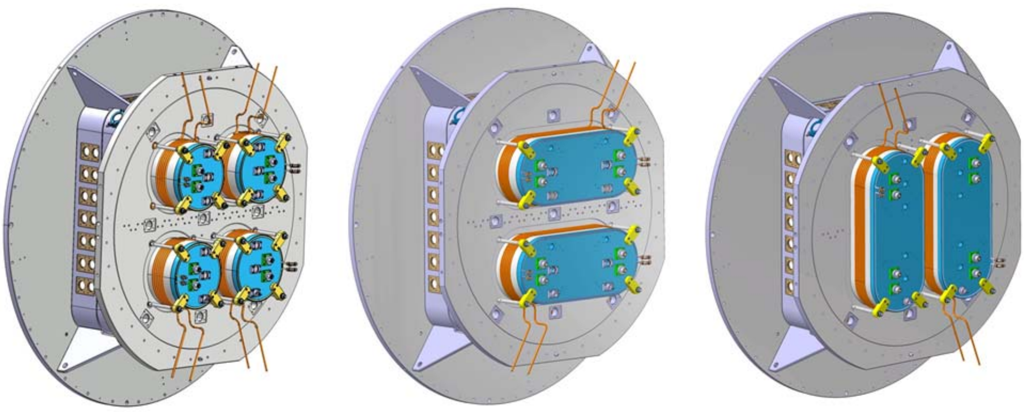

Figure 8. CAD drawing of the ELISE source with different driver options. Left: original design and present experimental setup. Centre and right: design with racetrack drivers arranged in horizontal and in vertical direction, respectively.

Alternative RF coupling concepts such as using a helicon antenna and an external magnetic field to make use of the propagating helicon waves as additional heating mechanism or using an RF source with planar coils are tested in small-scale setups in the laboratory at reduced power levels. Focus is laid on RF power transfer efficiency in hydrogen and deuterium operation at the low pressure of 0.3 Pa. The activities at the helicon setup [27,30] concentrate on the exploitation of what is known as the low-field peak [31] which is a local enhancement of the RF coupling efficiency with respect to the magnetic field strength. The standard helicon wave coupling usually requires magnetic field strengths up to 100 mT which might not be feasible to accommodate for in a DEMO source concept. In the present configuration, the low-field peak is observed at magnetic field strengths of 2 – 4 mT for hydrogen and deuterium depending on the pressure [30, 32].

The concept of using planar coils at the back plate of a source is being followed as well in a lab setup [27,32]. First results show that the RF coupling is very efficient at 0.3 Pa and 1 MHz. About 90% power transfer efficiencies are measured in hydrogen being slightly higher for deuterium plasmas than for hydrogen plasmas. The advantage of this source concept lies in the production of the plasma very close to the back plate of the source from where it diffuses into the chamber. This might simplify electron temperature and density reduction by a magnetic field which in turn has consequences on the plasma homogeneity. Alternatively the meshed grid concept [33] could be a candidate to be tested in this setup as well. This source concept could also markedly reduce the depth of the ion source. At present, investigations focus on the determination of the full set of plasma parameters, such as degree of ionization and dissociation, electron density and temperature as well as densities of the ion species.

All these concepts can be tested in a next step either at BATMAN (helicon in low-field peak and planar coil) or at ELISE (racetrack driver to replace two cylindrical drivers).

4.2. Cs consumption and Cs alternatives

Caesium is considered a critical issue regarding RAMI criteria. Besides determining stability and reliability of the beam at the desired performance, the caesium consumption that leads to the need of regularly replacing the caesium oven determines the maintenance interval. Hence, it is highly desirable to reduce either the Cs consumption or to identify alternatives to caesium. However, it should be kept in mind, that evaporation of fresh Cs has the major advantage of being able to re-condition a deteriorated surface.

Regarding the caesium consumption, the estimations for ITER and DEMO are presently based on the typical evaporation rate of 10 mg/h used in the prototype source equipped with one Cs oven. Taking into account the required beam time and the larger plasma grid area a consumption of 40 g/year is estimated for ITER (100 days with 20 pulses, 400 s each) using three Cs ovens [1]. In case of DEMO, the estimation yields 350 – 700 g/year with 80% availability through the year on the basis of using a similar source as for ITER [27]. Recently, the evaporation rate in the prototype source could be reduced by a factor of at least two owing to an improved oven concept which allows finely adjustable and reliable evaporation monitored by a surface ionization detector in front of the nozzle. ELISE, equipped with two ovens, requires the same amount of caesium despite its larger size, meaning that caesium consumption per source size is reduced by a factor of four or more. Consequently, this would markedly increase the maintenance interval for the DEMO Cs ovens and decrease the Cs contamination of the source. Although the Cs evaporation rate can be very well monitored with the surface ionization detector its calibration is delicate as it currently relies on the measurement of the weight loss of the oven after and before the campaign. For a better prediction of the Cs consumption, a dedicated campaign with high source performance consuming the total Cs content of the oven (1 g) needs to be conducted at ELISE.

In order to optimise the Cs dynamics in the source with the goal of achieving a sufficient and uniform flux onto the grid in the vacuum and during the beam phases, a caesium transport code (CsFlow3D) has been developed in the last years and benchmarked at the prototype source at BATMAN [34]. One of the main results in view of DEMO is that the position of the Cs ovens plays only a minor role compared to the distribution of Cs by the plasma interaction. The first results obtained for the large ion source ELISE confirmed that the Cs dynamics is influenced by the release of Cs due to the back-streaming ions in a similar manner as seen in the measurements (Figure 4).

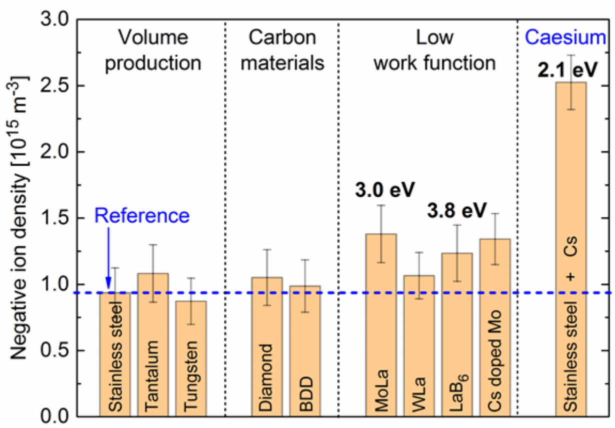

Figure 9. Negative ion density above the various surfaces in a low pressure hydrogen discharge (0.3 Pa, 300 W, [35]). For some materials the value of the work function measured in a different setup [22] is labelled as well.

Promising alternatives to caesium such as tantalum, (boron-doped) diamond as well as materials with inherently low work function materials are investigated in lab experiments regarding the enhancement of the negative ion density in the plasma [35]. These investigations are accompanied by measurements of the work function under ion source relevant parameters [22]. A comparative study shows a reasonable enhancement of negative ion densities when La-doped (0.7%) Mo, La-doped (1%) W or LaB_6 is used but the densities are still below the values achieved with caesiated surfaces, as shown in Figure 9 in which also the work function is given if available. Another approach is to provide Cs at the surface in a more stably bound form by ion beam implantation of Cs into Mo. This would reduce the Cs dynamics and consumption. A proof-of-principle campaign has been started using different implantation rates and either rough or polished surfaces [36]. Typically a surface concentration of less than 10% is achieved which results in a comparable increase of the negative ion density as for MoLa. However, none of the tested materials so far show the performance of the caesiated surface. Moreover, all of the tested diamond materials showed clear indications of plasma-induced erosion already within plasma on times of 10 h [35] contradicting the demanded long-term stability for the use in ion sources. An enhancement of the negative ion density above the surface is measured only for the low work function materials although their work function is still above the one for the caesiated surface. Hence, focus should be laid on the low work function materials and on the options to reduce their value to that of bulk caesium. An enrichment of La in Mo combined with an activation at high temperature is planned in a next step as well as investigations on an achievement of higher Cs concentrations for the Cs doped Mo surface. The ultimate test however requires a test facility with an extraction system as not only the production of a sufficient ion current has to be demonstrated but also reduction of the co-extracted electrons.

4.3. Laser neutralizer

Another important goal is the enhancement of the overall energy efficiency of an NBI system for DEMO. Replacing the gas neutraliser by a laser neutralizer could increase the overall wall-plug efficiency of the beam line by a factor of two to about 50-60% due to a larger neutralization fraction; in theory 100% neutralization can be achieved with a laser neutralizer whereas the efficiency of a gas neutralizer is limited to about 60% [37,38]. A further advantage would be a substantial reduction of the gas throughput which reduces the demands on the pumping capacity. The challenges for the realization of laser neutralization of such a large beam are, however, enormous: besides having to deal with the huge beam cross section the neutralization at the beam energy of 1 MeV requires very high optical power. The laser power needed is of the order of tens of megawatts which need to be achieved by utilization of optical cavities. Consequently, the highly reflective mirrors have to withstand the heat loads, the neutron flux and possible plasma–surface interactions and have to be sufficiently isolated from vibrations of the torus. The mode locking of the laser to the cavity is another demanding issue. Furthermore, resonant coupling of the laser and the cavity has to be sustained reliably at all times.

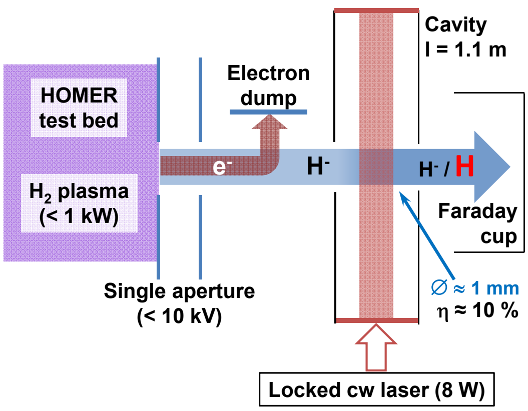

Figure 10. Concept of the proof-of-principle test of laser neutralization at the lab scale facility HOMER [35].

At present, proof-of-principle experiments are carried out in the lab in order to identify problems and potential show-stoppers. In a first step, a continuous wave driven cavity is installed on an independent test bed in atmospheric air and in vacuum at medium input laser powers of 8 W. The target is to demonstrate a stable lock of the laser frequency (1064 nm) to the resonance of the cavity. The second step will be the installation of the setup at a small, low-power negative ion beam to demonstrate the coupling of laser and ion beam as illustrated in Figure 10. If successful, a next step would aim to demonstrate laser neutralization at a large negative ion beam with higher energy.

5. Conclusions

The ELISE test facility serves at present as test bed for the beam source of the ITER NBI systems. Due to its high experimental flexibility it has moreover the potential to address issues relevant for a DEMO NBI system. For meeting the ITER requirements, the amount of co-extracted electrons is the limiting factor. The latter is in particular true for deuterium in which also a stronger temporal dynamics of the co-extracted electrons appears. In contrast, the ion currents are stable even in long pulses and at high RF power. New insights are expected when ELISE will operate in the next experimental campaign routinely at high RF by simultaneously exploring methods to stabilize the co-extracted electron currents in deuterium. In view of DEMO, concepts are being developed to either reduce the caesium consumption or to find alternatives. For improvements of the RF efficiency and reliability first steps have already been taken at the prototype source at BATMAN by using solid-state amplifiers in combination with a racetrack driver which could replace two cylindrical drivers in the large sources. The concept of a laser neutralizer is presently under investigation in proof-of-principle experiments in the laboratory with the potential to be explored at an NBI relevant ion source. The uniquely high experimental flexibility at ELISE and the permission to operate in deuterium and the wealth of experience gained renders this test facility particularly important for developments towards a negative ion source for DEMO NBI.

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