Possibilities for further optimizing the H^-/D^- RF source

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1. Introduction

RF sources for the production of positive hydrogen ions have been successfully developed at IPP for the AUG and the W7AS neutral beam heating systems [1], [2]. A collaboration on high frequency ion source development for negative hydrogen ions between CEA Cadarache and IPP Garching had been started in 1996 with first results reported in 1998 [2]. Compared to arc sources RF sources have less parts, requiring just a source body, an RF coil, and a matching transformer and are therefore cheaper to build and basically maintenance free in operation. The simple design is potentially quite beneficial for ITER with its remote handling requirements. In contrast to the arc sources RF sources do not require regular maintenance to replace worn out filaments. Furthermore it is being speculated, that the arc current of the arc sources might contribute to the plasma non-uniformity observed in the large arc sources [3]. Since September 2002 the development of the RF source is being supported by an EFDA contract aimed at demonstrating that the ITER requirements can be met. The ITER targets for current density, source pressure, and co-extracted electron fraction could already be achieved or exceeded. Further improvements are mainly aiming at improved efficiency and reliability.

The present paper is to some extend of a speculative nature with the aim to provoke discussions under the workshop participants.

2. Cesium Handling

Cesium is dispensed into the IPP RF source continuously during operation at a rate of approximately 10 – 20 mgr/h. Typical pulse cycles are 5 s plasma duration every 3 – 4 minutes. During maintenance at which the source is exposed to air we normally do not attempt to remove the cesium from the source. After the opening, the source efficiency improves continuously with ongoing operation as fig. 1 shows. During the period shown in fig. 1 approximately 650 mgr of cesium had been dispensed. The source efficiency, defined as the electrical current density to ground divided by extraction area and RF generator power, improves both during the experimental day and from day to day. Frequently the source is less efficient at the start of the day. It is assumed that this is due to contamination of the cesium during the night (the vacuum box is contaminated from previous operation with oil diffusion pumps). From fig. 1 we conclude that the Cs distribution is becoming more favorable with ongoing operation. However within the data shown in Fig. 1 there are cases, where one observes an improving performance with ongoing Cs evaporation (fig. 2), but also an improved performance, when Cs dispensing is stopped (fig. 3).

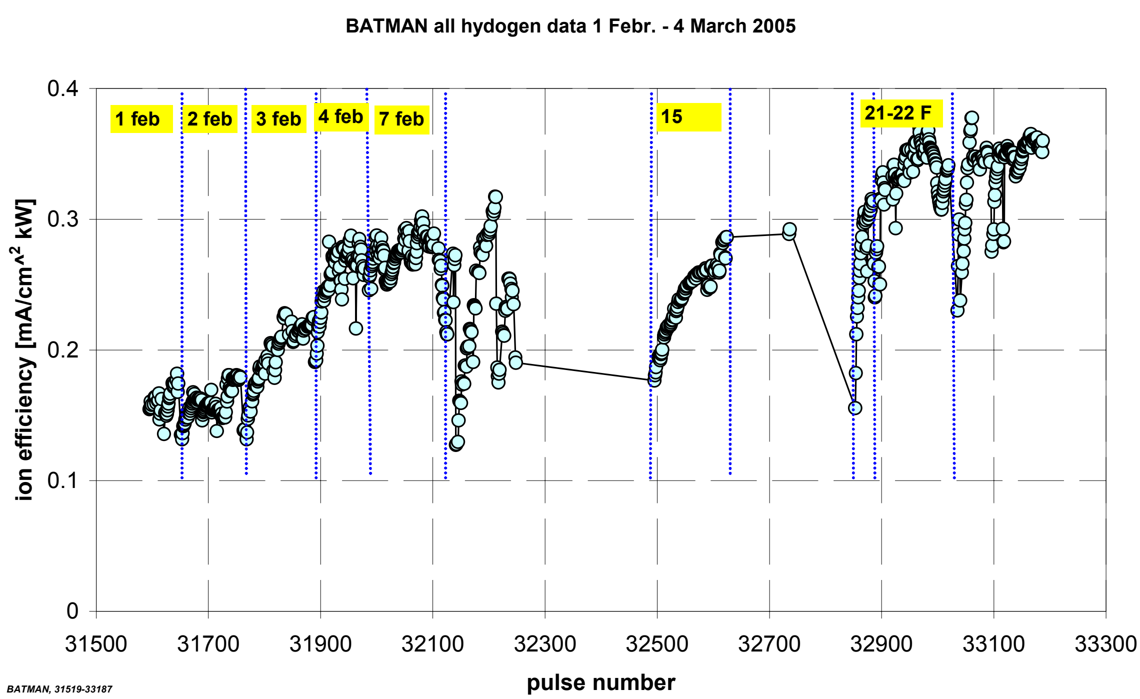


Fig. 1: Ion source efficiency j_{ion}/P_{RF} for H^- as a function of pulse number for a source conditioning period after exposing the source to air.

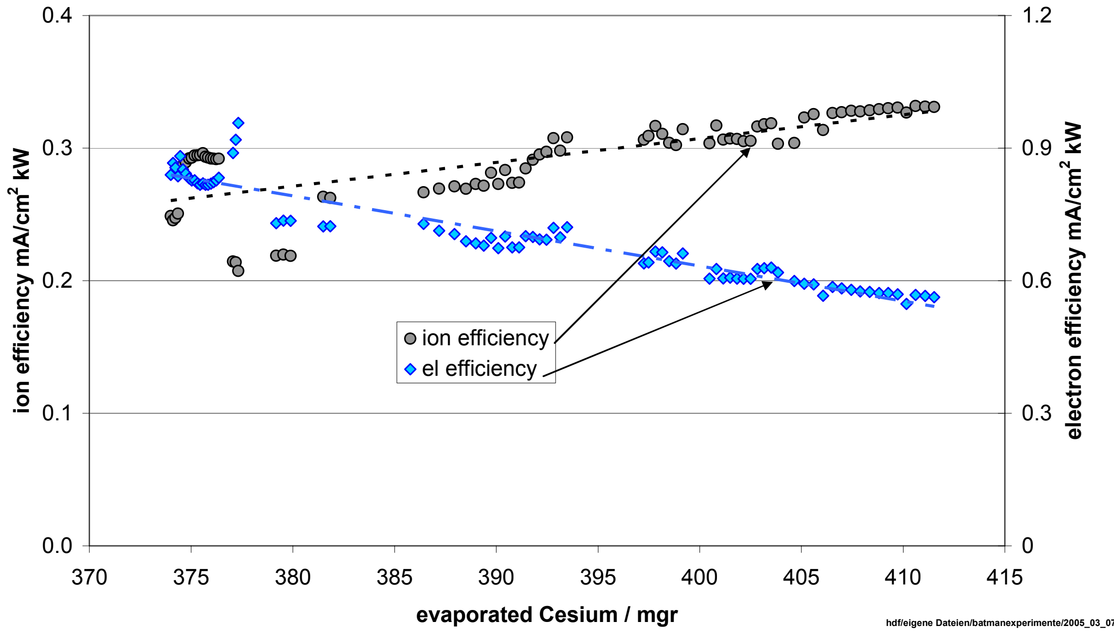


Fig. 2: Ion- and electron source efficiency as a function of the dispensed cesium. The data are part of the dataset in fig. 1.

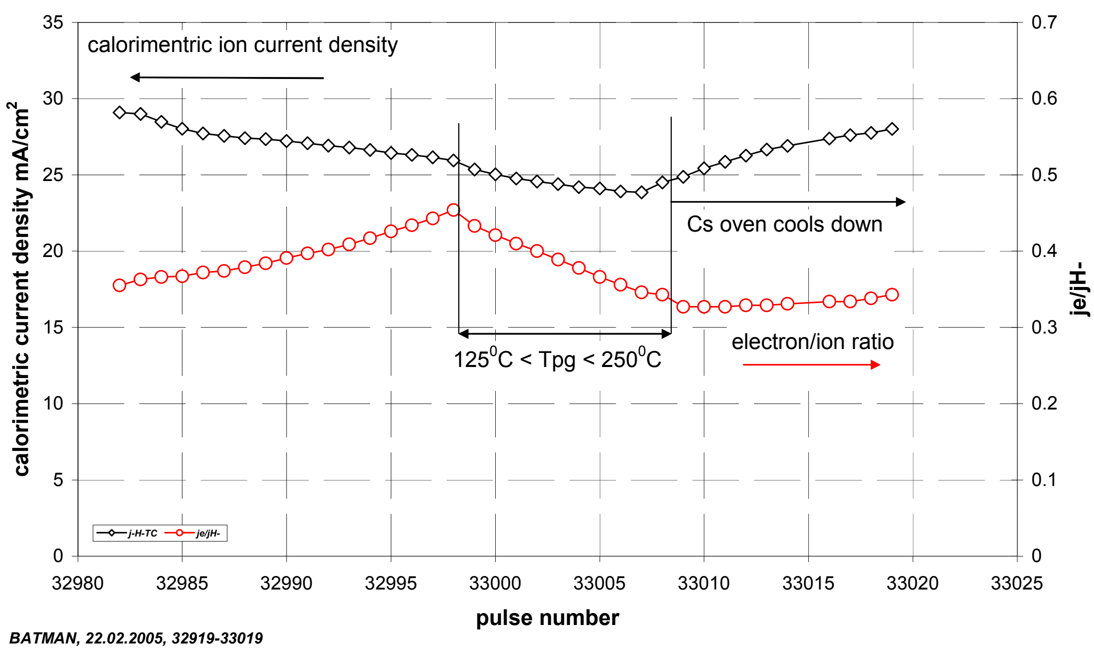


Fig. 3: Calorimetric current density and electron to ion ratio as a function of pulse number showing deteriorating performance left, improving performance with increasing plasma grid temperature(middle) and improving performance after stopping Cs dispensing.

When exposed to air the cesium reacts and forms a black compound. From these deposits one can deduce where the cesium is being stored in the source. In the case of fig. 4 (left) we see dripping marks from the top to the driver and metallic clean areas along the cusp lines of the confinement magnets with dark areas in between (fig. 4 right). From that we conclude that cesium can accumulate in cold areas where the removal rate by the plasma is not sufficient. This is likely to cause problems, when too much cesium has accumulated and flows into an erosion area thus causing an uncontrolled cesium release.

Fig. 4: View into the cesiated RF source after exposure to air. The cesium oven was located at the top above the dripping marks.

Cesium distribution in the source can be influenced through plasma grid temperature, source body temperature and rate of dispensing. To speed up the conditioning of the source and to stabilise the performance during long pulses we intend to:

- stabilise the body temperature by a cooling/heating loop with adjustable temperature,
- stabilise the plasma grid temperature through either a gaseous or liquid cooling medium which allows to regulate the grid temperature for extended pulse duration.
- install an additional fast acting cesium dispensers based either on SAES dispensers or on a cesium oven with fast acting remotely controlled valve and use feedback control for the cesium release rate.

3. Configuration of filter and confinement magnets

The IPP type 6.1 source consists of a race track shaped body with deep drilled cooling channels. The filter magnets are housed in internal grooves of a flange sitting between source and accelerator (fig. 5). Confinement magnets are attached to the outside of the body, normally forming a cusp field. The filter field can either be increased or reduced by using the same or the opposite polarity of the filter magnets for the first cusp line next to the filter magnets. Alternatively the filter field can be modified by adding additional external magnets which again either reinforce or weaken the filter field. Although the system is quite flexible, results are often misleading as a change in the magnet configuration also affects the flux and distribution of cesium in the source. Nevertheless there is some affect as shown for a hydrogen discharge in fig. 6. The source efficiency for ions and electrons drops when the first cusp row of the confinement magnets is reinforced, but there is a net gain in the electron/ion ratio. The highest source efficiency is obtained with two sets of confinement magnets on top of each other with a small penalty in increased electron to ion ratio.

For deuterium the degree of variation available through external magnets is not quite sufficient for suppressing the electron current to an extend that the maximum ion current density is no longer limited by the power deposition of the co-extracted electrons on the plasma grid. After several water leaks we restricted the average power deposition to 2 MW/m^2

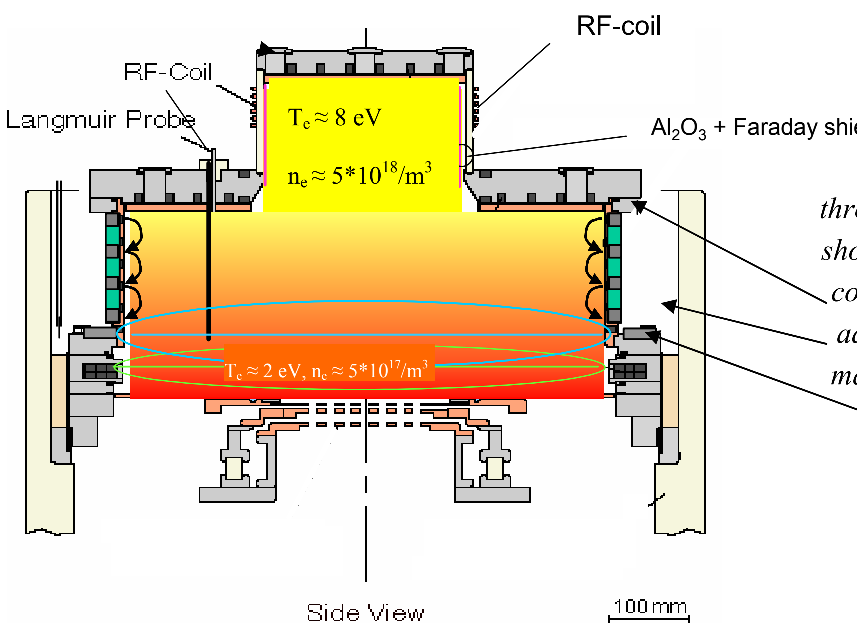


Fig. 5: cross section through the type 6.1 source showing the location of the confinement magnets, the additional external filter magnets, and the internal filter magnets

of projected area including the grid holes.

A further reduction in electron current would be beneficial, as it would either allow to optimize the beam optics by operating with a higher extraction voltage or to increase the availability of the system. In the case of the RF source we assume that the spacing between the filter magnets is with 320 mm too large and the ∫Bdl with 0.5 mTesla m is too small for effective electron suppression. We will therefore locate the filter magnets closer together. For a source with the ITER dimensions a combination of external magnets plus PG filter is probably not fully satisfactory.

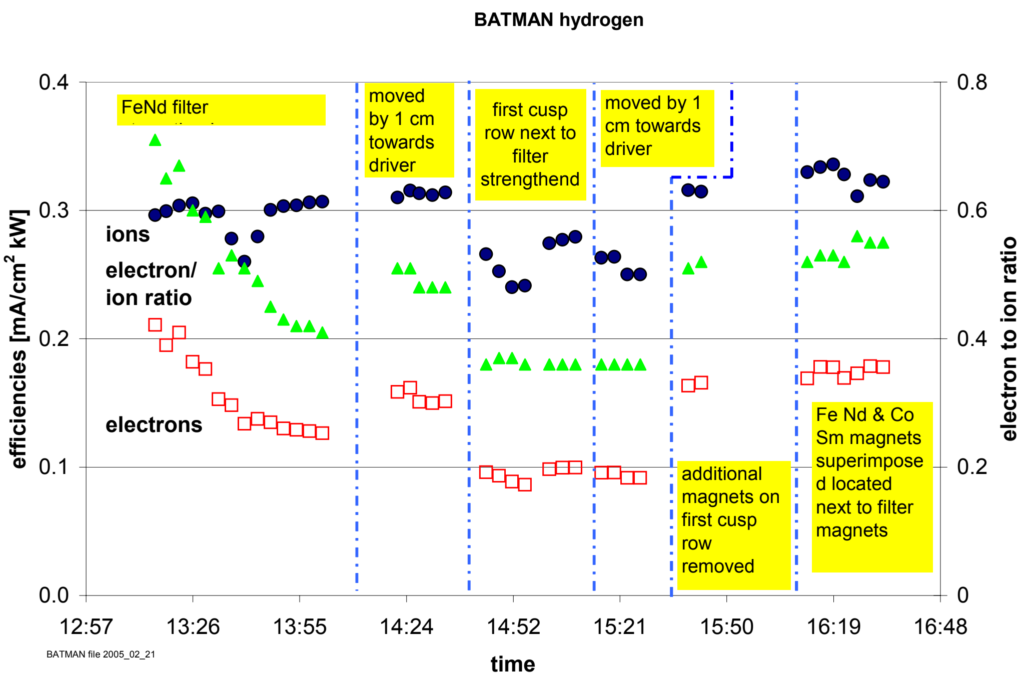


Fig. 6: source efficiency for extracted negative ions and electrons for different magnetic configurations.

4. Ion extraction

The calorimetric current varies considerably stronger with extraction voltage than expected. This is demonstrated in fig. 7 showing the current flowing to ground (corresponding the extracted ion current) and the current to the extraction electrode (corresponding to the co-extracted electrons). With increasing extraction voltage the ion current increases strongly and the electron current falls up to a voltage of roughly 9 kV. Plotting half the sum of ion and electron current we get a slope which is very similar to the slope one gets from modeling calculations. The scan in fig 7 was done with constant RF power. Varied was the total high voltage so that extraction and acceleration voltage kept roughly the same ratio. A reducing electron current with increasing extraction voltage looks strange and the observation that the slope of the sum of electron and ion current is as expected from modeling indicate that some of the "*electron*" current was rather ions hitting the extraction electrode. This means that an extraction voltage of 9 kV is required to get the ions passing the extraction electrode. An ion current of 1.5 A in Fig. 7 corresponds to a calorimetric current density of 20 mA D^{-}.

Also shown in Fig. 7 is the beam half width on the calorimeter, 1.5 m down-streams of the accelerator, which does not reflect the fact that the beam is scraped.

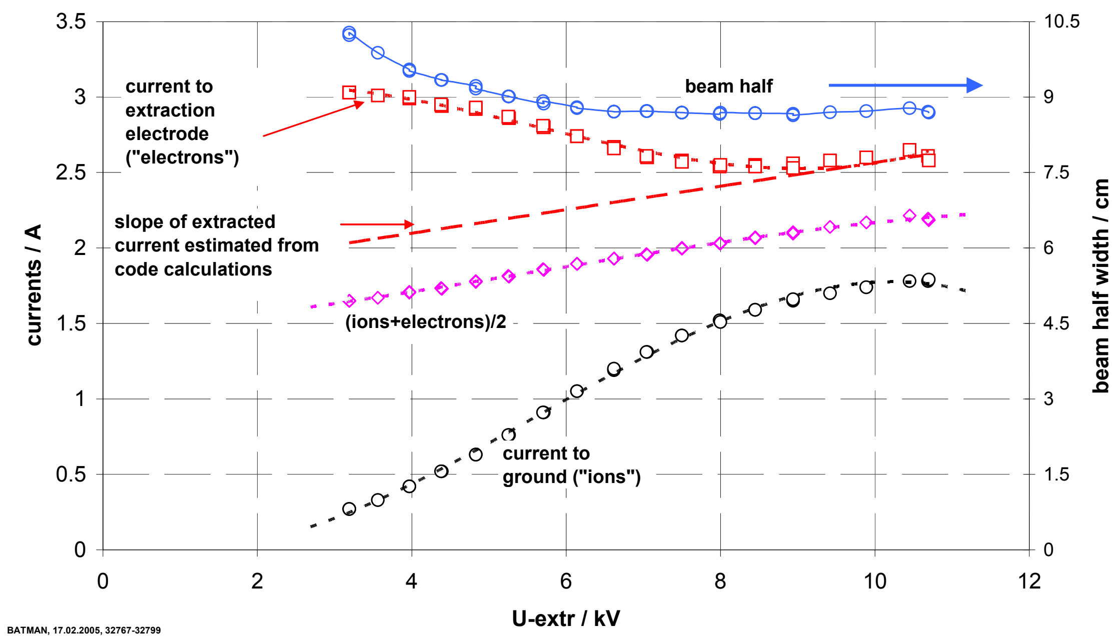
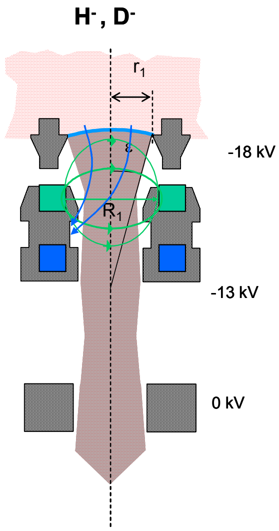


Fig. 7: Currents to ground and extraction electrode as a function of the extraction voltage. The acceleration voltage varies proportional to the extraction voltage. Also shown is the beam half width, half of the sum of both currents and the slope derived from modelling calculations.

A typical beam extraction system for negative ions is shown in fig. 8. The extraction electrode houses the magnets for deflecting co-extracted electrons and cooling channels and is therefore roughly 10 mm thick. The distance between plasma electrode and extraction electrode is just of the order of 3 – 4 mm to keep the extraction voltage and the power loading of the extraction electrode low. However for an efficient extraction of negative ions it appears beneficial to push the plasma backwards into the source. This leads to an initially converging beam with a beam waist near the extraction electrode. In the extraction electrode there is little



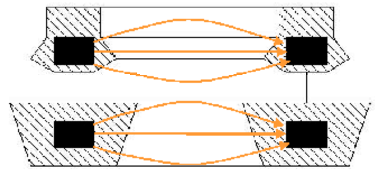
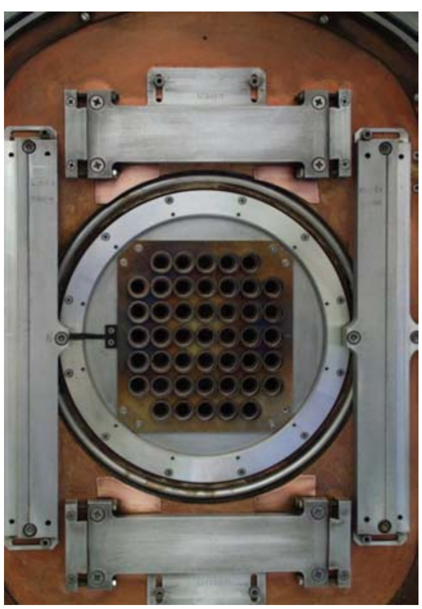


Fig. 8 (left): Schematic of a beam extraction system for negative ions.
Fig. 9: Electron deflection magnets spread over plasma and extraction electrode.

electrical field and the beam is blown up by its space charge and the electrostatic lens effect at the entrance of the extraction electrode. If the electrical field in the accelerating gap is high the beam is to some extend bent back during acceleration. If the thickness of the extraction electrode could be reduced and the bore increased, there would be more field penetration and the effect would be reduced. One possibility might be to split the bending magnets for the co-extracted electrons between plasma and extraction electrode (fig. 9). Furthermore a thinner extraction electrode would also reduce stripping losses.

5. Shape of the plasma grid



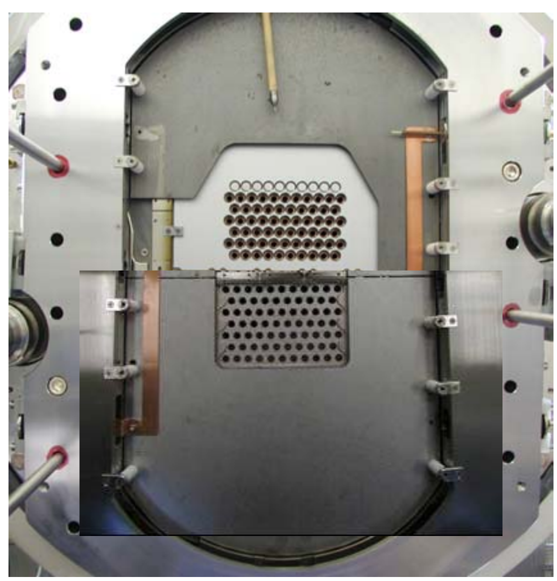


Fig 10: View on the CEA plasma grid used up to early 2003, the plasma grid used between April and November 2004 (right bottom) and the grid used from December 2004 onwards (top right).

In accelerator applications collars are used to increase the negative ion yield. In a multi aperture source there is little space but one can vary the shape of the aperture to some extend. In the IPP type 6.1 source we have added a 2 mm Mo plate with chamfered holes onto the plasma side of the plasma grid (fig. 10). This modification was done together with others such as increased distance of the extraction holes from components such as PG electrical heater and the so-called bias plate. Additionally the source was slowly conditioned with cesium in December 2004 and then left under vacuum until the mid January 2005. After restart in January the ion efficiency was improved, compared with the performance in 2004, as shown fig. 11. The 2005 data are improved by typically 20%. So far it is unclear which of the modifications caused the improvement, but it is unlikely that the increased surface on the plasma electrode has a negative effect. It should therefore be possible to increase the thickness of the plasma electrode so that space for some deflection magnets could be gained.

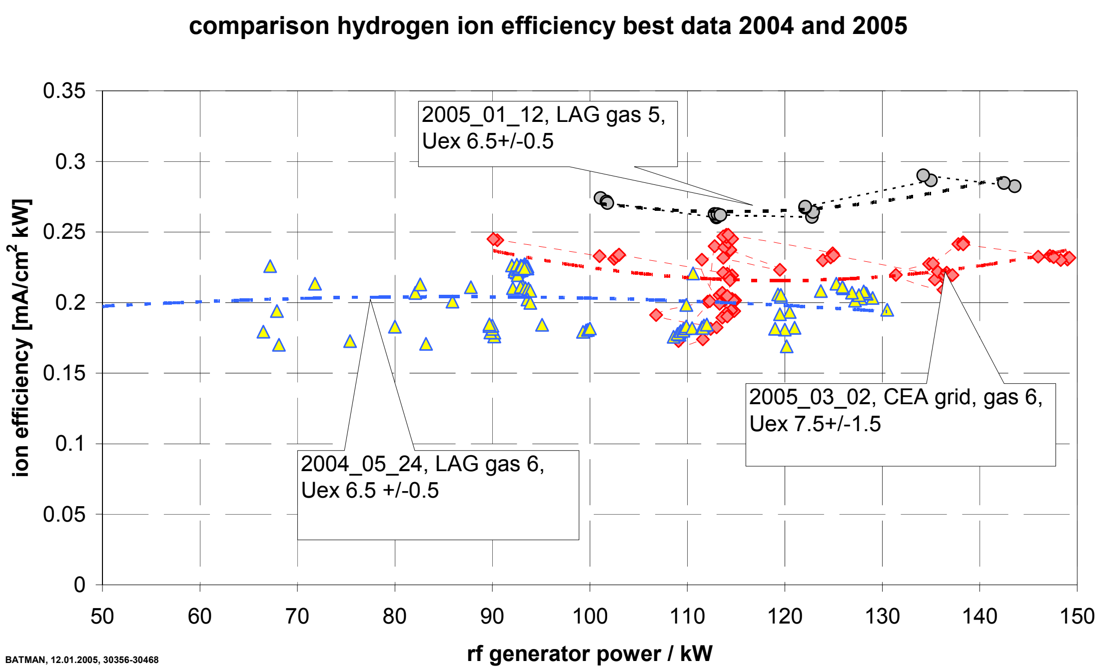
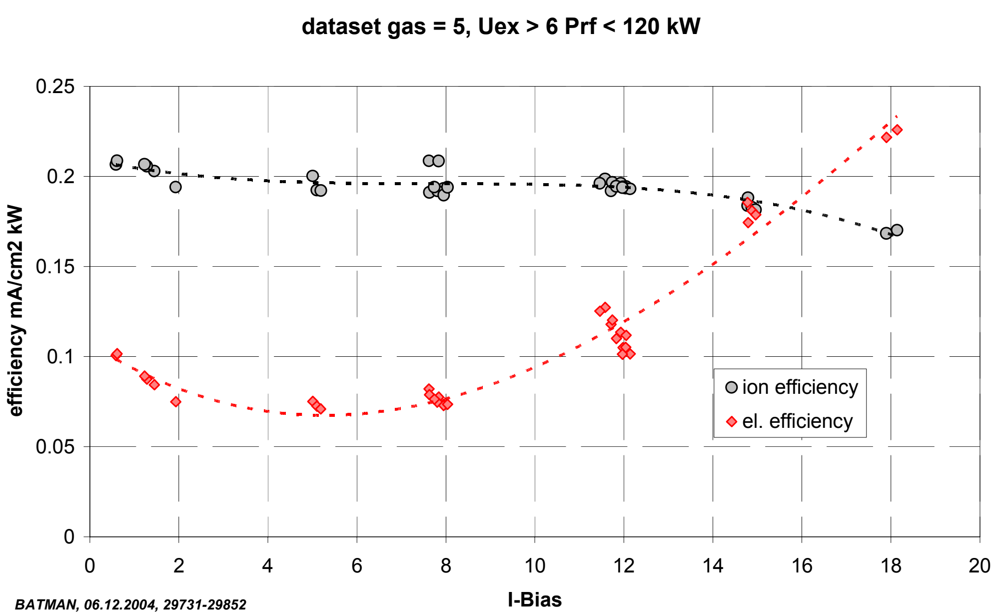


Fig. 11: ion efficiencies as a function of the generator power for the 2004 LAG accelerator-, the 2005 LAG accelerator, and the CEA accelerator- setup. Gas x gives the valve setting which closely corresponds to the filling pressure in steps of 0.1 Pascal.

6. Bias Voltage

Normally it is found in negative ion sources, that a positive bias voltage of the plasma grid against the source body reduces the co-extracted electron current. This was also the case for the RF source until lately we found that if the source operates well we get the lowest co-extracted electron current when the bias current is just above zero. Increasing the bias current increases the co-extracted electron current and reduces the ion current (fig. 12). We also observe, that the bias current falls sharply when extraction starts, and that this reduction in bias current corresponds to the extracted current to ground (ion current) (fig. 13). Both observations indicate that the plasma next to the plasma grid consists mainly of positive- and negative ions. Normally it is argued that the positive bias sucks electrons away, and one would expect that the bias current is carried by electrons and negative ions. If the electrons were a minority one would mainly suck ions away and consequently reduce the extracted ion current. Similarly if the bias current is mainly a negative ion current it will be reduced by the extracted ion current.



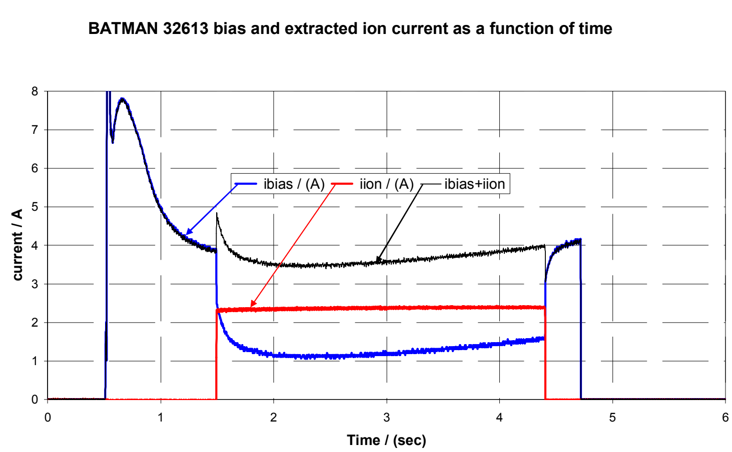


Fig. 12 *(top): Source efficiency for ions and electrons as a function of the bias current to the plasma grid. The grid is biased positively against the source, the current is carried by negative charges.*

Fig. 13*: Time traces of bias (blue) and extracted ion current (red). Also shown is the sum of both currents (black).*

7. Ion deflection

Even in operation with a neutralizer and therefore reduced conductance between source and vacuum box we observe a reduction in beam width with increasing pressure in the vacuum box (fig. 14). This means that the extracted beam is not fully space charge neutralized. As long as the beam reaches the calorimeter this is not a problem, however one has to take this beam blow-up into account when one extracts a beam divergence from the measured profiles on the calorimeter. The fact that a considerable fraction of the negative ions is not neutralized on the way to the calorimeter makes the calorimetric current measurement sensitive against ion deflection from stray electrical fields as was for example in the past the case at IPP when it was observed that the calorimetric ion current could be increased substantially by adding argon to the hydrogen source gas [4]. The effect of the argon was mainly an increase in tank pressure (titanium getter pumps) thus helping to neutralize the H^- ions and therefore avoiding deflection caused by electric stray fields between accelerator and calorimeter.

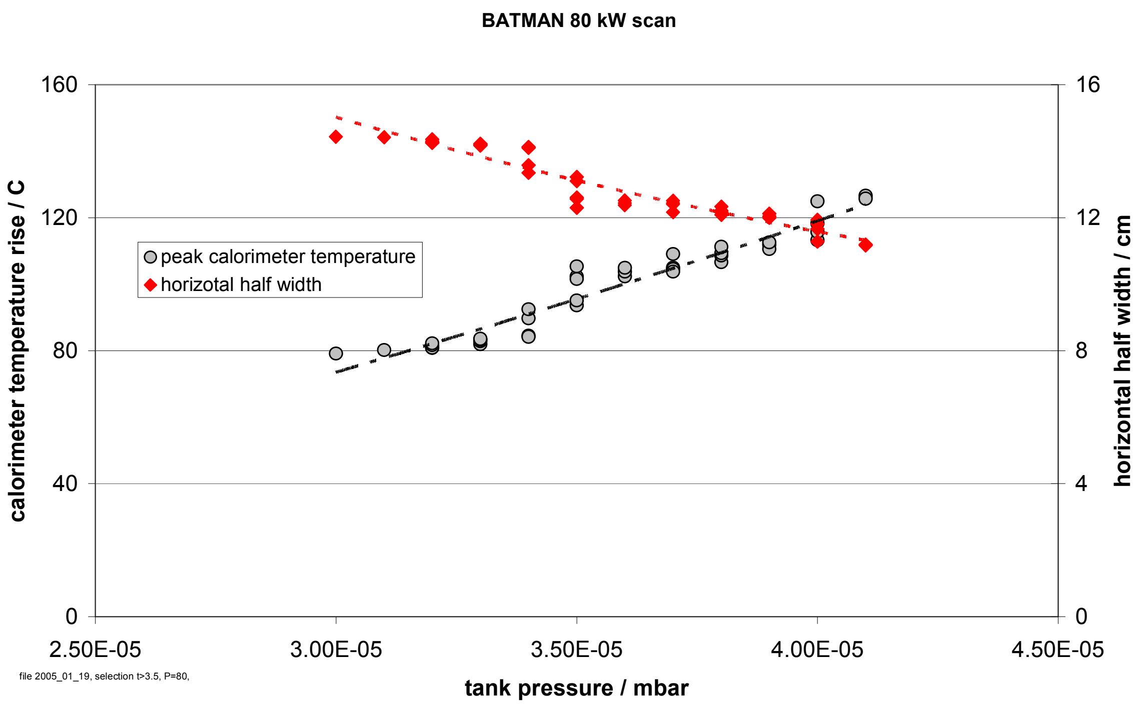


Fig. 14: peak thermocouple temperature (grey circles, left scale) and beam half width (red diamonds and right scale) on the calorimeter as a function of the tank pressure.

8. Summary

Although the IPP RF source already meets the ITER requirements in terms of current density and operating pressure, further improvements are desirable to increase the operating space and the source reliability.

By controlling the temperature of the source walls and by adding a fast acting cesium oven we will attempt to speed up source conditioning and to control source efficiency.

By an increased spacing of the extraction area from other source parts and by shaping the surface of the plasma grid reliable operation with high D^- currents could be obtained. Further optimisation is required to reduce co-extracted electron currents without affecting the source efficiency.

Ion transport could be improved and stripping losses reduced by reducing the height of the extraction electrode.

In a well conditioned source RF source best results are obtained with a bias of the plasma grid near the floating potential.

References

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