

# **Long pulse large area beam extraction with an RF driven H<sup>+</sup>/D<sup>+</sup> source**

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*IPP Garching is heavily involved in the development of the RF driven H<sup>+</sup>/D<sup>+</sup> ion source for the ITER NBI. After the successful demonstration of the required physical parameters, the experimental conditions have been extended to long pulses and large area beam extraction. This paper contains descriptions of the source and power supply modifications necessitated for long pulses as well as the latest results including the first one hour pulse. Suppression of the co-extracted electron current is a key issue. Experiments with potential control, different magnetic filter fields and caesium handling to suppress the electrons and stabilise the currents are also reported.*

## **Introduction**

Compared to the RF source the widely used arc sources have two main disadvantages in particular for long pulses and negative ion production: much shorter maintenance intervals necessary to replace the filaments and high caesium consumption due to the evaporated tungsten from the filaments. A smaller prototype has already exceeded the ITER requirements with respect to current density, pressure and electron content [1]. For these reasons the electrode less RF source has been chosen for the reference design for the plasma generation in the ITER neutral beam system. The results were achieved on the “Batman” testbed for an extraction area ( $\sim 70 \text{ cm}^2$ ) that is smaller than the ITER grid ( $2000 \text{ cm}^2$ ) and with the pulse length limited to less than four seconds.

On the MANITU testbed (multi ampere negative ion test unit) at IPP the beam extraction experiments are focussed on larger extraction area ( $206 \text{ cm}^2$ ) and pulse duration extended to up to 3600 s as required for ITER. Currently MANITU uses the same type VI-1 ion source as Batman [1] where the RF power is inductively coupled into a circular “driver” volume of 24 cm diameter out of which the plasma flows into the main chamber ( $b \times l \times d = 30 \times 60 \times 25 \text{ cm}^3$ ). In the ITER source it is planned to use eight of these drivers to support a source area of  $1.5 \times 0.6 \text{ m}^2$ .

### *Set-Up*

The modifications to the source design for long pulses are aimed at temperature control of all surfaces which are exposed to the plasma. This includes active cooling of the Faraday shield (protecting the insulator that forms the driver wall from the plasma load) and cooling of the side wall and back plate by temperature controlled water in order to prevent caesium trapping (Fig. 1).

The RF generator is 1 MHz and rated for 180 kW for CW operation. However, as the pulse length has been increased, weaknesses in the design of the connections, transmission lines, and the insulating transformer have become apparent. A concerted effort has been made to improve all these aspects of the RF system. All connections are now solid strips of considerable width as opposed to cable connections and where possible straps are used instead of cables, cooling has been added where necessary. Usually RF matching is done by a remotely controlled capacitor in the source circuit, but it has been demonstrated, that alternatively additional variable capacitors in the generator RF circuit can be used for matching by frequency change. This would avoid the remote controlling system at the ITER source [2].

New CW HV power supplies for extraction and acceleration voltage (max. 9 kV and 23 kV respectively) controlled by a unique dual tetrode system are in routine operation.

As a result of these modifications long pulses without thermal disruption of the source or RF power supply have been achieved. The key issue for stabilizing long pulses is control over Cs injected into the source to enhance negative ion production. To improve the situation remote control of the oven temperature has been installed, allowing change of the evaporation rate during long pulses.

A long pulse calorimeter that enables beam profile measurements has been commissioned only recently, therefore we can quote only electrically measured currents in this paper. According to short pulse calorimeter measurements the calorimetric current is expected to be lower by a factor 0.7 to 0.8.

The experiments reported here use a filter field of 1000 Gauß cm produced by rows of 4 x 2 Co-Sm magnets on each side. This set-up was identified in short pulse experiments as being most suitable operation.

At MANITU the plasma grid has 402 chamfered holes ( $r = 8$  mm, Fig. 2) and is temperature controlled by a novel forced air system. Chamfering the extraction holes gives the negative ions produced on the grid surface a more advantageous starting angle for reaching the extraction hole [1]. The advantage of an air cooled grid is that the grid temperature can be kept basically constant during the pulse at around 150°. The air flow is regulated by a control valve. Outside the pulse the flow is kept low enough to allow electrical heaters to warm up the air sufficiently to get the plasma grid to a pre-selected temperature. During the pulse the flow is increased to achieve sufficient cooling and the heaters are turned off. Air cooling is possible in the case of the RF source as the power deposition onto the plasma grid is only a few percent of the RF power.

Two Langmuir probes to measure the ion saturation current are placed close to the upper and lower edge of the extraction area at 20 mm from the bias plate (Fig. 2). Various spectroscopic diagnostics are installed parallel to the plasma grid, the results are reported in [3]. The level of the Cs content is detected by a simple Cs852 line intensity measurement with the line of sight 2.5 cm above the plasma grid.

A so-called bias plate on source potential was introduced covering the outer parts of the plasma grid. The goal was to enlarge the source area with respect to the extraction area which is important for experiments with biasing the plasma grid with respect to the source potential. The plate is cooled with the same temperature controlled water as the source walls.

The test bed pumping is provided by a cryopump which was developed in collaboration with FZ Karlsruhe [4]. Source and calorimeter are neutron shielded allowing 6h/year beam-on time with deuterium.

## ***Results***

To achieve high  $H^-$  currents by surface production it is necessary to generate a 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), beam extraction (releasing of Cs from the back plate by back streaming positive ions) and the pulse length.

After finishing this tedious procedure a power efficiency ( $H^-$  current density/RF power) of  $0.3 \text{ mA/cm}^2\text{ kW}$  has been measured which is consistent with the results on Batman under the same conditions. In shorter pulses a maximum  $H^-$  current density of  $250 \text{ mA/cm}^2$  based on the electrically measured ion current has been achieved.

Previous to the installation of the air cooled plasma grid a continuously increasing co-extracted electron current limited the pulse length to less than 200 s. The simultaneous

increase of the caesium 852 nm light indicated that caesium came off the heated plasma grid. With cooling of the plasma grid the longest pulse length obtained was 3600 s (Fig. 3) - one more of the ITER requirements has been fulfilled. Due to the high current of co-extracted electrons which stresses the extraction grid with a high heat load, the RF power had to be limited to 45 kW in this experiment and hence the ion current density is reduced to 12 mA/cm<sup>2</sup>. However, the ion current showed no signs of degradation and the electron current no further increase. The option to regulate to a constant ion current by the RF power, if necessary, has already been demonstrated in shorter pulses of several 100 seconds.

The increase of co-extracted electron current within the first 150 sec of the pulse remains a critical concern (see Fig. 4). A positive bias of the plasma grid against the source body is widely being used to reduce this current: The plasma potential is normally positive against the source body and the potential drop between plasma and wall controls the current to the respective wall. By increasing the grid bias the potential difference between plasma and plasma grid reduces and an increasing electron current is flowing to the plasma grid. Unfortunately, if the optimum conditions are not achieved in the ion source (e. g. optimum Cs on the plasma grid), it is found that the extracted electron current cannot be reduced sufficiently by increasing the bias, as the extracted current starts to decrease before the electron current reduces to the desired value.

If the caesium conditions are good enough, no biasing is needed. This has been demonstrated on Batman with the small extraction area but has not yet been achieved on MANITU with the large area. It is assumed that further conditioning is needed. Fig. 4 shows as an example the importance of the potential distribution inside the source: If the connection of bias plate to the source is cut, the potential of the plate adjusts itself to a different potential with respect to the plasma and the electron current drops significantly.

The caesium evaporation rate is typically about 10 mg per hour. This is very low compared to arc sources of similar size (180 mg per hour at MANITS [5]), which suffer from the contamination of the Cs layer by evaporated tungsten from the filaments.

It is widely known that in negative ion sources the use of magnetic filter field leads to  $E \times B$  forces to the plasma. In the currently used configuration the plasma density at the top edge of the extraction area is 5 to 6 times higher than at the bottom edge. This asymmetry disappears completely if the magnetic filter field is weakened by 30 % (Fig. 5). However, the negative ion current does not change, which shows that the plasma density close to the plasma grid surface is not the leading parameter for the  $H^-$  current.

During the first preliminary Deuterium experiments the source performance was similar to Hydrogen, but the electron current was higher, demanding an increase in the strength of the magnetic filter field. It is foreseen to continue the Deuterium experiments at the end of this year.

### *Next steps*

For a faster Cs evaporation control during the pulse a shutter between Cs oven and source will be introduced. The experiments for the optimization of the bias plate and plasma grid potential will be continued. During long pulses sputtering of the copper Faraday shield can be a problem, therefore a Molybdenum coating like it has been successfully tested at Batman is under way.

### *Summary*

The RF source design and the RF power supply have been successfully upgraded for long pulse operation. The efficiency for  $H^-$  production remained unchanged with the enlarged extraction area. The first one hour pulse with  $H^-$  beam extraction has been performed,

showing stable ion and electron currents. Suppression of the co-extracted electrons and Cs handling in long pulses is still an issue. For this purpose the conditioning procedure for the Cs layer on the plasma grid and the potential distribution inside the source together with the magnetic field has to be further optimized.

## References

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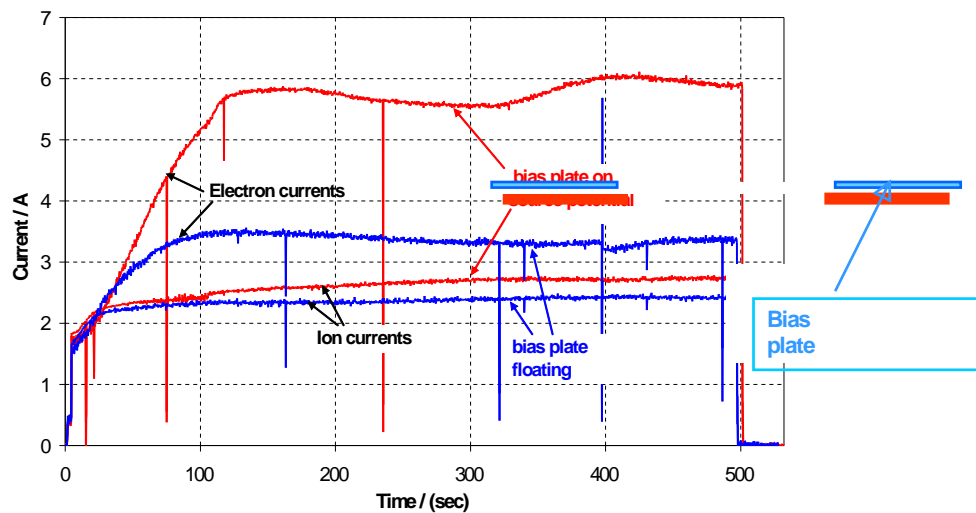
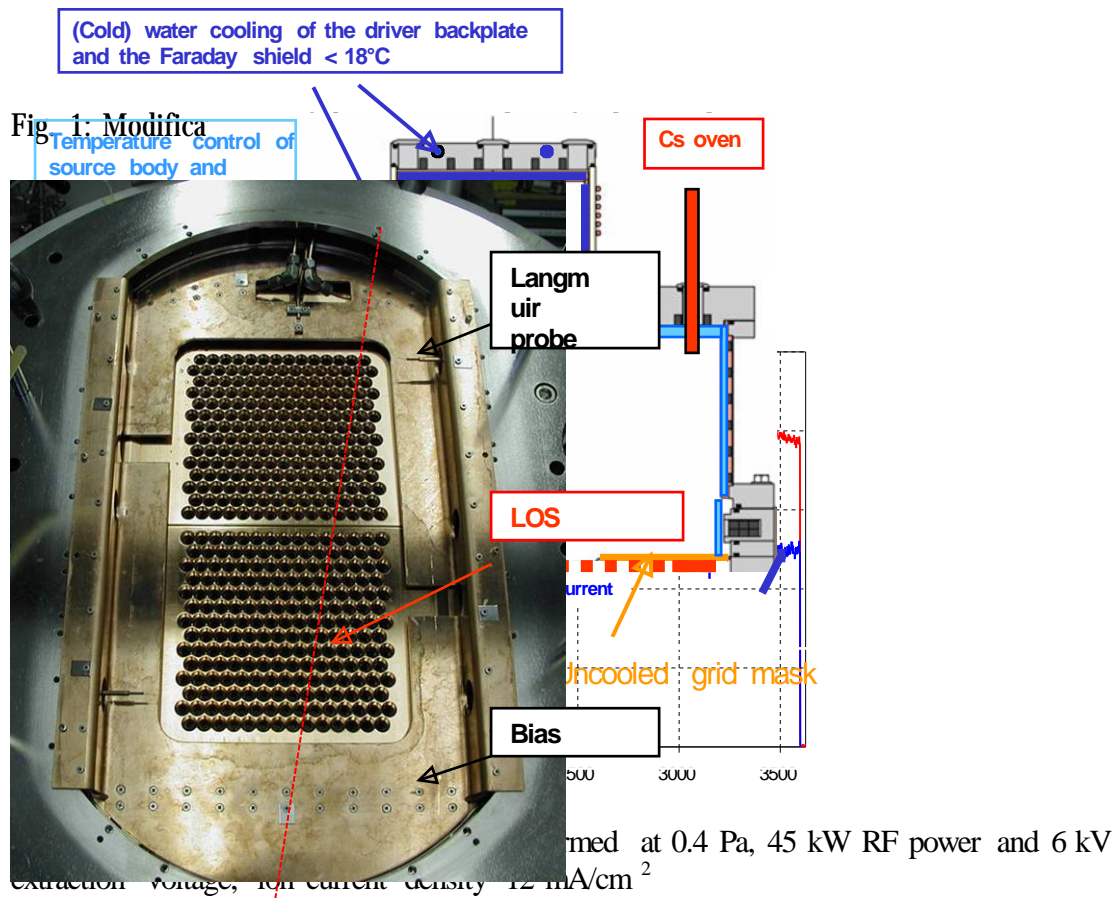


Fig. 4: Beam pulses at 50 kW and 0.4 Pa with bias plate floating and on source potential respectively, the bias current was in both cases the same

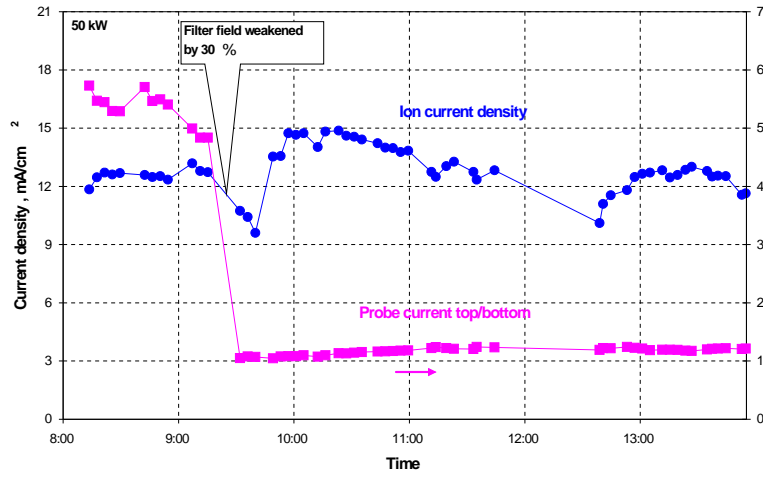


Fig. 5: Symmetric plasma density after reduction of the magnetic filter field strength.