Performance of the BATMAN RF Source with a Large Racetrack Shaped Driver

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Abstract. In the negative ion sources in neutral beam injection systems (NBI) of future fusion reactors the plasma is generated in up to eight cylindrical RF sources ("drivers") from which it expands into the main volume. For these large sources, in particular those used in the future DEMO NBI, a high RF efficiency and operational reliability is required. To achieve this it could be favorable to substitute each pair of drivers by one larger one. To investigate this option the cylindrical driver of the BATMAN source at IPP Garching has been replaced by a large source with a racetrack shaped base area and tested using the same extraction system. The main differences are a five times larger source volume and another position of the Cs oven which is mounted onto the driver`s back plate and not onto the expansion volume. The conditioning characteristics and the plasma symmetry in front of the plasma grid were very similar. The extracted H^- current densities j_{ex} are comparable to that achieved with the small driver at the same power. Because no saturation of j_{ex} occurred at 0.6 Pa at high power and the source allows high power operation, a maximum value 45.1 mA/cm^2 at 103 kW has been reached. Sputtered Cu from the walls of the expansion volume affected the performance at low pressure, particularly in deuterium. The experiments will be therefore continued with Mo coating of all inner walls.

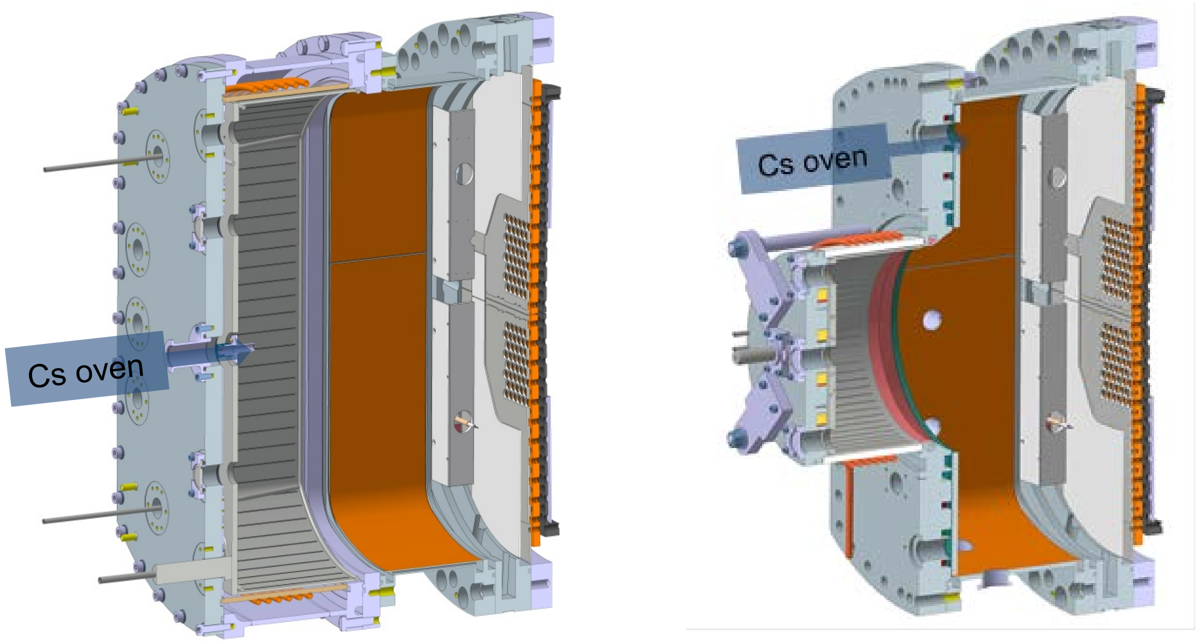
INTRODUCTION

Large RF driven negative ion sources will be used for the NBI of ITER and beyond that for DEMO. The ITER source which will be tested at the NBTF (Neutral Beam Test Facility) in Padua will use eight cylindrical drivers for plasma generation which are similar to that of the small prototype source [1]. Each two horizontally arranged drivers are switched in series and supplied by one RF generator. The ELISE source at IPP, which is half the size, has four of these drivers [2]**.** This modular source concept has several drawbacks: (i) For the required H^-/D^- currents an RF power of minimum 80 kW per driver is necessary, in total more than 640 kW in cw operation for the whole source which is a challenge for cooling and for RF issues like breakdowns and RF noise. (ii) Due to the small driver volume the power density is very high (about 10 kW/l), leading to high power loads to the inner walls. (iii) At low pressure and high power the neutral density decreases due to heating of the neutral gas and high ionization degree; consequently the plasma density can saturate due to neutral depletion when the power is raised [3]. (iv) Finally the mutual inductance of neighboring drivers was probably the reason for damages of the internal copper Faraday shield inside the sources. Therefore additional shielding of the individual drivers had to be implemented which complicates the set-up [2].

Replacing a driver pair by one larger source can overcome some of these issues, simplify the design and improve the reliability. Due to the larger volume the plasma density is expected to be lower, and due to the larger volume to surface ratio plasma losses are lower and the dissociation degree is expected to be higher at the same plasma density. Because of these potential advantages a large driver has been tested at the BATMAN test facility.

EXPERIMENTAL SETUP

In the well-known BATMAN source the cylindrical driver has a diameter of 24.5 cm and a height of 14 cm. It was replaced by a large source with a race-track shaped base area (see Figure 1). This source type is being used in the positive ion NBI of ASDEX Upgrade and is operated since 1997 very reliably [4]. The volume of the „racetrack driver“ is 38 l (width x height x length = 32 x 23 x 58 cm^3) and therefore about five times larger than that of the cylindrical driver (7.5 l). The plasma is generated by inductive coupling using a 6 turn RF coil is wound around a 6 mm thick quartz insulator which insulated by Teflon coating. The quartz vessel is mounted inside a vacuum chamber to avoid cracking by the atmospheric pressure. An internal copper Faraday shield protects the inner quartz walls from erosion and heat load of the plasma. To prevent sputtering is the shield coated by molybdenum (see Figure 2).



(a) (b)

FIGURE 1. Drawing of the BATMAN source with racetrack shaped driver (a) and cylindrical driver (b).

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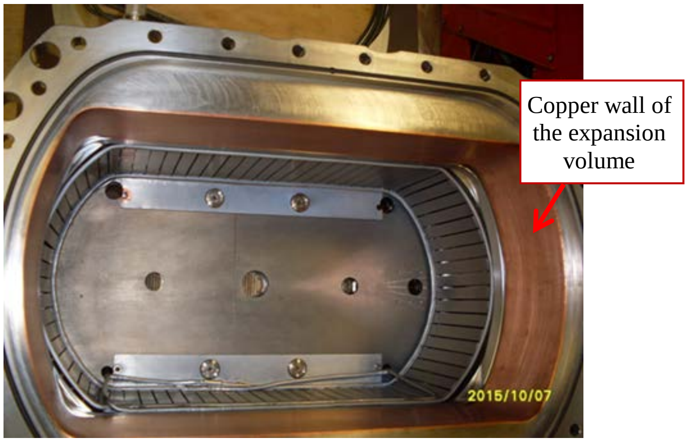


FIGURE 2. View inside the BATMAN source with race-track shaped driver.

The racetrack driver is mounted onto a shorter expansion volume (14 cm instead of 19 cm) to keep the total length constant. With the racetrack driver the total source volume increased from 43 l to 62 l. However, because the shape of the expansion volume is the same as of the racetrack source, no plasma expansion like with the cylindrical driver can take place. The plasma streaming out of the driver is already at the exit in contact with the copper walls of the expansion volume.

A fundamental difference between the two sources is the position of the caesium oven. With the cylindrical driver the oven is mounted onto the upper end of the backplate of the expansion volume, whereas at the large source it is placed onto the center of the backplate of the driver (see Figure 1). Hence the Cs is evaporated symmetrically direct into the driver plasma. Another difference is that the walls of the expansion volume are exposed to higher plasma density than in the previous source, so much less Cs can be trapped on the walls. Both issues lead to a different Cs dynamics in the sources [5].The distribution of the plasma light has been observed by a camera from the top side of a 19 cm long expansion volume which is equipped with more diagnostic ports. Figure 3 shows impressively the effect of magnetic filter field on the expanding plasma. The magnetic filter field set-up is the same as in the prototype source. It is generated by rods of permanent magnets, which are mounted 3 cm above the PG in 30 cm distance from each other along the sides of the plasma grid. The source is mounted onto a 3-grid extraction system with up to 9 kV extraction and 13 kV acceleration voltage and an extraction area of 63 cm^2. The source operates in a cycle of 7s plasma with 4.5 s extraction and 3 min interruption. Details of the test facility can be found in [6].

FIGURE 3. Plasma light inside the BATMAN source with racetrack shaped driver.

The same matching circuit is used for both drivers, the higher coil inductance of the racetrack driver (10µH instead of 6 µ H for the cylindrical driver) is compensated by an different setting of the variable series capacitor. For the RF power supply 1 MHz solid-state amplifiers of 75 kW or 150 kW maximum powers have been used. Compared to the tube based oscillators which are foreseen for the ITER sources, this type of generator has the advantage of a much higher efficiency (90 % instead of 55 %) and easier and stable matching due to the high frequency stability [7]**.**

The diagnostic system includes electrical current measurements, two Langmuir probes, the tips located 7 mm from the plasma grid, optical emission spectroscopy (OES) on the backplates of the drivers, the line of sight perpendicular to the plasma grid on and cavity ring-down spectroscopy (CRDS) 22 mm from the plasma grid [5].

RESULTS

General operation and conditioning

Although the Cs vapor can change the plasma impedance considerably, the direct evaporation of the Cs into the driver did not affect the matching very much. The position of the nozzle seems to be far enough away from the part of the source where the RF power is coupled in. So an RF power up to 130 kW could be applied to the source during Cs evaporation.

At the beginning of the experimental campaign the Cs has to be evaporated and distributed (“conditioning”). During this phase the source with the racetrack driver behaved as usual: the electron current decreased and the ion current increased simultaneously. But then the electron current increased again. This can be caused by the sputtered Cu from the walls of the expansion chamber. The appearance of copper in the discharge was a problem which had considerable impact on the experiments at low pressure and in deuterium. The line intensity of the Cu 324.75 nm and Cu 327.4 nm lines measured by OES increased from 0.6 Pa to 0.3 Pa by a factor 2 to 3. The reason for the copper emission is sputtering from the uncoated Cu surface of the expansion chamber which is exposed to a higher plasma load than with the cylindrical driver (see Figs 2 and 3). With the latter no copper at all was observed in the source. The impact of copper on the work function of the plasma grid leads to a lower performance, an increasing electron current and a worse reproducibility of the results. This effect had already been observed in the BATMAN source at the MANITU testbed with a copper Faraday shield, which was not coated with Mo [8]. With deuterium the line intensities were considerably higher, such that experiments also at high pressure were affected and no regular experiments were possible. So the next improvement of the design will be to coat also the inner walls of the expansion chamber with molybdenum.

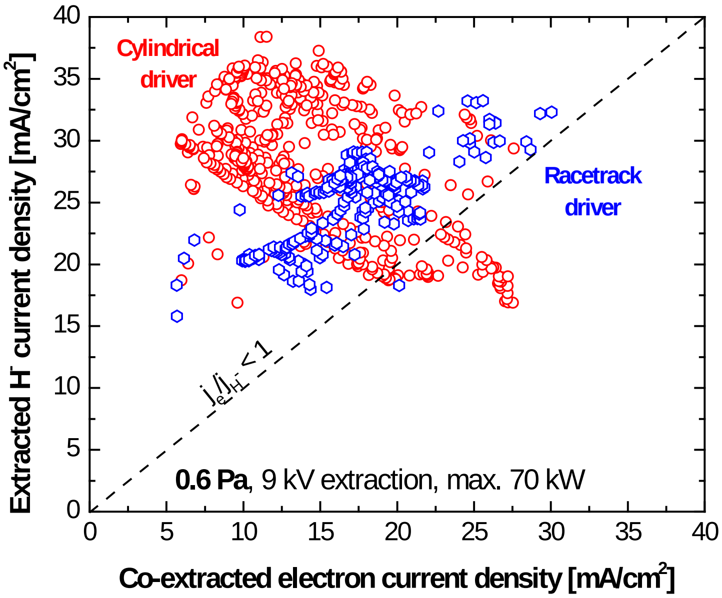


FIGURE 4. Comparison of the extracted H^-current density vs. electron current density at a power up to 70 kW for different drivers.

However, despite the much larger source volume and the copper in the source, the extracted ion current density j_{ex} in hydrogen was generally only slightly lower at the same power than with the cylindrical driver. But as shown in Fig. 4, the electron current or the j_e/j_{ex} ratio respectively was higher due to the increasing electron currents during conditioning.

During the conditioning phase the ratio of the plasma densities measured by the two Langmuir probes close to the top and the bottom end of the plasma grid increased, but did not fall below 3. Fig. 5 shows the plasma density measured after conditioning as a function of the power. Because the same ratio was observed with the cylindrical driver, the plasma drift seems to be determined by the volume close to the plasma grid rather than by the driver geometry and plasma expansion.

In the OES spectra a higher line ratio $H_\gamma/H_{2,\mathrm{Fulcher}}$ has been measured in the racetrack driver at the same power, which is equivalent to a slightly higher dissociation degree [5].Considering the larger driver volume this corresponds to a much larger flow of hydrogen atoms out of the driver. Because the atoms contribute predominantly to the surface conversion, a more efficient H^- production can be expected.

Another important observation was that the plasma density in the racetrack driver measured by OES was only by a factor two three lower than in the cylindrical driver.

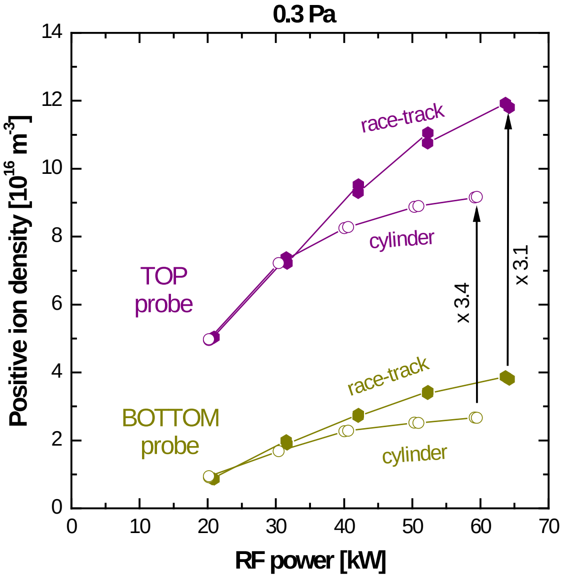


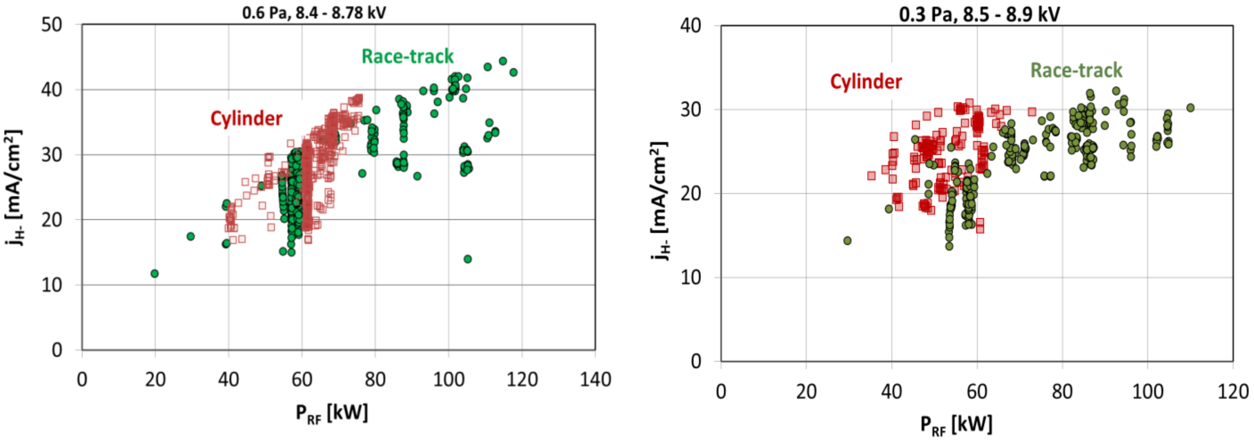
FIGURE 5. Plasma symmetry in front of the plasma grid.

Source performance

Figure 6 shows the extracted H^- currents as a function of the RF power achieved at 0.6 Pa and 0.3 Pa during the last experimental campaigns for different values of the bias potential and with different status of the caesium conditioning. Shown are only pulses performed with an extraction voltage of 8.4 kV to 8.9 kV to ensure that the extracted currents were not limited by extraction effects. The source was operated with the cylindrical driver only with the 75 kW RF generator.

At 0.6 Pa no saturation was observed with both drivers at high power. The racetrack driver could be operated with higher power due to the more powerful RF generator and the lower power density in the source. The power scan in Fig. 7 demonstrates that j_{ex} follows exactly the increase of the H^- density in the source measured with CRDS. A maximum value for the extracted ion current density j_{ex} of 45.1 mA/cm^2 was achieved with 115 kW and with j_e/j_{ex} = 0.7. Further increase of the power was limited by too high electron currents or power load on the second grid respectively. That at 0.3 Pa “only” 32.2 mA/cm^2 (with j_e/j_{ext} = 1 at 95 kW) could be extracted can be caused by the higher amount of copper in the discharge.

At low pressure (0.3 Pa) no further increase of j_{ex} could be achieved with the cylindrical driver at high power, whereas no clear saturation of the extracted ion currents occurs with the racetrack driver. This is consistent with the probe measurements of the plasma density shown in Fig. 5 and confirms the assumption that due to the large volume the neutral depletion is less important in the racetrack driver. The lower overall efficiency with the racetrack driver at 0.3 Pa is presumably contributed to the higher amount of copper in the source.



(a) (b)

FIGURE 6. Extracted H^- current density as a function of the RF power for 0.6 Pa(a) and 0.3 Pa(b).

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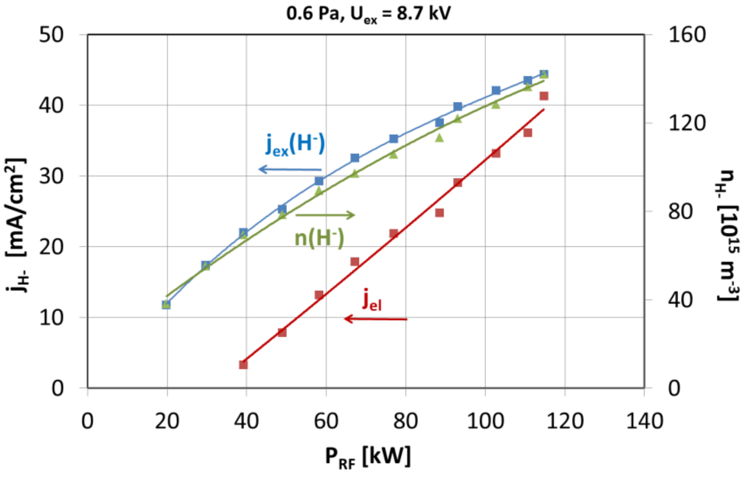

FIGURE 7. Power scan of the extracted H^-current density and the H^- density measured with CRDS with the racetrack driver source at 0.6 Pa.

SUMMARY

The extracted H^- currents with the racetrack driver are comparable with that achieved with the small cylindrical driver, although the five times larger driver volume. Less saturation of the H^- currents and the plasma density at high power was observed. Due to the almost linear dependence on the RF power and the higher available power a new record value of 45.1 mA/cm^2 with j_e/j_{ext} = 0.7 at 0.6 Pa was achieved, the applicable power limited only by the power load of the co-extracted electrons on the second grid.

The comparison of the two drivers in view of an application to the ITER source is of limited meaningfulness, because the plasma expansion is not realistic, the filter field is generated by permanent magnets and the problem with the sputtered Cu affected the source performance particularly in deuterium. However, from the absence of saturation of the H^- current at high power and the higher dissociation degree an improved efficiency can be expected, which makes the racetrack driver a promising alternative for the driver of large negative ion sources of future NBI system like for DEMO.

Because the tested driver source was designed for positive ion production, it is far from being optimized for this application. The first improvement will be Mo coating of all inner surfaces. An important step will be the upgrade of the test facility by a new extraction system, in which the filter field is generated by a current through the plasma grid like in the ITER source [9].

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