

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

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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 in hydrogen with repetitive 10 s beam extraction pulses every 3 min with 9.3 A extracted current and an electron-to-ion ratio of 0.4 at the pressure of 0.3 Pa required by ITER but using only one quarter of the available RF power. At half of the available RF power a stable 400 s plasma discharge was achieved with 18.3 A beam pulses at an electron-to-ion ratio of 0.7. Linear scaling towards full RF power (90 kW/driver) predicts that the target value of the negative ion current can be achieved or even exceeded. Increasing the RF power is limited presently by breakdown between the coils. Issues in long pulse operation are the caesium dynamics and the stability of the co-extracted electron current. For studies on a DEMO NBI system ELISE could serve in a later stage as a test bed for concepts concerning RF efficiency, operation without caesium or with largely reduced caesium consumption, and neutralization by a laser neutralizer in order to improve efficiency and reliability.

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 to ITER the plug-in efficiency and the RAMI issues (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 requirements for the source are comparable to the ones for the ITER beam source. More advanced stripping 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 [3].

The ITER requirements, and thus consequently the DEMO requirements for the operational parameters of ion source and accelerator are very challenging and exceed by far the existing devices at 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]. As the current densities of negative deuterium ions that have been achieved up to now are in the range of several 100 A/m² only, the ITER ion source area has to be rather large with dimensions of 1.9x0.9 m² and an extraction area of 0.2 m². In contrast to the sources at existing devices which use arc sources, 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/m² D^- for one hour and 330 A/m² 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 the beam homogeneity of this large beam needs to be better than 90% with a divergence of 7 mrad in order to be transported adequately to the fusion device.

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 [8]. 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, developed at IPP for many years and still in operation at the short pulse test facility BATMAN [7]) via the 1/2 size ITER source (ELISE) to the ITER source. The size scaling is based on the modular concept placing several cylindrical drivers on an expansion chamber as illustrated in Figure 1. The ITER source 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) [9]. The same source will be used for ITER's Diagnostic Beam (DNB) which is under the responsibility of ITER-India [10].

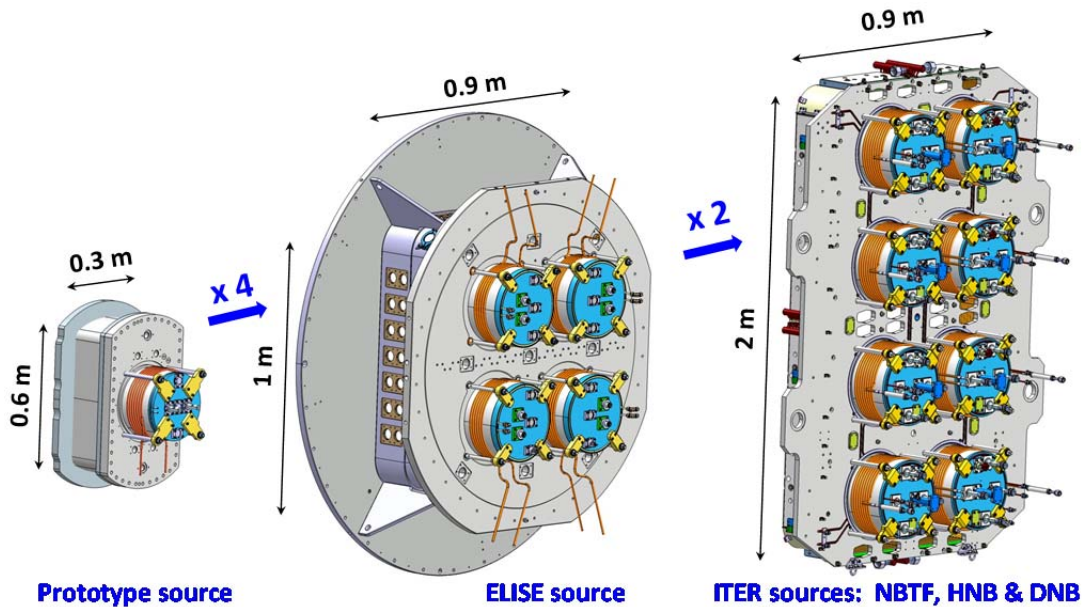


FIG. 1. Modular concept of the RF-driven beam sources: from the prototype source via the 1/2 size ITER source at ELISE to the ITER size sources.

ELISE provides early experience with the performance and operation of large RF-driven negative hydrogen ion sources with plasma illumination of a source area of $1 \times 0.9 \text{ m}^2$ and an extraction area of 0.1 m^2 using 640 apertures corresponding to a half-size ITER source. Consequently, the test facility aims at demonstrating large-scale extraction and acceleration of negative hydrogen ions (H^- , D^-) for pulses of up to one hour with 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. 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 have better access for source and beam diagnostics (see [11-13] for details]. Unlike at ITER, the source vessel is in air allowing for easy source access and modifications, but the four drivers are enclosed in a vacuum containment such that the RF drivers can be operated in vacuum like in ITER.

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 up to the desired value of one hour. 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 in the source. 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 [14]. The first grid is the plasma grid (PG) and can be biased against the source.

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, 30 cm diameter) 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 with a maximum power of 180 kW and a frequency of 1 MHz (self-excited oscillator). 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 done by a combination of a series and a parallel capacitor, the latter being remotely tunable for possible changes 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 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. A magnetic filter 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. In contrast to the small prototype sources where permanent magnets can be used to create field strengths of about 7 mT in the grid center, the field in the large sources is created by a current of several kA flowing through the plasma grid (PG). At ELISE the design allows for currents up to 8 kA limited to 5.3 kA maximum in the present setup corresponding to 5 mT in the PG center.

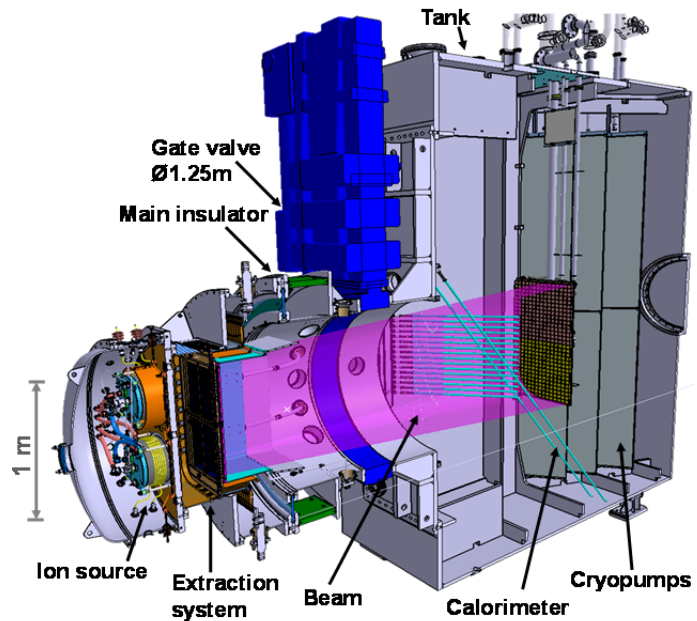


FIG. 2. Sketch of the ELISE test facility.

ELISE is equipped with several diagnostic techniques, mainly optical emission spectroscopy and pin probes using ports close to the extraction system [15]. A set of beam diagnostic tools provides information about the large ion beam: a tungsten wire calorimeter is used for beam monitoring during operation, whereas quantitative parameters such as divergence and uniformity are obtained from beam emission spectroscopy using 20 lines-of-sight and a dedicated diagnostic calorimeter [13].

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 for a comparison with the performance of the prototype source at the test facility BATMAN [7]. Due to RF issues (see next section), only 55 kW/driver could be supplied, allowing together with the high power results of BATMAN for extrapolations to the ITER requirements as shown in Figure 3. All data are taken at extraction voltages between 8.5 kV and 9.5 kV.

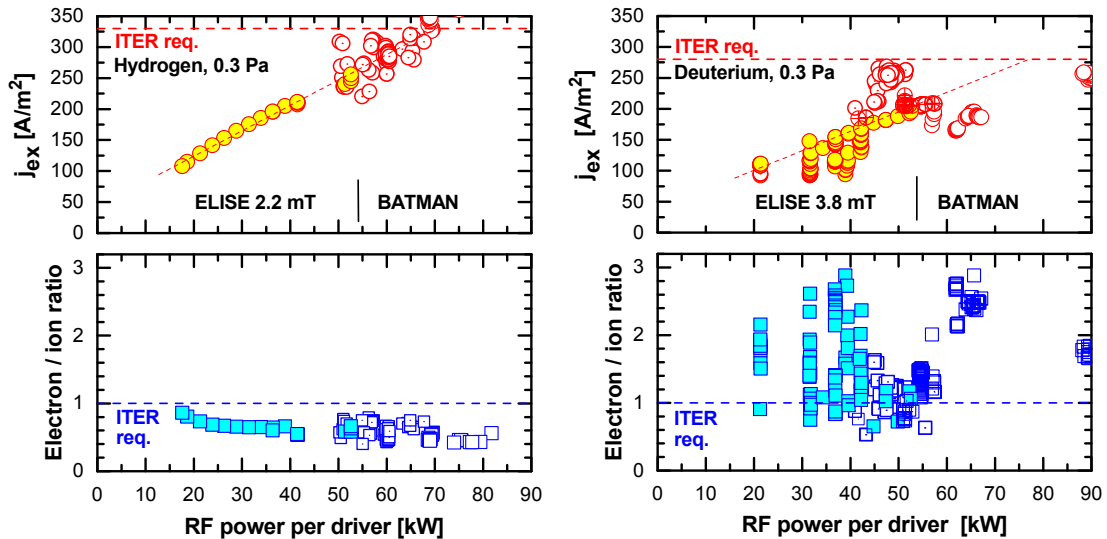


FIG. 3. Extrapolation of the source performance of the ELISE source (closed symbols) and the prototype source (BATMAN, open symbols) the ITER beam source parameters.

For both hydrogen and deuterium, a required RF power of about 80 kW per driver can be extrapolated which is less than the power being installed for the ITER source (100 kW/driver). In hydrogen, operation with a low co-extracted electron current is no issue, neither on BATMAN nor on ELISE, whereas for deuterium ratios below one are difficult to achieve. Less filter field than expected is needed at ELISE: only 2.2 mT (hydrogen) and 3.3 mT (deuterium) are used, whereas the peak value at BATMAN is 7 mT in the PG centre. 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 $1 - 2 \times 10^{17} \text{ m}^{-3}$). 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 with 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 amount and the dynamics of the co-extracted electron current which strongly depends on the caesium dynamics, i.e. the evaporation, distribution and deterioration of the caesium by the background gas in the vacuum phase as well as on the redistribution and cleaning effect of the caesium layers during plasma phases ([16] and references therein).

The dynamics of the Cs signal and the current densities is illustrated in Figure 4 for a 400 s pulse in hydrogen at moderate RF power at an extraction voltage of 7 kV to keep the electron-ion-ratio below one. The extracted ion current density of 18.3 A/m^2 (corresponding to 18.3 A current) represents one of the best pulses achieved so far. Stability within 5% is obtained. The strong dynamics of the co-extracted electrons between the beam blips and during the beam blip is clearly seen and an open issue in source operation. 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. This is assumed to be caused by positive ions created in the accelerator 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. Particularly in long pulses, this influences the Cs dynamics.

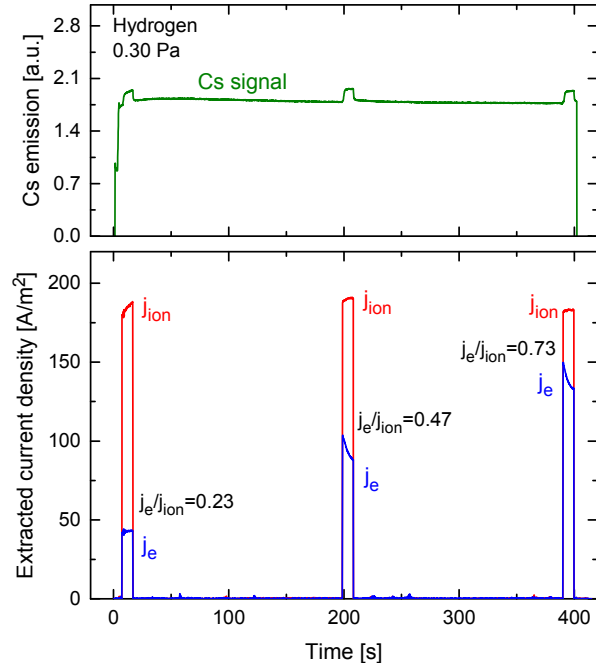


FIG. 4. Hydrogen pulse with three beam blips at the RF power of 45 kW/driver (180 kW in total).

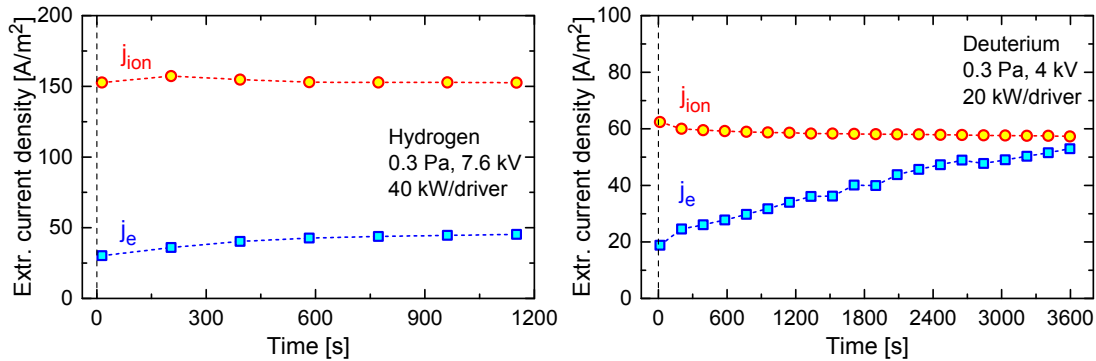


FIG. 5. Best pulses at ITER parameter: 1000 s hydrogen and 1 hour deuterium using an extraction voltage of 7.6 kV and 4 kV, respectively at 0.3 Pa with an electron-to-ion ratio below 1.

The high and unpredictable dynamics of the co-extracted electron currents in long pulses prevents an increase of the RF power as this is unavoidably correlated with an increase of the co-extracted electron current. Figure 5 shows the extracted current densities for best pulses achieved in hydrogen and deuterium for the required duration of 1000 s and one hour, respectively. Higher extraction voltages and power levels are possible in hydrogen whereas in deuterium only 20 kW/driver can be used, i.e. one fourth of the target value with an extraction voltage being less than one half. This underlines that the source performance is hampered by

the co-extracted electrons and not by the ion current, which is fortunately quite stable.

3.3 Present Status

Table 1 summarizes the ITER 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.

TABLE I: ITER REQUIREMENTS AND ACHIEVEMENTS PERFORMED AT THE PROTOTYPE AND THE ELISE SOURCE.

Species		ITER requirements		IPP prototype source (BATMAN and MANITU)				IPP (ELISE)			
		H ⁺	D ⁺	H ⁺		D ⁺		H ⁺		D ⁺	
Pulse length	s	1000	3600	4	1000	4	3600	9.5	1000	9.5	3600
Extracted current density	A/m ²	329	286	339 (90 kW)	159 (47 kW)	319 (76 kW)	98 (43 kW)	256 (53 kW/dr.)	153 (38 kW/dr.)	176 (47 kW/dr.)	57 (21 kW/dr.)
Accelerated current	A	46	40	1.3	2.9	1.4	1.1	20.0	11.9	15.2	5.1
Electron-ion-ratio		1		0.43	1.13	0.99	1.17	0.66	0.3	0.74	0.92

In order to meet the ITER requirements, highest priority has been given to increase the RF power which is limited at ELISE by RF issues such as breakdowns between the coils and the co-extracted electrons. Here the understanding of the interplay of magnetic filter field, bias and caesium conditioning needs to be improved by enhanced diagnostics of the ELISE source accompanied by modelling. The latter is in particular important to understand the higher amount of co-extracted electrons and caesium consumption in deuterium.

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. The beam divergence is typically between 1.5° and 2° [17] and varies from 0.9° to 1.5° between the 20 lines-of-sight of the beam emission spectroscopy in optimum perveance and a total voltage of 35 kV.

Regarding the caesium consumption, the evaporation rate in the prototype (typically 10 mg/h) could be reduced by a factor of two at least thanks to an improved oven concept which allows for finely adjustable and reliable evaporation monitored by a measuring device 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. This reduces remarkably the maintenance interval for the Cs ovens and the Cs contamination of the source.

4. Relevance for DEMO NBI systems

The high experimental flexibility of the ELISE test facility allows for investigations in view of an NBI source for DEMO. The reliability of negative ion sources might profit if they could be operated without caesium or at least even further reduced caesium consumption. Promising Cs-free alternatives to caesium such as tantalum, (boron doped) diamond as well as low work function materials are investigated in lab experiments regarding their enhancement of the negative ion density in the plasma. These investigations are accompanied by measurements of the work function under ion source relevant parameters [18]. A comparative study shows a reasonable enhancement of negative ion densities when La-doped (0.7%) Mo and LaB₆ is used but the densities are still below the values achieved with caesiated surfaces. 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. Proof-of-principle experiments show promising results. However, it should be kept in mind, that evaporation of fresh Cs has the main advantage to re-condition a deteriorated surface. ELISE could serve as a test facility for such alternatives.

In order to improve the efficiency of the RF system and its reliability, state-of-the-art solid state RF generators were tested successfully at BATMAN with up to 150 kW power. Together with industry automatic frequency matching and coupled power feedback control was implemented. Very promising results have been obtained at BATMAN up to 120 kW using the solid-state RF generator working very reliable and allowing for a wider RF matching window. Further steps included the test of a large race-track driver at BATMAN with the goal to replace two cylindrical drivers at the ELISE source as illustrated in Figure 6. This would also remarkably reduce RF issues as breakdowns and matching and thus improve the source reliability. Alternative RF coupling concepts (such as Helicon sources) are tested in small-scale setups before testing them at BATMAN or ELISE.

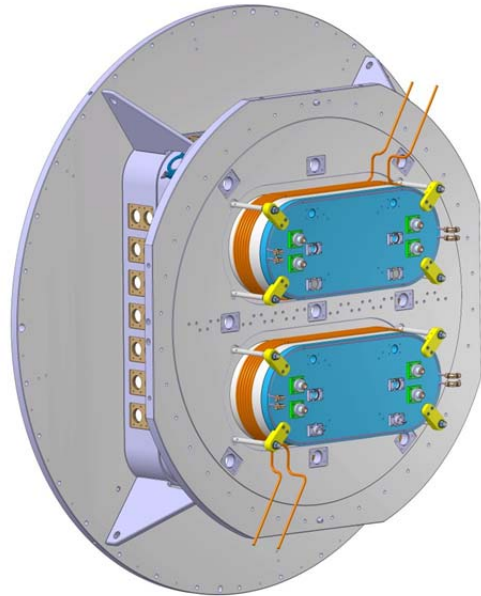


FIG. 6. CAD drawing of the ELISE source with two racetrack drivers.

Another important goal is to enhance the overall energy efficiency. Replacing the gas neutraliser by a laser neutralizer could increase the overall plug-in-efficiency of the beam line by a factor of two to about 0.6, but its feasibility has still to be demonstrated. 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 cavity is installed in an independent test bed in atmospheric air and in vacuum at medium laser power of 8 W. The target is to demonstrate mode matching and mode locking, a prerequisite for having a stable lock of the laser frequency (1064 nm) on 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 targeting at 10% neutralization. Laser photoneutralization could later be tested then at either BATMAN and at ELISE.

5. Conclusions

The ELISE test facility serves at present as test bed for the beam source of the ITER NBI systems and has due to its high experimental flexibility 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 dynamic appears. In contrast, the ion currents are stable even in long pulses and higher RF power. New insights are expected when ELISE will operate at the ITER relevant RF power which is planned for the next campaign. In view of DEMO, concepts could be developed to either reduce the caesium consumption or to find alternatives. For improvements of the RF efficiency and reliability first steps are already taken at the prototype source at BATMAN by using a racetrack driver which can replace two cylindrical drivers in combination with solid-state amplifiers. The concept of a laser neutralizer presently under investigations in proof-of-principle experiments in the lab can be explored as well at ELISE.

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