Physical Performance Analysis And The Progress Of The Development Of The Negative Ion RF Source For The ITER NBI System

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Abstract. For heating and current drive the neutral beam injection system for ITER requires a 1 MeV deuterium beam for up to 1 h pulse length. In order to inject the required 17 MW the large area source (1.9m x 0.9m) has to deliver 40 A of negative ion current at the specified source pressure of 0.3 Pa. In 2007 the IPP RF driven negative hydrogen ion source was chosen as the new reference source for the ITER NBI.

Although the IPP RF source has made substantial progress towards ITER's requirements in the last years there are still open issues to be addressed. Apart from the homogeneity of such a large RF source and the long pulse stability, a very critical factor is the amount of co-extracted electrons limiting also the maximum achievable ion current density. For all these issues, the control of the plasma chemistry and the processes in the boundary layer in the source are the most critical item as cesium evaporation is needed for the production of negative hydrogen ions in sufficient quantities. The development efforts at the IPP test facilities are now focused on the achievement of stable long pulses at the test facility MANITU and on demonstration of a sufficiently homogeneous large cesiated RF plasma operation at the large ion source test facility RADI. MANITU is operating now routinely at stable pulses of up to 10 min with parameters near the ITER requirements; RADI demonstrated that a pure deuterium plasma is sufficiently uniform. Overall objectives are to identify tools for control of the source performance. The performance analysis is strongly supported by an extensive diagnostic program and modelling of the source and beam extraction. As an intermediate step between the MANITU and the NBTF RF source, IPP is presently designing the new test facility ELISE for long pulse plasma operation and short pulse, but large-scale extraction from a half-size ITER source; commissioning is planned for 2010.

1. Introduction

The development of large Cs seeded negative hydrogen ion sources for the ITER NBI system [1] was started in the early 90's in Japan with filamented arc sources as the basis for the design. Due to the advantages of the RF source — it is in principle maintenance-free — and due to the good experience with the positive ion based RF sources [2] at the NBI system for ASDEX Upgrade and W7-AS, IPP Garching started the development of a RF driven negative ion source end of the 90's, from 2002 on within a framework of an official EFDA contract. The development was very successful [3-6]: recently, in July 2007, the RF source was chosen by the ITER board as the reference source [1,7,8].

The development of the RF driven negative hydrogen ion source is being done at three test facilities in parallel: current densities of 330 A/m^2 with H$^-$ and 230 A/m^2 with D$^-$ have been achieved with the IPP RF source on the small test facility BATMAN (Bavarian Test Machine for Negative Ions) at the required source pressure (0.3 Pa) and electron/ion ratios, but with a small extraction area (70 cm^2) and limited pulse length (<4 s) [3]. The long pulse test facility MANITU (Multi Ampere Negative Ion Test Unit) equipped with the same source as it is used at BATMAN but having an extraction area of about 200 cm^2 demonstrated recently stable one hour pulses; the parameters however, are still below the ITER requirements [9]. The ion source test facility RADI, equipped with a source of approximately the width and half the height of the ITER source, aims to demonstrate the required plasma homogeneity of a large RF source [10-12]; RADI, however, has no extraction. Hence, IPP is presently designing a new test facility ELISE (Extraction from a Large Ion Source Experiment) for large-scale extraction from a half-size ITER source.

The performance of the source, given in terms of ion current density, amount of co-extracted electrons, and beam homogeneity, is mainly determined by the Cs dynamics and the interplay of the processes in the boundary layer near the plasma grid. This layer extends several cm’s into the source and its properties depend on the magnetic and electrical field structures as well as on the amount of negative hydrogen ions that are produced at the plasma grid. For stable operation, the IPP RF source is kept at 40 °C and the plasma grid at 150 °C, respectively [3]. For sufficient electron suppression a magnetic filter near the grid as well as biasing the plasma grid with respect to the source is essential. The latter is supported by an additional plate (bias plate) in front of the plasma grid.

The paper discusses the status of the RF source development at IPP Garching and dedicated experiments which are supported by modeling for a better understanding of the processes in this boundary layer.

2. Basic Studies

2.1. Hydrogen/Deuterium Operation

The processes in the boundary layer depend also on the isotope. This can be seen in figure 1 showing a comparison of the BATMAN source performance for hydrogen and deuterium. The internal filter field was in both cases optimized for deuterium operation.

Similar extracted ion current densities and hence source efficiencies are achievable in deuterium than in hydrogen for that special filter field. The reason for that might be the larger ionization and dissociation degree in deuterium — as measured by OES — leading to a larger amount of atoms and ions available for the surface effect [13]. The maximum achievable calorimetric current densities are similar for both cases. This is most probably a consequence of beam optics — being worse in deuterium due to limits in the IPP HV systems — than of basic physical processes.

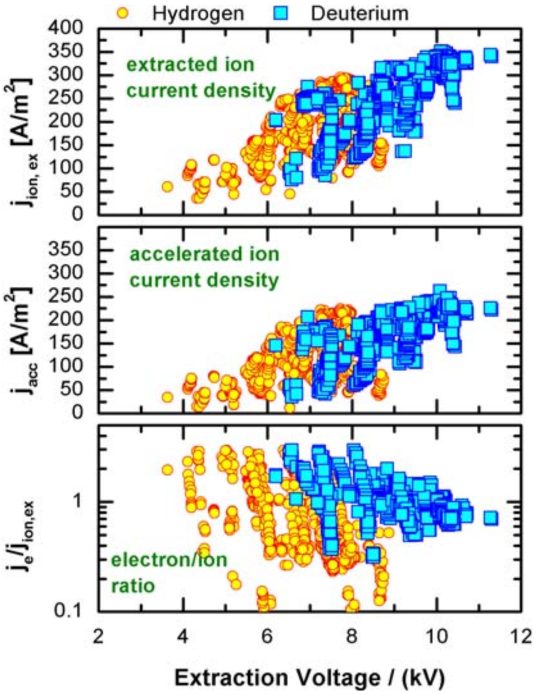

FIG 1. Comparison of hydrogen and deuterium performance at BATMAN.

The amount of co-extracted electrons is larger in deuterium than in hydrogen. This is even more pronounced as the extraction voltage in deuterium needs to be larger (8 kV for H, 10-11 kV for D). The maximum achievable current density is not limited by the production and acceleration of negative ions, but by the amount of co-extracted electrons and hence by the maximum power load on the extraction grid. Thus suppression of the co-extracted electron current seems presently to be the most relevant issue. A larger filter field is needed in deuterium operation which reduces, however, also the negative ion current.

Therefore, other means of a further suppression of the amount of co-extracted electrons and an improved understanding of the boundary layer are highly desirable for a further increase of the ion current in deuterium in order to have some margin for a stable and reproducible operation: presently the ion source performance required by ITER is at the upper limit.

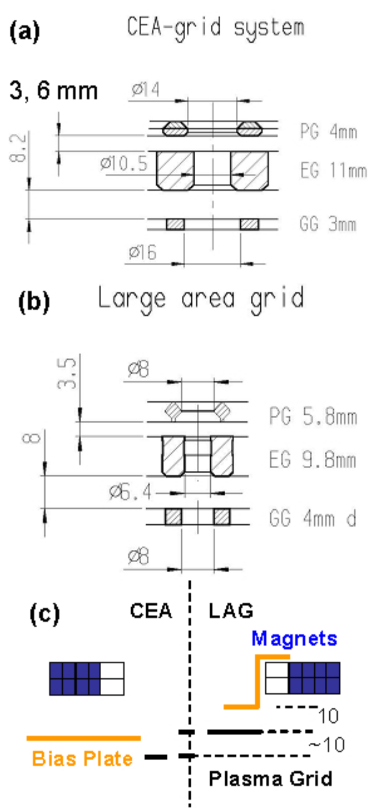

FIG 2. Geometry of the two different grid systems at BATMAN (CEA, aperture diameter 14 mm, LAG, 8mm).

2.2. Aperture Size

Calculations of the extraction probability of negative hydrogen ions with an ion trajectory code [14] showed that the extraction probability depends — apart from other parameters like the magnetic field or the background plasma — on the detailed geometry of the plasma grid. The increase of the conversion area by using chamfered apertures has increased the performance of the RF ion sources [3].

Another open issue is the aperture diameter. The high performance discharges at BATMAN and MANITU have been obtained with the so-called large area grid (LAG) system with 8 mm diameter apertures (figure 2), mainly for cost reduction reasons as spare parts from the positive NBI system at ASDEX Upgrade could be used [2]. ITER, however, foresees up to now apertures of 14 mm diameter for beam optic reasons.

Recent single aperture experiments at the SINGAP test facility [15] showed that the accelerated current density may depend on the aperture size of the plasma grid: the current density increased when reducing the aperture from 14 to 8 mm diameter. In order to countercheck these results with a multi-aperture grid system, an available 14 mm diameter grid system (CEA grid) system was used in BATMAN with chamfered apertures (figure 2). Apart from the different geometry of the electron suppression field in the extraction grid, the distance of the bias plate differs, and the distance of the plasma grid to the internal filter field magnets is larger by about 10 mm for the CEA system.

Figure 3 shows the comparison of the performance with the two different grid systems for hydrogen discharges. For the CEA grid, the gap between plasma and extraction grid was set to 3 mm and to 6 mm, the latter being the ITER reference value. For all cases, the performance of the source was rather similar[*]; the clear dependence shown by the single aperture experiments could not be seen.

Ion trajectory calculations are under way in order to understand the difference between the single and multi-aperture experiments [16]. First results show that the extracted current depends mainly on the ratio of the negative conversion area to the aperture area which itself depends on the detailed

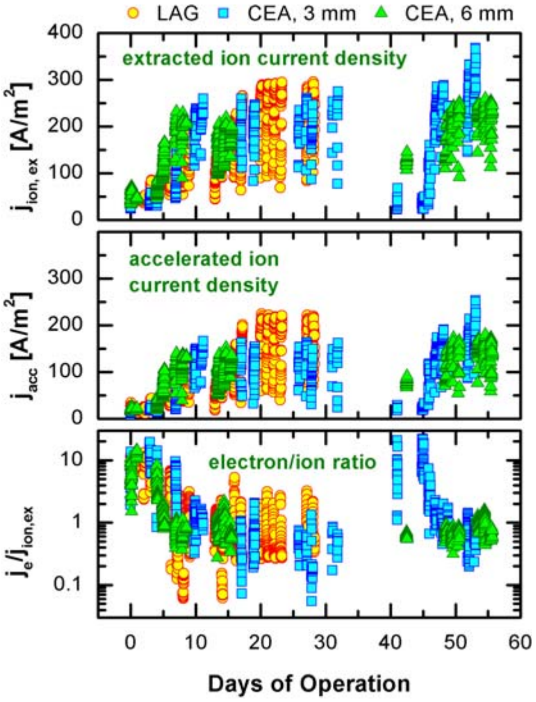

FIG 3. Performance of the different grid systems at BATMAN.

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[*] The CEA grid experiments with the 6 mm distance were hampered by a failure of the HV system of BATMAN limiting the maximum voltage and conditioning time. Hence, experiments in deuterium could not be performed up to now; they are subject of the next experimental campaign for BATMAN.

plasma grid geometry and is different for single and multi-aperture systems.

2.3. Plasma Parameters in Boundary Layer

The extraction probability for a negative hydrogen ion being produced at the plasma grid depends also on the parameters in the boundary layer that is formed near the plasma grid in the extraction region. That layer is accessible for diagnostics. As measured with a Langmuir probe system and optical emission spectroscopy (OES) the electron density is typically 2×10^{17} m^{-3} and the electron temperature is around 1 eV (60 kW RF power and 0.3 Pa) [17]. The ten times higher electron densities as well as temperatures above 10 eV in the driver where the plasma is produced have been reduced by the plasma expansion and the magnetic filter field. The undisturbed plasma potential is roughly 20 eV. The potential distribution of the source and the magnetic field causes in volume operation, i.e. negligible negative ion production at the plasma grid, E×B drifts and thus plasma non-uniformity [5].

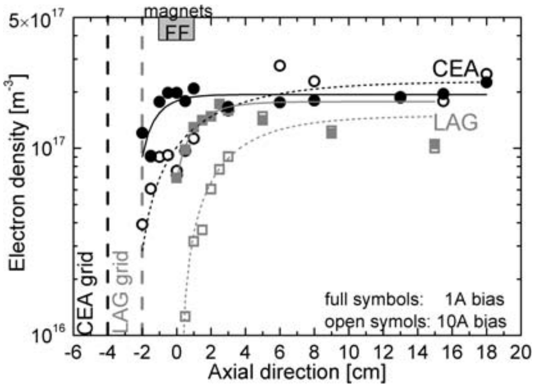

FIG 4. Electron density distribution for the CEA and LAG grid systems at BATMAN.

The boundary layer extends roughly 3 cm into the source and can be influenced by applying a bias voltage between the plasma grid and the bias plate which is at source potential. As shown in figure 4 for the two grid systems (LAG and CEA), the electron density near the grid is drastically reduced at high bias current, accordingly the co-extracted current density is reduced. As discussed in detail in [18] a bias voltage between the undisturbed floating potential of the plasma grid and the plasma potential is most effective. In this range the ion current is unaffected.

The boundary layer is being influenced by the amount of negative ions. In volume operation the negative ion density is less than 10% of the electron density, whereas for a cesium seeded source at high performance the negative ion density is comparable or even higher than the electron density [18]. Negative ions produced at the plasma grid penetrate into the plasma and push the electrons away to keep the quasineutrality in the boundary layer [5]. With increasing amount of negative ions and cesium the plasma potential changes. As a consequence the potential distribution changes resulting in symmetrical plasmas (see below), i.e. the plasma drift is compensated near the plasma grid.

The understanding of the complex physics of the boundary layer is an ongoing task which is supported by modeling efforts. A PIC code is being developed to study the influence of negative ions on the sheath generation [19]. Both volume production and surface production of negative ions have been included.

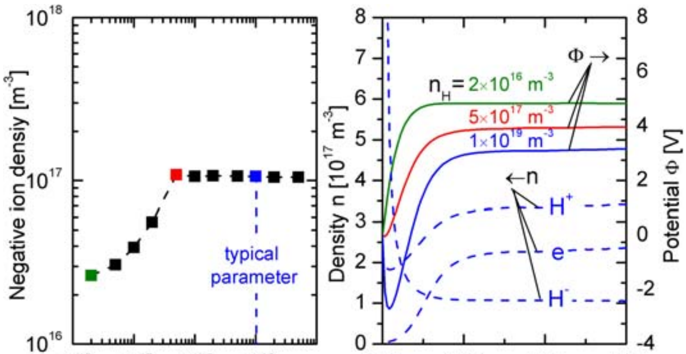

FIG 5. Calculation of the space charge limitation of the negative ion density in front of the plasma grid.

Since for typical plasma parameters of the RF source the flux of neutral hydrogen atoms towards the plasma grid is roughly 60 times larger than the positive ion flux a strong negative space charge builds up in the vicinity of the wall (figure 5). Thus, the transport of the negative ions from the surface towards the plasma volume is hindered. The negative space charge accumulation can be reduced only by increasing the positive ion flux towards the plasma grid.

3. Long Pulse Stability and Performance Control

For the ITER neutral beam system, a feedback performance control system will be required both the ion current (in order to provide a perveance matched beam) and the electron current (for protection of the extraction grid). The long pulse stability is mainly determined by the dynamics of the cesium layer at the plasma grid where the negative ions are formed.

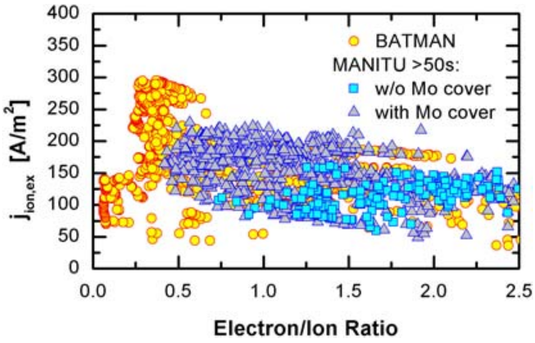

FIG 6. MANITU performance in hydrogen with and w/o Mo coating of the source compared to BATMAN.

It is well known from all fusion relevant cesium seeded negative ions sources [3-6,20,21] that the cesium conditioning of the source is a tedious task. This is especially true for the conditioning of a clean source, but some conditioning must be also done when the source was not operated for some hours. One of the reasons for this need of source conditioning is the ‘poisoning’ of the cesium layer by impurities, increasing the work function of the plasma grid. This poisoning happens during extended non-operating periods — the typical vacuum is in the range of 10^{-6} mbar and hence rather poor —, during the regeneration of the cryo pumps, and due to sputtering in the source. The latter was drastically reduced at MANITU by coating almost all inner copper surfaces of the source with molydenum, as it was seen in a strong reduction of the copper emission lines from the source plasma. As a result, the source performance of MANITU increased drastically (figure 6): pulses with stable ion and electron currents near the ITER requirements have been achieved for several 100 seconds.

The understanding of the detailed processes leading to a cesium layer for a high performance source is rather poor; first vacuum calculations of the cesium distribution for realistic conditions are under way [16].

Long pulse experiments at MANITU indicate that the cesium distribution between the discharges, i.e. during the vacuum phase, is important [22]. This is demonstrated in figure 7, where the cesium influx during a long discharge was changed by increasing the source temperature without any change in the extracted currents. The subsequent discharge, however, had then a better performance. Furthermore, the electron is not stable during the pulse. The cesium effect can be counteracted by varying the RF power and the bias voltage, as also demonstrated at MANITU [22].

The amount of cesium in the source was measured up to know solely during a discharge by emission spectroscopy. In order to investigate also the dynamics of the cesium in the vacuum phase, a light absorption diagnostic is presently prepared at a small laboratory experiment[†]. A first example is shown in figure 8, where the principle feasibility of the method for the expected cesium densities is demonstrated in vacuum and also in plasma operation.

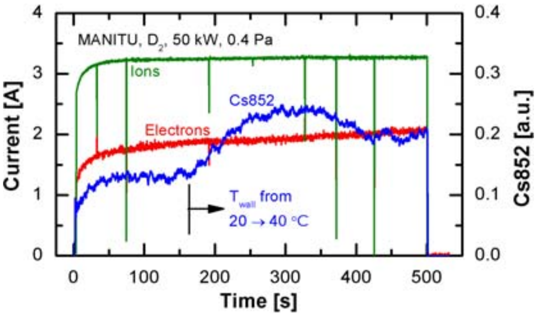

FIG 7. Increase of Cs influx, indicated by the emission of the neutral Cs line at 852, in the source during a long pulse in MANITU.

[†] Planar ICP discharge at Universität Augsburg, Lehrstuhl für Experimentelle Plasmaphysik

4. Homogeneity

ITER requires for a good transmission a beam homogeneity in terms of extracted current density of ±10% [7]. This is directly connected with the negative ion density distribution at the plasma meniscus. As this quantity, however, is not accessible by diagnostic techniques, the correlation of the uniformity of the boundary layer parameters with the uniformity of the beam divergence is being investigated.

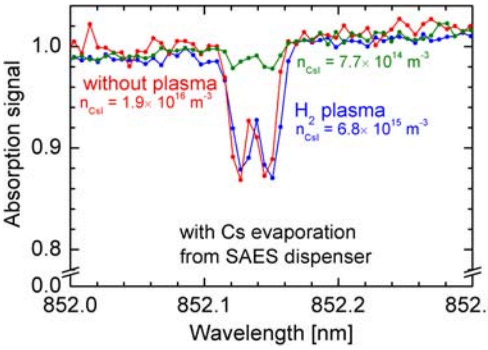

FIG 8. Feasibility experiments on Cs absorption.

The latter is measured at MANITU with the H_α Doppler beam spectroscopy system using 13 LOS in vertical and 7 LOS in horizontal direction at a distance of 1.2-1.5 m and a viewing angle of 50°. The temporal stability and spatial homogeneity of the beam can be determined by analyzing the width of the Doppler shifted H_α line which is proportional to the local, LOS-averaged beam divergence. MANITU is typically operating below or in the optimum perveance. This is shown in figure 9 together with the calculated beamlet divergence using KOBRA3 [23]. The calculation reflects the perveance dependence very well; the absolute number however depends on the amount of space charge compensation taking into account. For the actual case at MANITU, full space charge compensation at 12 cm distance from the grounded grid fits the experimental data which is in the expected range for the given tank pressure.

The plasma emission and the plasma parameters, such as electron density and negative ion density, are measured by OES [13]. Spatial resolution is provided by using several LOS arranged symmetrically to the grid centre at different distances to the grid. This allows the determination of a symmetry factor, the top-to-bottom symmetry. As standard, the emission of the Balmer line H_β is used, which depends basically on the atomic hydrogen density, electron density and temperature. The sources are equipped with fixed Langmuir probes (pin probes) operating in the ion saturation current — being a measure for the ion density — and are placed in the outermost upper and lower diagnostic port.

The dependence of the source performance, the plasma symmetry, and the beam homogeneity on the applied RF power is shown in Figure 10 for hydrogen discharges. The plasma symmetry improves with RF power as shown by the symmetry factor of the pin probes (I_{sat}) and H_β both at 3 cm distance to the grid. At a distance of 1 cm, however, the symmetry is unaffected by the RF power which demonstrates the dynamics of the spatial behaviour of the boundary layer in vertical and axial direction. The beam homogeneity defined by the rms-value improves also and correlates well with the plasma symmetry.

The experiments at MANITU/BATMAN showed [12] that for a well conditioned source, i.e. high negative ion currents and a low amount of co-extracted electrons, the plasma is symmetric for both the electron density, and much more important, the negative ion density. The beam homogeneity correlates with the negative ion density and is better than 10% at high source performance.

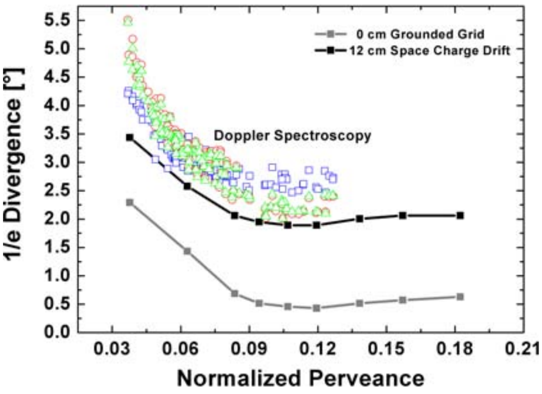

FIG 9. Calculated and measured beam divergence at MANITU

At the size scaling experiment RADI, the plasma uniformity is measured in front of the grid by OES using 3 LOS in vertical and 3 LOS in horizontal direction at a distance of 2 cm to the grid. Like in the ITER source, the magnetic field is created by a plasma grid current. The dependence of the D_β emission in vertical direction on the PG current is shown in figure 11 for a total RF power of 200 kW, i.e. at an ITER relevant power level.

Without magnetic filter field almost the same D_β line emission is observed for all LOS indicating a uniform plasma illumination of the grid (the respective values for the horizontal LOS are not shown). An exception is the centre LOS in vertical direction. The increase is most probably caused by an overlap of the plasma from the vertical drivers although the distance between the vertical drivers is larger than the one for the horizontal drivers. This might indicate a different mutual coupling between drivers in vertical (individually powered) and horizontal (in series powered) drivers.

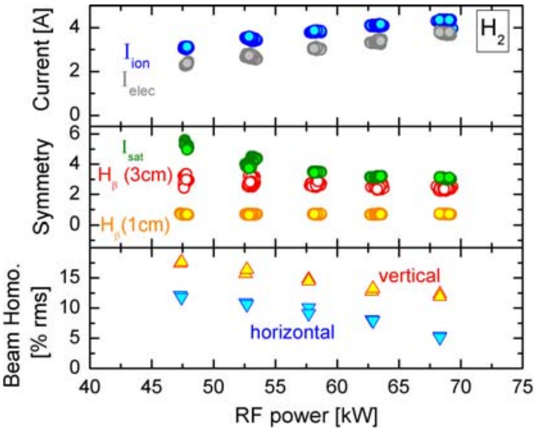

FIG 10. Source and beam symmetry at MANITU

With increasing magnetic field strength the D_β intensity decreases, due to a reduction of the electron temperature [18]. The vertical distribution shows a separation of the top and bottom with a depletion of the signal of the centre. The far reaching filter field, which has a sufficiently large value in the drivers (almost 2/3 of the strength at the grid), reduces the plasma expansion in vertical direction and is much more pronounced at lower power levels. At ITER relevant power levels and magnetic fields, the plasma illumination turns out to be satisfactory: no strong depletions and enhancements are observed.

The above reported results have been obtained in volume operation. It can be expected from the MANITU results that the homogeneity of the plasma improves with an increasing amount of negative ions produced at the plasma grid. This will be investigated at RADI in the near future where cesium seeding is foreseen.

5. Future Experiment: ELISE

For long pulse plasma operation and short pulse, but large-scale extraction from a half-size ITER source IPP is presently designing the new test facility ELISE. ELISE is an important step between the small scale extraction experiments at BATMAN and MANITU and the full size NBTF/ITER neutral beam system [8]. The integrated commissioning is planned for 2010, assuming a start of the project end of 2008. The detailed technical details are given in [24]. The aim of the design of the ELISE source and extraction system was to be as close as possible to the ITER design; it has however some modifications allowing a better diagnostic access and more experimental flexibility than the NBTF sources [25].

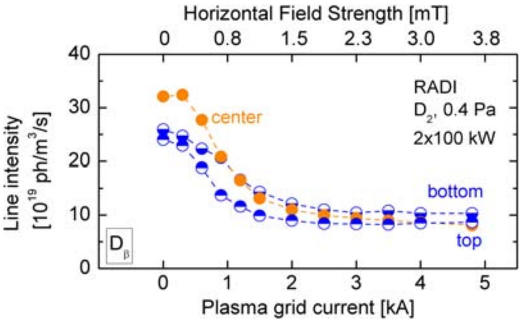

FIG 11. Plasma symmetry of RADI vs. the horizontal magnetic filter field.

Figure 12 shows the details of the ELISE ion source and the extraction system. In contrast to the ITER source, the ELISE source will usually be operated in air — with a possibility to operate the drivers in vacuum — to facilitate diagnostic access near the most important region, i.e. the region near the plasma grid (see above), and to enhance the experimental flexibility for e.g. an easy change of the magnetic field configuration. Due to the limits of the IPP HV system, only pulsed extraction during a long plasma pulse is possible. Experiments at MANITU (see figure 13) showed that at least for a well conditioned source the same performance could be obtained during pulsed extraction during a long pulse.

6. Conclusion

The development of the IPP RF source for the NBI system has made substantial progress in the last two years in achieving the required source performance, especially regarding source homogeneity and long pulse operation, and in improving the understanding of the complex processes in a negative hydrogen ion source.

7. Acknowledgments

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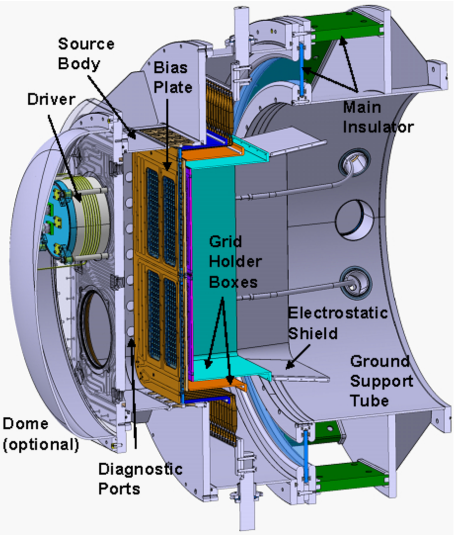

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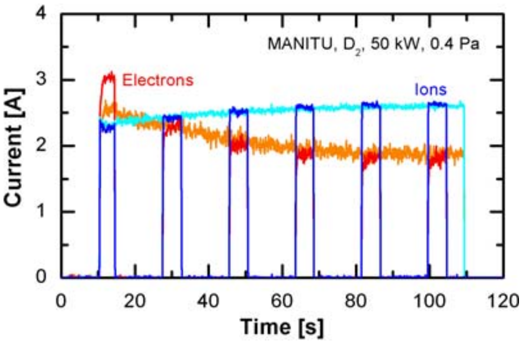

FIG 13. Comparison of pulsed with cw extraction at MANITU.

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