Long Pulse H^- Beam Extraction With A RF Driven Ion Source With Low Fraction Of Co-Extracted Electrons

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Abstract. IPP Garching is developing H^-/D^- RF ion sources for the ITER neutral beam system. On the MANITU testbed the experiments are focussed on long pulse H^-/D^- beam extraction with a 100 kW prototype source. The negative ion production is based on surface conversion of atoms and positive ions on Caesium layers. In long pulses with H^- beam extraction the ion currents were stable but with too high fraction of co-extracted electrons. The electron current could be lowered considerably by avoiding copper impurities from the Faraday screen in the plasma which was achieved by coating of the inner surfaces of the source with Molybdenum. A positive bias potential with respect to the source applied to the plasma grid, the bias plate or to a metal rod installed near the plasma grid enables regulation of the electron current during long pulses. In this way low values consistent with the ITER requirements can be achieved without significant loss of ion current.

Keywords: H^-, Ion Source Development, Neutral Beam Heating, ITER, Radio Frequency Ion Source
PACS: 52.50.Dg, 52.50.-b, 52.59.-f, 52.70.-m, 52.80.Pi

INTRODUCTION

In 2007 the RF source was chosen for the reference design for the plasma generation in the ITER neutral beam system. The reasons for this decision were the in principle maintenance free operation, which is expected due to the filamentless discharge, the lower Cs consumption compared to arc sources because of the tungsten free plasma. Last, but not least, the results achieved with a smaller RF source prototype decided the issue, which demonstrated the suitability of an RF driven source to meet the ITER design requirements, concerning operation pressure, extracted ion current density and fraction of co-extracted electrons. But these experiments were carried out with the pulse length limited to less than four seconds and only an extraction area of ~70 cm^2 [1].

The long pulse “MANITU” test facility (multi ampere negative ion test unit) was built in order to demonstrate that the ITER requirements are also achievable in long pulses up to CW operation and with an enlarged extraction area.

It was found, that the negative ion current density at the same power did not change substantially, when the extraction area was enlarged by almost a factor three (to 206 cm^2) [2]. After various technical modifications of the source and the testbed it was possible to perform pulses up to 3600s [3]. The ion current was remarkably constant, but the fraction of co-extracted electrons could not be kept on the low level known from short pulses. Within the first 100 s to 150 s the electron current increased, exceeded the ion current and reached a constant but too high level. The subsequent high power load on the extraction grid was one reason that prevented operating the source with high RF power; the other one was damage to the RF antenna from RF breakdowns.

This paper will concern itself mainly with reduction and stabilisation of the electron currents, with the source modifications aiming for higher reliability at high RF power and with experiments in Deuterium.

THE RF SOURCE

The RF power is inductively coupled into a circular volume of 25 cm diameter (“driver”), out of which the plasma is flowing into the main chamber (b x l x d = 30 x 60 x 25 cm^3) (Fig. 1). The ITER source will have eight of these “drivers”.

The negative ions are produced by conversion of hydrogen ions and atoms on the cesiated surface of the plasma grid. The Cs is evaporated into the source by a Cs oven mounted onto the back plate. The level of the Cs content in the source is detected by measurement of the Cs852 line intensity (neutral Cs). A magnetic filter field of approx. 850 Gcm is used to reduce the electron temperature close to the plasma grid. The negative ions are extracted through 404 chamfered holes of 8 mm diameter in the plasma grid of a 3 grid extraction system. In this paper only extracted ion currents are quoted. The co-extracted electrons are deflected out of the beam by permanent magnets mounted in the second grid (extraction grid). More details of the set-up and of the modifications to the source design and the upgrade of the testbed for long pulse operation in Deuterium are described in [3].

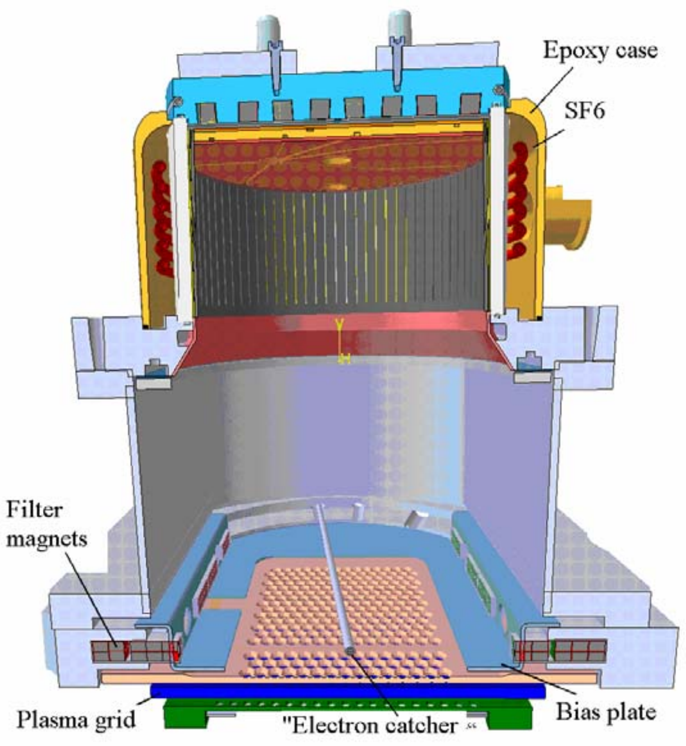

FIGURE 1. Cross section of the RF source

IMPROVEMENTS OF THE SOURCE DESIGN

Particularly in long pulse operation it was observed that after intense operational time all inner surfaces were covered by a thin layer of copper and copper lines were observed in the plasma light. The copper was apparently sputtered from the copper Faraday shield which protects the alumina insulator of the driver from plasma erosion. It was suspected that this would affect the work function and hence the e/H$^-$ ratio close to the plasma grid. To reduce the sputtering the Faraday shield and almost all inner surfaces have been coated with a 3 μm Molybdenum layer. This had great impact on the source performance:

- Almost no more Copper lines and no coatings were found in the source.
- The co-extracted electron current, which was an issue in previous long pulse experiments, now remains stable on a much lower level, in particular during long pulses. This is demonstrated in Fig. 2 by an example of two typical pulses, one before and one after the coating.
- The maximal achievable power efficiency (H$^-$ current density/RF power) simultaneously increased from 0.3 mA/cm^{2}kW to 0.4 mA/cm^{2}kW at 50 kW. At high power the efficiency decreases; however, a maximum extracted ion current of 27 mA/cm^2 has been reached (Fig. 3).

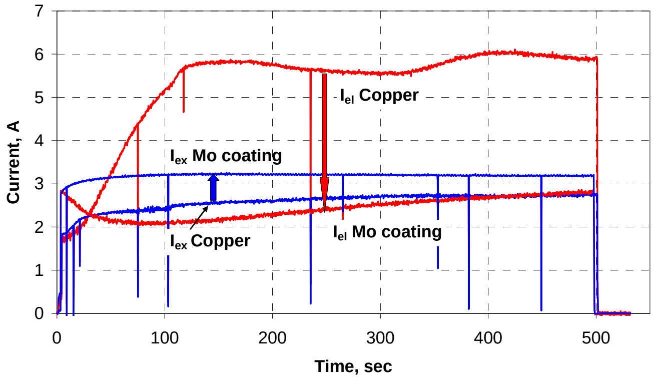

FIGURE 2. The arrows show the effect of the Mo coating of the inner source walls on the currents

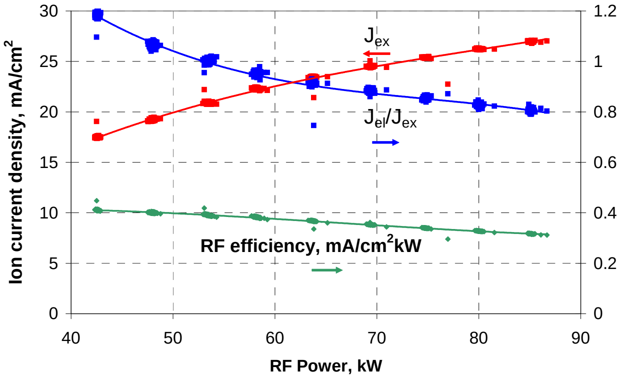

FIGURE. 3. Power scan performed during one pulse in Hydrogen at 0.4 Pa

In Fig. 4 the data of the last experimental campaign with a Mo coating are compared with previous results and show the progress in long pulse operation up to 1000 s, where for the first time an electron fraction below one is achieved, even at ion current densities of about 20 mA/cm^2.

Because of the changed surface conditions the role of the plasma grid temperature has been investigated again. A minimal temperature of 140° is required for the optimal source performance (Fig. 5); a further increase up to 220° has no significant effect on currents extracted from the source.

High power operation in particular in long pulse operation so far suffered greatly from RF breakdowns at the coil, which could happen above approx. 70 kW and can destroy the coil. This will not occur at the ITER source, because there the coil is in vacuum like has been the case for many years at the ASDEX-Upgrade NBI sources. At MANITU the problem was solved by a case made from epoxy resin filled with SF6, in which the coil is immersed (Fig. 1). This enabled to extend the operation range to >100 kW without breakdowns even with long pulse duration. Unfortunately this modification could so far not be tested with a well conditioned source, and so the maximal power was still limited by the electron current which in this case increases rapidly at high power.

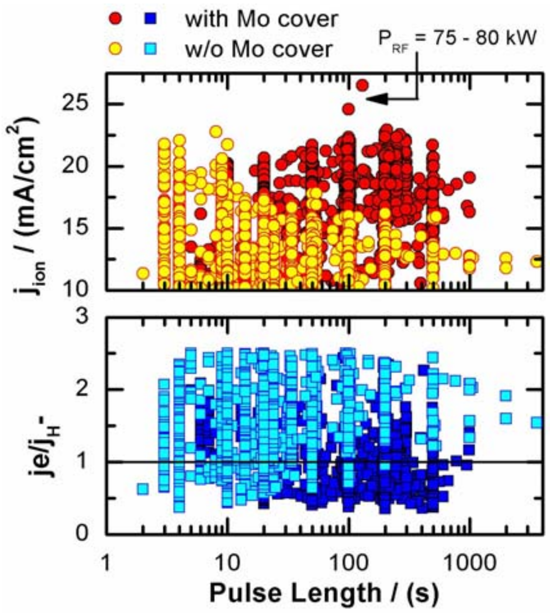

FIGURE 4. Comparison of the H$^-$ current density and fraction of co-extracted electrons before and after the Mo coating of the inner source walls, at a RF power of 50 – 60 kW and 0.45 Pa, two pulses with 75 – 85 kW

CS HANDLING

To achieve high H$^-$ currents by surface production it is necessary to generate a homogenous Caesium layer on the plasma grid surface. Many pulses are needed to distribute the Cs into the source. Parameters to control this "conditioning" are the Cs-oven temperature (evaporation rate), the wall temperature (Cs inventory on the walls) and the pulse length. Beam extraction can be useful to release the Cs which is trapped on the back plate by back streaming positive ions. This tedious procedure is finished when the electron current is lower than the ion current, and the electron fraction does not increase at high power (Fig. 3) and at low pressure. This indicates that the surface production is dominating the H$^-$ yield.

In arc sources the high Cs

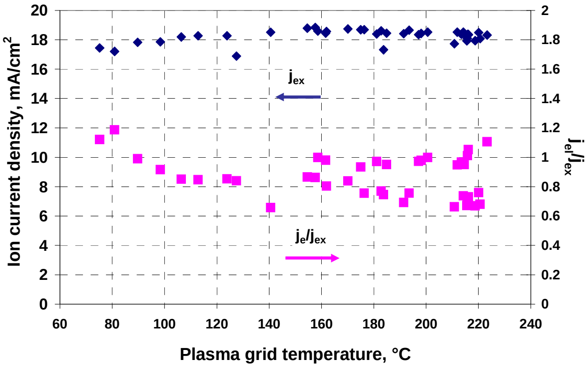

FIGURE 5. Dependence of extracted ion current and the fraction of co-extracted electrons current on the plasma grid temperature at 0.45 Pa and 55 kW

consumption is an issue because the tungsten evaporated from the filaments covers the Cs layers and makes it therefore necessary to evaporate Cs more frequently. The RF source does not have such a problem, apart from sputter products, now avoided by Mo coating, so the Cs consumption is expected to be much less. Unfortunately a common method for the estimation of the Cs consumption does not exist. It depends on the plasma on time, the total time, the evaporation rate and the wall temperatures and the avoidance of the copper sputtering will probably also have an effect. However, in an operation mode with pulse durations from 100 s to 500 s one g of Cs lasted for 12 experimental days within one month, corresponding to 20 hours plasma-on time or 14 µg/plasma-s Cs consumption. This is a pessimistic estimation, because the Cs oven used evaporates not continuously but in single bursts of very much Cs and it is not clear if all of the Cs was evaporated.

Experiments indicate that Cs evaporation during the pulses has no immediate impact on the source performance. In Fig. 6 the Cs is released from the source walls during a 500s pulse by raising the temperature of the cooling water and in this way of the wall temperature from 20°C to 40 °C. The currents did not change during this pulse, but in the next pulse.

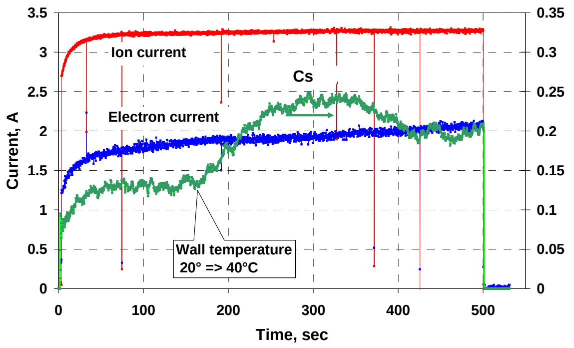

FIGURE. 6 Increasing Cs signal caused by a raised wall temperature

ELECTRON SUPPRESSION

Although the overall current of the co-extracted electrons could be reduced by the Mo coating to a remarkably low level, it can differ from pulse to pulse or even during one pulse due to changes of the surface conditions. Therefore it is still required to be able to control the j_e/j_{H^-} fraction. This can be done in different ways:

- The common method is to apply a positive bias voltage to the plasma grid with respect to the source
- Biasing the “bias plate“ in the same way is a second method
- Shifting a Langmuir probe parallel to the plasma grid into the source reduced the electron current in previous short pulse experiments [4]. This was the motivation to

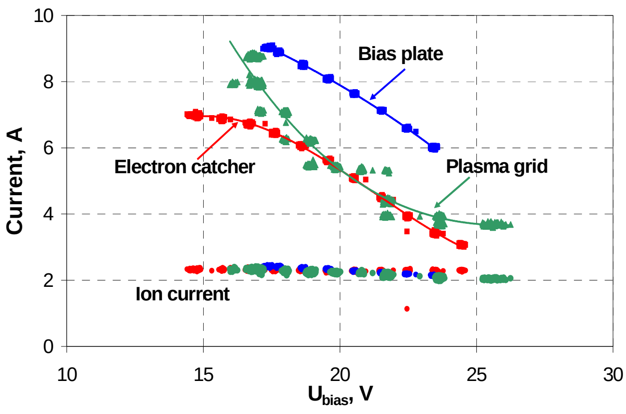

FIGURE 7. Reduction of the electron current by a positive bias voltage applied to the bias plate, the electron catcher or the plasma grid with respect to the source body; each of the scans was performed within one pulse

place a 6 mm metal rod (“electron catcher”) in 2 cm distance from the plasma grid perpendicular to the filter field into the source at MANITU (s. Fig. 1). In this way the electrons which are trapped parallel to the filter field should be removed from the plasma more efficiently.

All these methods have been tested in various combinations. Fig. 7 shows an overview of the results in the case of a badly conditioned source, which is indicated by the high electron current. All methods seem to work and reduce the electron current without affecting the ion current. But no clear preference could be seen, because the differences can at least partly be caused by changes of the surface conditions, which can occur from pulse to pulse and lead to different electron currents.

OPERATION IN DEUTERIUM

Due to the legal restriction of the radiation dose the total beam-on time in Deuterium is limited at the MANITU testbed to 6 h/year [2]. In order to maximize the number of pulses the pulse length has been limited to less than 100 s. This is reasonable, because the currents are more or less stable after this time since the source has been coated with Mo. In addition the beam extraction was pulsed with typically 10s/20s beam/off time. The comparison of two 100 s-pulses in Fig. 8 shows no difference in source performance with and without interruption of the extraction and so for the conditioning the duration of the beam extraction can be reduced. This result is very important for the future Elise testbed [5], for which a pulsed operation mode is planned for technical reasons.

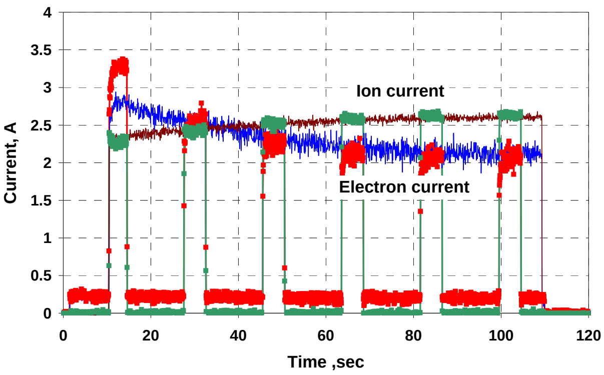

FIGURE 8. Two subsequent pulses in Deuterium with/without interruption of the beam extraction at 50 kW and 0.4 Pa

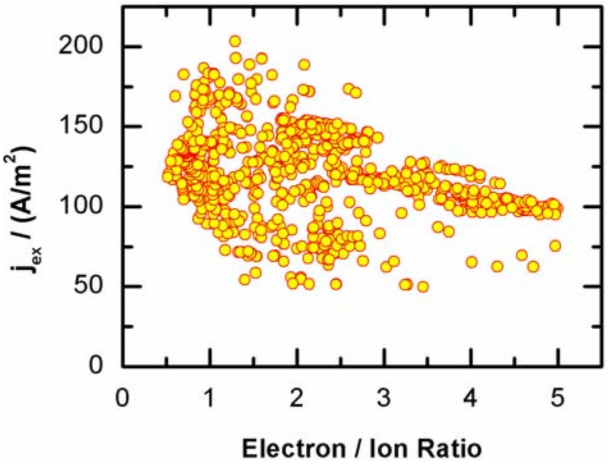

FIGURE 9. Electrically measured ion current density vs. electron fraction in Deuterium at 0.4 Pa and 50 - 60 kW

In previous experiments in Deuterium on MANITU and Batman the electron current was much higher as in Hydrogen. Therefore it was necessary to strengthen the filter field by additional rows of permanent magnets at the sides of the source in order to suppress the co-extracted electrons [1]. After the Mo coating, the electron current is still higher in Deuterium, but it was possible to keep the electron fraction below 1 without changing the magnet configuration (Figs. 8 and 9). Unfortunately it was not enough time to finish the conditioning procedure in Deuterium, which is indicated by insufficient power efficiency and an increasing electron fraction in the beam at high power.

NEXT STEPS

The next step will be conditioning at high power, which is now possible with the improved antenna insulation, with the goal to reach the high ion current density according to the ITER requirements also in long pulses. Revising of the Cs oven design and investigating the Cs dynamics in the source are further important tasks in order to find reproducible conditioning and operation procedures.

ACKNOWLEDGMENTS

This work was supported by a grant (#TW6-THHN-RSFD4) from the European Union within the framework of EFDA (European Fusion Development Agreement). The authors are solely responsible for the content.

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