Long pulse H$^-$ beam extraction with an RF driven ion source on a high power level[a]

W. Kraus[b], U. Fantz, P. Franzen

Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany

IPP Garching is investigating the applicability of RF driven negative ion sources for the NBI of ITER. The set-up of the tested source was improved to enable long pulses up to 100 kW RF power. The efficiency of negative ion production decreases at high power. The extracted H$^-$ currents as well as the symmetry of the plasma density close to the plasma grid and of the beam divergence depend on the magnetic filter field. The pulse duration is limited by the increase of co-extracted electrons, which depends on the RF power and the Caesium conditions on the plasma grid.

I. INTRODUCTION

The future ITER neutral beam system is based on negative hydrogen ions. It will be equipped with RF driven ion sources, the design derived from prototypes developed and tested at IPP Garching. The negative ions are produced on the plasma grid by Caesium enhanced surface conversion of atoms and positive ions. In one of the test facilities at IPP Garching the capability of stable negative ion production in long pulses of up to 3600 s is being investigated. The target values of the accelerated ion current density are 24 mA/cm^2 (H$^-$) and 20 mA/cm^2 (D$^-$) respectively. For these experiments a smaller source prototype of only one eighth of the size of the ITER source and a proportionally reduced extraction area of 133 cm^2 to 200 cm^2 is used.

In previous experimental campaigns constant H$^-$ ion currents for up to 3600s were demonstrated; but, because of RF breakdowns in air at the RF coil, the RF power had to be limited to less than 50 kW and subsequently only about half of the current density required for ITER was produced[1]. Further improvements of the source design now allow for reliable long pulse beam extraction with considerably higher RF power.

II. THE PROTOTYPE RF SOURCE

In the prototype source the RF power at a frequency of 1 MHz is inductively coupled into a circular volume of 25 cm diameter and 14 cm height ("driver"), out of which the plasma is flowing into the main chamber (b x l x d = 30 x 59 x 25 cm^3). The design is described in detail in ref. 1. The ITER source will have eight of these "drivers".

The main improvement of the source set-up was to encase the RF coil in a fibre glass box that is filled with SF$_6$ (Fig. 1). In this way the insulation of the RF coil against RF breakdowns was much improved, allowing the power limit for long pulse operation to be raised from 60 kW to more than 100 kW. In the ITER source the insulation of the RF coils is not an issue, because the drivers as well as the total source are in vacuum.

The Faraday shield, which is mounted inside the driver in order to protect the insulator from the plasma erosion and power load, had straight slits and therefore an optical transparency of approx. 10 %. An improved version with z-shaped slits and near zero transparency has been installed recently (Fig.2) in order to avoid the power load on the insulator. During source operation the temperature rise of the cooling water of the new Faraday shield was only slightly higher when compared to the old one. As the difference is not larger than the change in the transparency no additional power losses by eddy currents seem to occur and so the new design can be used also for future sources.

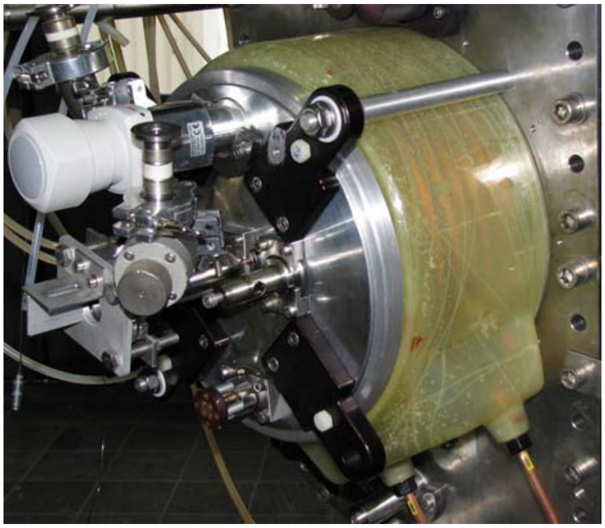

Fig. 1. SF$_6$ insulation of the RF coil

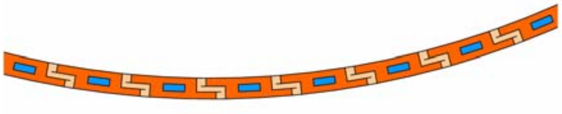

Fig. 2. Cross section of the Faraday shield with z-shaped slits and water cooling channels

III. HIGH POWER OPERATION

Fig. 3 shows a correlation between the pulse duration and the extracted H$^-$ current density. The achieved maximum values are lower in long pulse operation, because the RF power has to be reduced with increasing pulse duration. This reduction is caused by the steeper raising electron current on the high power level. The current of co-extracted electrons reaches after shorter time a limit that is defined by the maximum allowed power load on the extraction grid and the beam has to be stopped earlier. This electron current rise can be controlled to a certain extend by adjustments to the plasma grid bias voltage[1] but cannot be suppressed for all pulse durations.

The spread in the H$^-$ current measured at a fixed RF power over a longer period (Fig. 4) is caused by different magnetic filter

---

[a] Contributed (or Invited), published as part of the Proceedings of the 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September, 2009.

[b] kraus@ipp.mpg.de

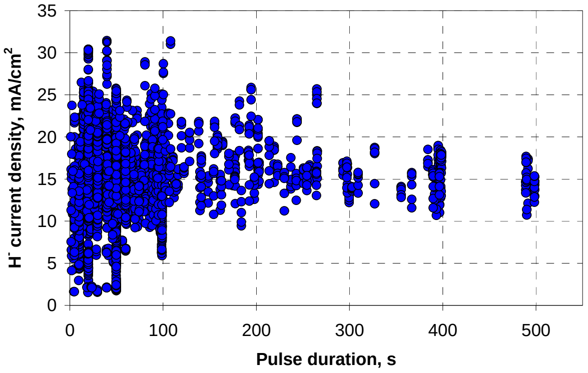

Fig. 3. Extracted ion current density as a function of the pulse duration at 0.4 to 0.6 Pa and with a RF power from 55 to 110 kW. The data are from 34 experimental days.

fields, source pressures and Cs conditions on the plasma grid surface. The latter has great impact on the fraction of H^- ions in the plasma close to the plasma grid.

At high power the ion current seems almost to saturate. The corresponding efficiency in terms of H^- current density/RF power is highest at low power and decreases steadily as a function of the power (Fig. 5).

The best results so far are an extracted current density of 31 mA/cm^2 for 100 s and 26 mA/cm^2 for 260 s and an extraction voltage of 8.5 kV. With a higher voltage of 10 kV, as it is planned for ITER, higher currents would be possible. The accelerated current density is around 70 % of these values for the used extraction system and has reached up to 22 mA/cm^2.

IV. CAESIUM HANDLING

The increase of the electron current is correlated with the Cs852 line measured in 2.5 cm distance parallel to the plasma grid. As long as the Cs signal rises, the electron current is stable, as soon as the Cs signal saturates or starts to decline, the electron current increases (Fig. 6). This rise happens earlier and with a steeper slope at higher RF power. After long term “conditioning” of the source, that is careful Cs evaporation and optimized duty cycle, the stability of the electron current improves slowly, but there is still a great demand for investigating the long pulse stability of the cesiated plasma grid surface[2].

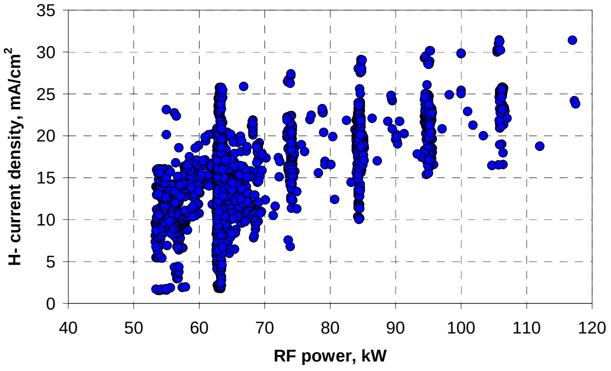

Fig. 4. Extracted H^- current density as a function of the RF power at a pressure of 0.4 to 0.6 Pa and pulse durations of 20 s to 400 s. The data are from 34 experimental days

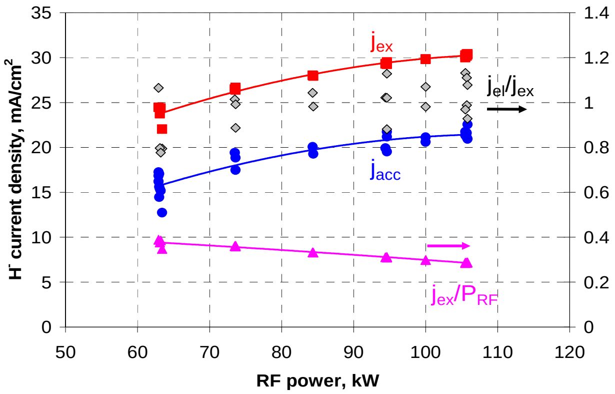

Fig. 5. Power scan of electron fraction, efficiency, extracted and accelerated H^- current density at a pressure of 0.6 Pa and pulse length of 20 s.

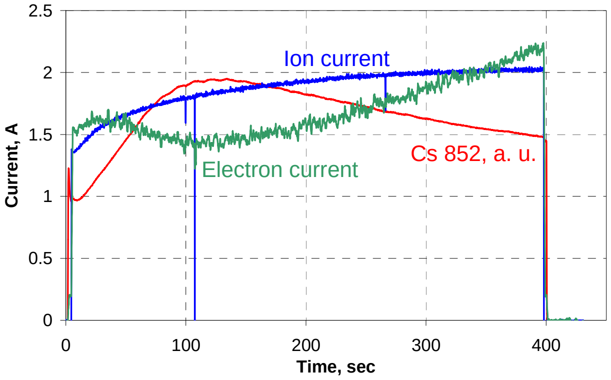

Fig. 6. Example of a decreasing Cs signal and the simultaneously increasing electron current at 60 kW and 0.4 Pa

V. MAGNETIC FILTER FIELD

The magnetic filter field is generated by 8 rows of Co-Sm permanent magnets on either side of the source 2.5 cm from the plasma grid. To modify the magnetic field three additional rows have been placed 4.5 cm above them with different polarity in order to weaken or strengthen the initial field. The ion saturation current close the plasma grid, measured by two pin probes, depends very much on the magnetic filter field[3]. With stronger magnetic field the current in front of the grid is more or less asymmetric (Fig. 7). The asymmetry changes invert, when the direction of the magnetic filter field is inverted.

With the weakest field the currents are almost symmetric and the extracted H^- current reaches maximal values but on the other hand the current of co-extracted electrons is the highest. These symmetry changes have also been observed in the beam divergence profiles measured by Doppler shift spectroscopy 2 m downstream (Fig. 8). With the weakest field a constant beam divergence has been observed, which indicates a constant beam perveance and a hence homogenous H^-profile close to the plasma grid.

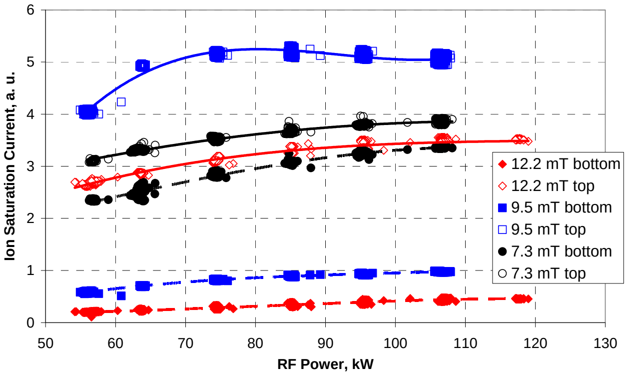

Fig. 7. Power scan of the ion saturation current for three different magnetic filter field strengths at 0.45 Pa and 20 s pulse length. The currents have been measured with two Langmuir probes placed at the upper and lower edge of the extraction area in 2.5 cm distance from the plasma grid.

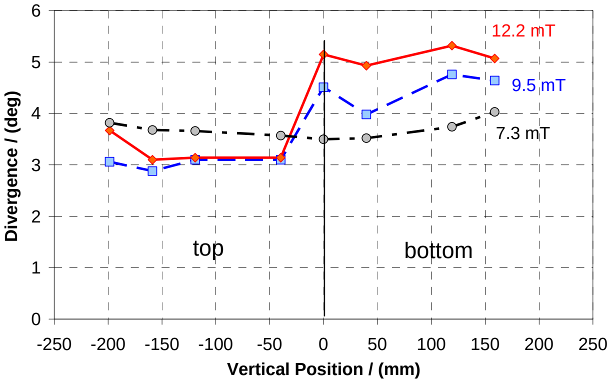

Fig. 8. Beam divergence of the extracted H^- beam at 60 kW and 0.45 Pa, parameter is the filter field strength.

The second effect of the magnetic filter field is a dependence on the source pressure which occurs only at low filter field (Fig. 9).

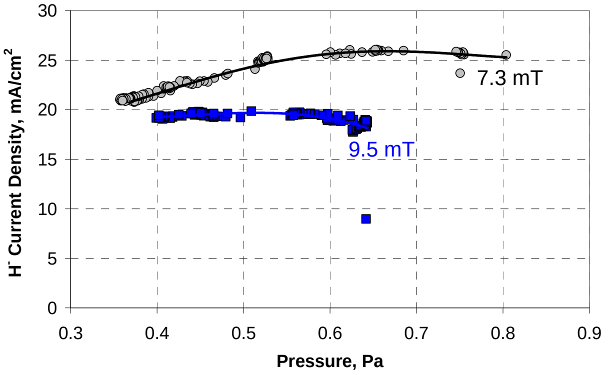

Fig. 9. Extracted H^- current density as a function of the source pressure at 60 kW in 20 s pulses

VI. DISCUSSION

According to surface production theory the negative ions are produced predominantly by conversion of hydrogen atoms on the cesiated plasma grid surface[4]. It is well known that the dissociation of the hydrogen molecules saturates in a RF source at high plasma density or RF power respectively, the maximum is determined by the wall recombination of the atoms. This has been confirmed by spectroscopic measurements in the driver[5]. Although the positive ions contribute less to the negative ion production they are important for the neutralization of the space charge created by the negative ions[4]. Plasma density also does not increase linearly at high power which is shown in Fig. 7 where the measured ion saturation current close to the plasma grid shows only a slight increase at high power. As the flow of the hydrogen atoms as well as of the positive ions increases only slowly at high power, it is not surprising, that this is observed also with the negative ions.

One way to avoid such "saturation effects" would be to improve the volume/surface ratio of the driver simply by enlarging the diameter, which is planned for the future sources designed for ELISE and ITER[6]. There not only a higher efficiency of the drivers can be expected, additionally the loss areas in the expansion chamber are smaller for atoms as well for ion compared to those in the IPP prototype.

Because the Caesium vapour is released into the source by a nozzle in the back plate at the side of the driver the Caesium handling is determined by the very time-consuming distribution of the Cs onto the plasma grid. A more central position of the Cs-oven or a dispenser close to the plasma grid would facilitate this procedure[2].

The experiments with different filter field configurations have demonstrated how much impact small changes can have on the RF plasma. Interpretation is difficult; the field generated by the permanent magnets in this source is very inhomogeneous and has a different topology inside the source and the driver when the configuration is changed with additional rows of magnets. Because of their limited range permanent magnets cannot be used in large sources anyway, therefore, alternative concepts have to be investigated as foreseen for ELISE and ITER.

Acknowledgements

This work was (partly) supported by a grant from the European Union within the framework of EFDA. The authors are solely responsible for the content.

References

[1] W. Kraus, H.-D. Falter, U. Fantz, P. Franzen, B. Heinemann, P. McNeely, R. Riedl, E. Speth, Rev. Sci. Instrum. 79, 02C108(2008).
[2]. R. Gutser, , U. Fantz, D. Wünderlich, this conference
[3] P. McNeely, L. Schiesko, this conference
[4] D. Wünderlich, R. Gutser, U. Fantz, to be published in Plasma Sources Sci. and Technol., 2009
[5] U. Fantz, H.-D. Falter, P. Franzen, E. Speth, Rev. Sci. Instrum. 77, 03A516(2006).
[6] P. Franzen, U. Fantz, W. Kraus, H.-D. Falter, B. Heinemann, R. Nocentini, AIP Conf. Proc. 1097, 451(2008).