RADI - a RF source size-scaling experiment towards the ITER neutral beam negative ion source

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Keywords: ITER Neutral beam system, RF source, Negative Ion Source

Abstract

IPP Garching is currently developing a negative hydrogen ion RF source for the ITER neutral beam system. The source demonstrated already current densities in excess of the ITER requirements (> 200 A/m^2 D$^-$) at the required source pressure and electron/ion ratio, but with only small extraction area and limited pulse length. A new test facility (RADI) went recently into operation for the demonstration of the required (plasma) homogeneity of a large RF source and the modular driver concept.

The source with the dimension of 0.8 m x 0.76 m has roughly the width and half the height of the ITER source; its modular driver concept will allow an easy extrapolation in only one direction to the full size ITER source. The RF power supply consists of two 180 kW, 1 MHz RF generators capable of 30 seconds pulses. A dummy grid matches the conductance of the ITER source. Full size extraction is presently not possible due to the lack of an insulator, a large size extraction system and a beam dump.

The main parameters determining the performance of this “half-size” source are the negative ion and electron density in front of the grid as well as the homogeneity of their profiles across the grid. Those will be measured by optical emission and cavity ring down spectroscopy, by Langmuir probes and laser detachment. These methods have been to the extracted current densities achieved at the smaller source test facilities at IPP for similar source parameters. However, in order to get some information about the possible ion and electron currents, local single aperture extraction with a Faraday cup system is planned.

1. Introduction

The ITER neutral beam heating and current drive system [1] is based on the acceleration of negative hydrogen ions due to their high neutralization efficiency (0.6) at the required 1

Table 1: ITER neutral beam system: requirements and achievements of the IPP NNBI ion source at the test facilities BATMAN and MANITU.

Parameter	**ITER Requirements**	**IPP NNBI RF-Source**	
		BATMAN	**MANITU**
Extraction Area	0.2 m^2	7.0x10^{-3} m^2	1.88x10^{-2} m^2
Calorimetric Current Density	200 A/m^2 D^- 280 A/m^2 H^-	230 A/m^2 D^- 330 A/m^2 H^-	120 A/m^2 D^- 150 A/m^2 H^- *
Extraction Voltage	9 kV	9 kV	8 kV (Hydrogen) 7 kV (Deuterium)
Source Pressure	0.3 Pa	0.3 Pa	0.3 - 0.4 Pa
Electron Content (je/jH-)	1	< 1	< 1 (Hydrogen) 1.5 - 2 (Deuterium)
Pulse Length	3600 s	< 4 s	< 600 s (Hydrogen) < 200 s (Deuterium)
Source Dimension	1.5 x 0.6 m^2	0.32 x 0.59 m^2	0.32 x 0.59 m^2
Uniformity	± 10%	t.b.d.	t.b.d.

** estimated from the electrically measured ion current*

MeV beam energy (see Table 1). In order to inject the envisaged 17 MW, the source has to deliver 40 A of negative deuterium ion current. As alternative to the filamented arc sources of the present reference design of the ITER neutral beam system, IPP Garching is currently developing a RF source for negative hydrogen ion production [2]. RF sources for the production of positive hydrogen ions [3], [4], [5] were developed at IPP for the neutral beam heating systems of the fusion experiments ASDEX Upgrade and W7-AS and are successfully operational in the last decade.

Compared to filamented arc sources RF sources are basically maintenance-free in operation because they lack of parts requiring regular replacements. The arc source filaments have a limited lifetime requiring a remote handled replacement about twice a year in the case of ITER. Furthermore RF sources are cheaper to build as they have fewer parts, requiring just a source body, a RF coil and a matching circuit. In addition there may be an advantage with respect to cesium consumption, which is needed to enhance the source performance (see below), as in the RF source there is no filament material that is evaporated and bury the Cs layer on the walls [6].

In order to minimize the stripping losses, i.e. the neutralization of the negative ions in the accelerator, the source pressure and hence the gas flow into the accelerator has to be sufficient low. The specified pressure of 0.3 Pa for the ITER source is a compromise between source operation and achievable current densities on the one side and stripping losses (0.25 – 0.3) on the other side [1]. The maximum (routinely) achieved current densities — both for

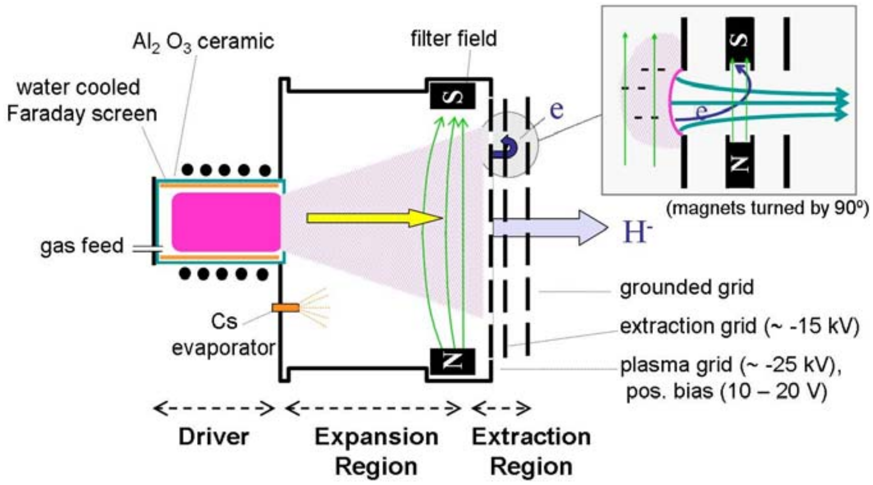

Figure 1: Schematic view of the IPP RF source with one driver. The extraction region is shown in detail; the magnets in the extraction grid are shown rotated by 90º.

arc and RF sources — at this low pressure are in the range of 200 – 300 A/m^2; hence a large source with an extraction area of 0.2 m^2 is required (see Table 1). However, present large filamented negative ion sources suffer from significant plasma non-uniformities [7], [8] which are assumed to be caused by the arc current and the magnetic filter field.

The IPP RF source (see Figure 1 and the detailed description in the next section) has already demonstrated current densities in excess of the ITER requirements at the specified pressure and electron/ion ratio at the test facility BATMAN [2], [9], [10], but with only small extraction area and limited pulse length (see Table 1). Hence, the further development at IPP Garching concentrates now both on long pulse operation (at the test facility MANITU [10], [11]) in order to explore the long term stability of the RF source and on source size extension in order to explore the homogeneity of large RF plasmas which is not known yet.

At present, the source body dimensions (32 x 59 cm^2) of the IPP RF negative ion source are those of the positive ion system presently installed at ASDEX Upgrade [4]. As an intermediate step between the present small source and the full size ITER source — with a height of 1.6 m and a width of 0.6 m — the so-called "half-size source" was designed and constructed. The source has approximately the width and half the height of the ITER source; its modular driver concept will allow an easy extrapolation to the full size ITER source without any change of the source width.

As mentioned above, the half-size source is devoted to demonstrate the required homogeneity of large RF plasmas, but also to test the geometry and the optimum number of drivers and to test an ITER-like RF circuit. The experience of the operation of this source will then be

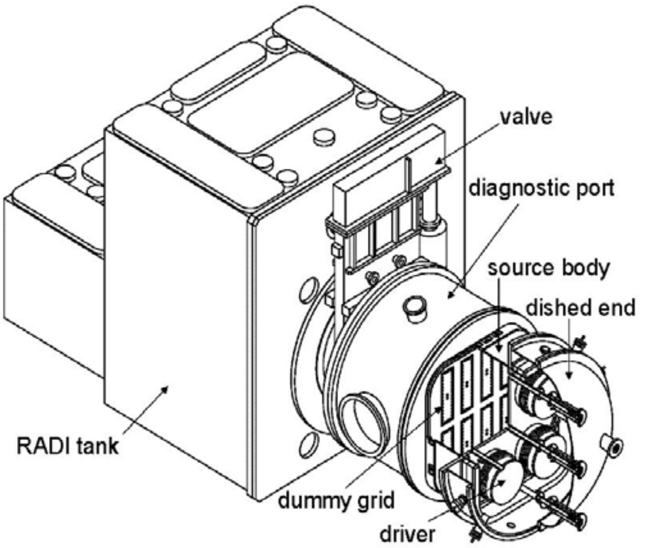

Figure 2: 3D sketch view of the RADI test facility with the half-size source. The ITER grid segmentation is indicated in the dummy grid.

used in the final design of an ITER RF source that was started in the last year by RFX Padua in collaboration with IPP Garching.

This paper discusses shortly the principle design of the IPP RF ion source and discusses in detail the design of the half-size size and the parameters of the new test facility for testing the source. Finally, the first plasma pulses are presented.

2. The IPP RF source

Figure 1 shows the principle design of the IPP RF driven negative ion source. The details are given elsewhere [12],[13]. The source consists of three parts: the so-called driver, where the RF is coupled to the plasma, the expansion region, where the plasma expands into the actual source body, and the extraction region. The latter are separated by a magnetic field of the order of 5 - 10 mT, the filter field. The driver is mounted on the back of the source body and consists of an alumina cylinder with a water-cooled RF coil connected to a 1 MHz oscillator. An internal water-cooled copper Faraday screen protects the alumina cylinder from the plasma.

The subdivision of the source is necessary in order to keep the ‘hot’ electrons, which are generated by the RF and have energies of about 8 eV, away from the extraction region, where electron temperatures below 2 – 3 eV are necessary for minimizing the destruction rate of the negative hydrogen ions by electron collisions; then mutual neutralization with positive ions takes over being the dominant destruction process.

The extraction of the negative ions is done at the small IPP test facilities with a three grid system (see also Figure 1): the plasma grid that is together with the source at high potential, the extraction grid, and finally the grounded grid. The extraction grid is equipped with magnets in order to deflect the co-extracted electrons out of the accelerated beam. In order to keep the electron power on the extraction grid on an acceptable level, typical extraction voltages are 7 – 10 kV. In the second gap between extraction and grounded grid the ions are accelerated to about 20 – 30 kV. (In the ITER neutral beam system the (pre)acceleration is at 60

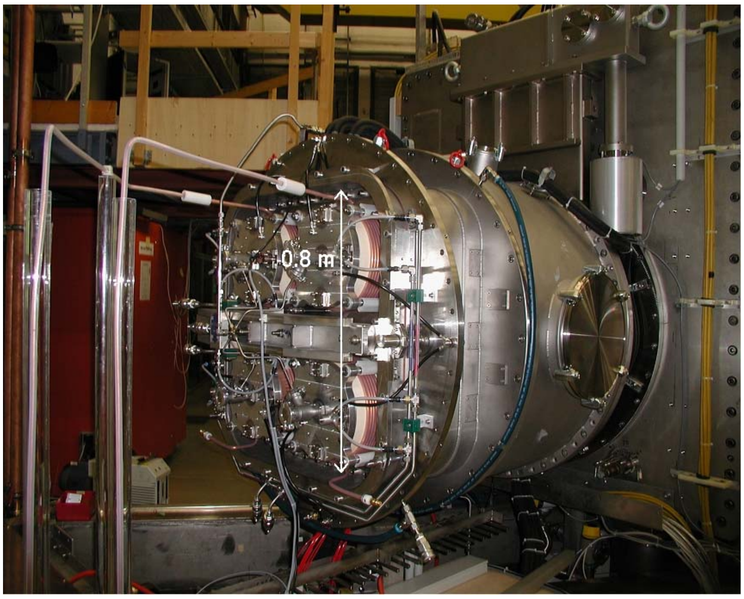

Figure 3: Photograph the ½-size source mounted on the RADI test bed. The upper drivers are connected to the matching circuit by water-cooled copper pipes.

kV, the final acceleration to 1 MeV is done in one or several additional acceleration stages [1].)

For optimum performance, i.e. high negative ion current density and a low amount of co-extracted electrons, Cs evaporation into the source is mandatory [2]. The underlying process is the "surface process", i.e. the interaction of atoms or ions with materials of low work function:

$$H, H_x^+ + \text{surface } e^- \rightarrow H^-.$$

Due to the short survival length of the negative ions (some cm's) in the plasma [14], only ions created at the plasma grid can be accelerated. The negative ions produced at the plasma grid are then accelerated into the plasma by the sheath potential and have to bend back to the extraction system by collisions, charge exchange, or by the magnetic fields near the apertures. The evaporated cesium covers the plasma grid with a thin layer, which reduces the work function depending on the thickness of the Cs layer [15]. The latter can be controlled (somewhat) by heating the plasma grid to temperatures in the range of 150 – 200 °C. A further reduction of the amount of co-extracted electrons is achieved by biasing the plasma grid with 10 – 20 V against the source body together with a sufficient filter field across the plasma grid [2].

3. RADI Setup

A new test facility (called RADI) is currently commissioned with first plasma pulses in order to prepare the size-scaling demonstration of the IPP RF source. The new test facility makes use of one of the injector boxes — the radial box — of the decommissioned injectors of the W7-AS fusion experiment [5]. The main parameters of the RADI test facility are summarized in Table 2.

Figure 2 shows a 3D-sketch of the whole test facility with the half-size source. Figure 3 shows a photograph of the test facility. As extraction is not possible in the present setup, the

Table 2: Main parameters of the RADI test facility.

Isotope	H or D
Source Size	0.8 x 0.76 m^2
Equivalent Plasma Grid Size	1000 cm^2
Tank Volume	5 m^3 (1.3x1.6x1.8 m^3)
Pulse length	10 - 30 s
RF System	2 x 180 kW @ 1 MHz
Pumping System	1 turbo molecular pump 3 Ti Getter pumps
Pumping Speed	2 x 60000 l/s, 1 x 40000 l/s
Extraction	local single aperture extraction only
Plasma Grid Bias	power supply 50 V, 500 A
Filter field	grid current 15 V, 5 kA rod filter permanent magnets
Cs Oven	2 ovens with 3 g each

whole source can be operated on ground potential. An advantage of only plasma operation is that RADI can be operated with deuterium without radiation protection measures.

Due to technical limitations of the RADI test facility large scale extraction and therefore measurements of the extracted ion and electron current densities are not possible. Hence, IPP Garching is currently investigating and testing plasma diagnostic tools at the other test facilities (BATMAN and MANITU). The measured plasma parameters — especially the negative ion density in front of the grid — are then calibrated together with modeling to the source efficiency; the latter is defined by the ion and electron current densities divided by the RF power.

3.1. Source Design

Figure 4 shows a sketch of the half-size source. It consists of 4 parts: (1) the main rectangular source body with the dimension of 0.8 m x 0.76 m; (2) the source back plate hosting the drivers; (3) the drivers themselves and (4) the driver back plates. In contrast to the present NNBI (negative neutral beam injection) sources at the various test facilities, the source in the ITER NNBI system is kept in vacuum (VIBS --- vacuum immersed beam source [1]) for the 1 MV insulation. Hence, the back plates do not have to withstand the vacuum forces.

In contrast, the back plate of the half-size source is re-enforced, so that source operation in air is also possible; this is advantageous for the commissioning — hence presently the source is operated in air — and increases the ease of access of diagnostic tools to the source, but problems may arise with the voltage holding of the RF coils (see section 3.3). In order to simulate the VIBS of ITER the RF drivers of RADI can be enclosed by a dished end connected to the driver back plate. This vacuum is pumped via a bypass valve that is closed during plasma pulses separating it from the source vacuum, similar to the positive RF sources at the ASDEX Upgrade NBI system [4].

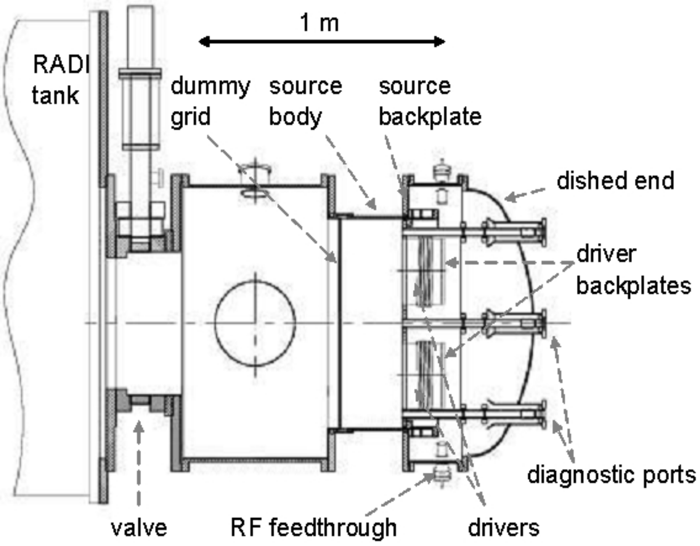

Figure 4: Sketch view of the half-size source. Details are given in section 3.1.

The source body consists of a 6 mm stainless steel wall with 3 mm diameter axially deep drilled cooling water channels as it is shown in Figure 5. The water manifolds are incorporated inside the flanges. The inner side of the source is covered with an electro-deposited 1 mm thick Cu layer for better heat distribution and conductance. The source body is not equipped with any magnets for the plasma confinement; however, our source design with the flat side walls has the advantage of allowing an easy change of the magnetic confinement by external magnet packages.

The present design of the half-size source offers a great amount of flexibility not only for the magnetic confinement, but also for the source depth and the driver geometry.

It is expected that in contrast to the large filament driven source of the ITER refreence design (Kamaboko, [1]), the source depth of the RF source can be kept rather shallow due to its principle cuboidal form. The half-size source body has a depth of 250 mm. The distance of the drivers to the grid however can be varied: the source back plate can be moved inside the source body by spacers. The physical source depth can be varied between 150 mm and 250 mm by venting the source. This possibility allows for an investigation of the influence of source depth on source performance and plasma homogeneity without major rebuilding of the test facility.

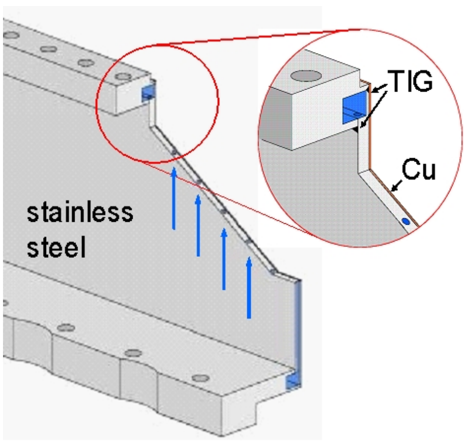

Figure 5: Detail drawing of the water manifold in the source body wall. The wall thickness is 6 mm; the cooling channels have a diameter of 3 mm. The inner part is covered with a 1 mm thick Copper layer. The flanges are connected to the source walls by TIG (tungsten inert gas) welding.

In order to optimize the number and geometry of the drivers, three different driver configurations are presently designed for RADI as shown in Figure 6.

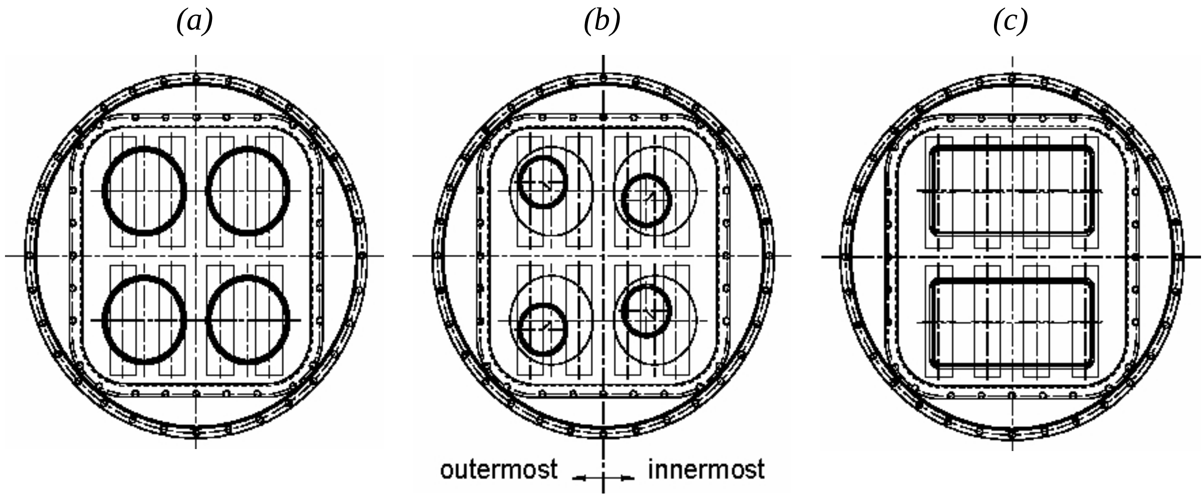

Figure 6: Driver configurations foreseen for the half-size source: (a) 4 drivers with 240 mm ∅ (start-up configuration); (b) 4 drivers with 150 mm ∅ on an eccentric flange; and (c) two race track drivers. The ITER grid segmentation [1] is indicated by the 2x4 rectangles.

Previous experiments at our test facility MANITU [9], [11] showed that the standard IPP RF driver with a diameter of 240 mm can illuminate a plasma grid extraction area of 150 – 200 cm^2 with sufficient homogeneity. The first approach which is presently installed is an arrangement of four of the standard IPP drivers (Figure 6a). This might be sufficient for the case of an equivalent of 1000 cm^2 extraction grid area taking a certain degree of plasma 'overlap' into account. The second approach is to use four smaller drivers with a diameter of 150 mm; these are mounted on the same source back plate but with eccentric flanges in order to change the positions of the driver centre (Figure 6b). This will allow for an optimization of the driver position — with the drawback of a smaller plasma grid "illumination", which might cancel the effect of the driver position. The third approach is to use two "race track" formed drivers with the dimension of 510 mm x 250 mm (Figure 6c). For this configuration a new source back plate is necessary. This approach is based on the one that has be successfully used for the positive ion RF sources at the neutral beam injection system of ASDEX Upgrade [4] for many years.

In all configurations, the drivers with a depth of 14 cm consist of an alumina or quartz cylinder and a copper Faraday screen inside the cylinder protecting the quartz or alumina being sputtered by the plasma. This should not be problematic for the cylinder, but the sputtered material would be reducing the voltage holding capacity of the grid system.

Due to the resulting pure inductive coupling of the RF power to the plasma, a high gas pressure as well as a so-called starter filament for the plasma ignition is necessary. The high gas pressure is obtained by a short (few 100 ms) gas puff into the source; once the plasma is ignited, the pressure is reduced to the required operating pressure within one second. The low current, low voltage (5 mA, 12 V) tungsten starter filament is switched-off when the plasma is ignited. Hence, the life time of this filament is not critical. The half size source is equipped with four starter filaments, one in each driver; however, due to the mutual influence, two operating filaments are sufficient, as the first plasma pulses showed.

A large number of ports exist in the source body for diagnostics, starter filaments feedthroughs and the gas and Cs supplies (see the photograph of the inner part of the half-size source in Figure 7). For the four driver configuration five axial ports in the source back plate are planned mainly for the Cs ovens and for the axial Langmuir probe. In front of the plasma grid five vertical and three horizontal ports allow access for plasma diagnostics near the grid (~1 cm distance) and for possible filter field modifications (see next section). The ports have a diameter of 40 mm; hence, axial profiles of the plasma parameters using two or three line-of-sights for optical diagnostics are possible. The port configuration is adjusted to the segmentation of the ITER source grid system [1].

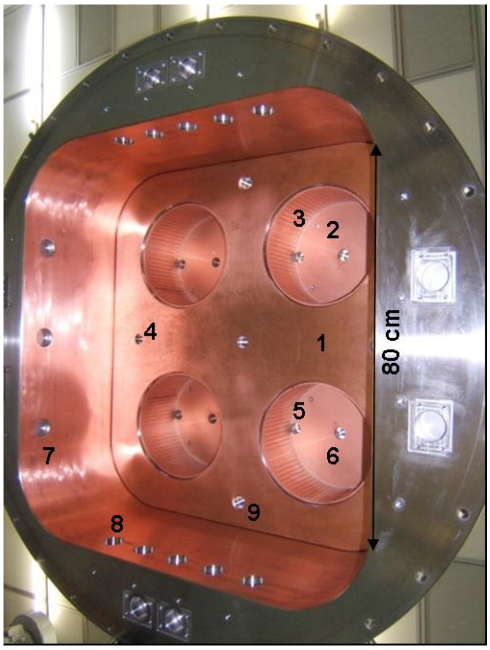

Figure 7: Photograph of the interior of the half-size source: source back plate (1), drivers with back plate (2) and Faraday screen (3), Cs oven ports (4), feedthroughs for the starter filaments (5) and gas (6), three vertical (7), five horizontal (8) and three axial (9) diagnostic ports.

3.2. Half-Size Source Test Facility

The existing pumping system of the RADI tank consists of one turbo molecular pump (2000 l/s) and three Titanium getter pumps with a total pumping speed of 160,000 l/s. The box dimensions are 1.3x1.6x1.8 m^3. This pumping system limits the possible pulse length to about 10 – 30 s, depending on the gas flow.

The available circular port of the RADI test facility has a diameter of 1 meter. Between source and tank a valve with 500 mm diameter and a 600 mm long diagnostic duct is mounted to allow vacuum separation and diagnostic access ‘downstream’ of the plasma grid.

RADI will be equipped with a Molybdenum dummy grid matching the gas conductance of the ITER grid system and hence the gas flow conditions of the ITER source. This is achieved with narrow slits in the dummy grid. In order to have some control of the conduc-

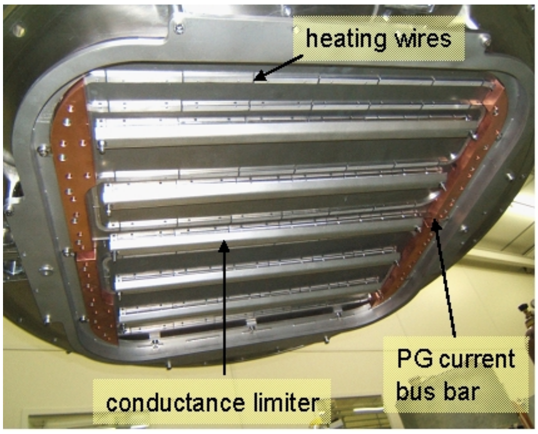

Figure 8: Photograph of the dummy plasma grid from the 'downstream' direction. Indicated are the heating wires, the current conductor (5 kA) for the PG filter field and the conductance limiters. The details of the latter are shown in Figure 9.

tance without the exchange of the whole grid and to prevent plasma losses into the tank volume, the grid slits are shielded by moveable 'chevrons' at the back. Figure 8 shows a photograph of the dummy grid (from the rear side) with the current conductor for the plasma grid (PG) filter field (see below), the heating wires and the chevrons. The details of the geometry of the slits and the chevrons are shown in Figure 9. The distance of the chevrons to the grid can be varied between 5 – 10 mm.

The performance of a negative ion source depends on the work function of the plasma grid and hence on the Cs coverage and the temperature of the plasma grid. Although RADI will not have extraction and hence no possibility to study the influence of Cs on the negative ion and the co-extracted electron currents, Cs evaporation is still necessary for its influence on the local plasma parameters and the negative ion density in front of the grid. The Cs monitoring tools already in use at the other IPP test facilities [14], [16] allows a correlation between the amount of Cs evaporated into the source and the amount of Cs (both atomic and ion) in the plasma volume near the grid. This will help to understand the Cs dynamics and transport in a (large) RF source. Cs will be supplied by two ovens, sitting on the source back plate; each oven is equipped with 3 ampoulae containing 1 g of Cs each.

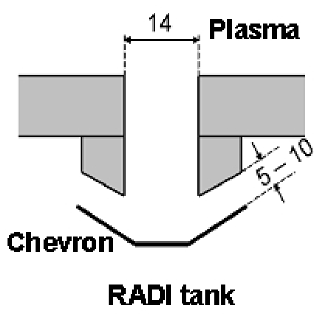

Figure 9: Sketch of the geometry of the conductance limiter of the dummy plasma grid. Dimensions are given in mm.

The plasma grid can be heated electrically to temperatures of 100 °C to 300 °C; for the IPP RF sources the optimum temperature with regards to the maximum yield of extracted negative ions and a minimum amount of co-extracted electrons is in the range of 120 °C to 150 °C [2].

The plasma grid is usually biased positively against the source body in negative ion sources in order to reduce further the co-extracted electrons [2]. Although there is no large scale extraction in RADI, bias is also installed in order to study the influence it has on the plasma parameters.

At the present small IPP RF source, the magnetic filter

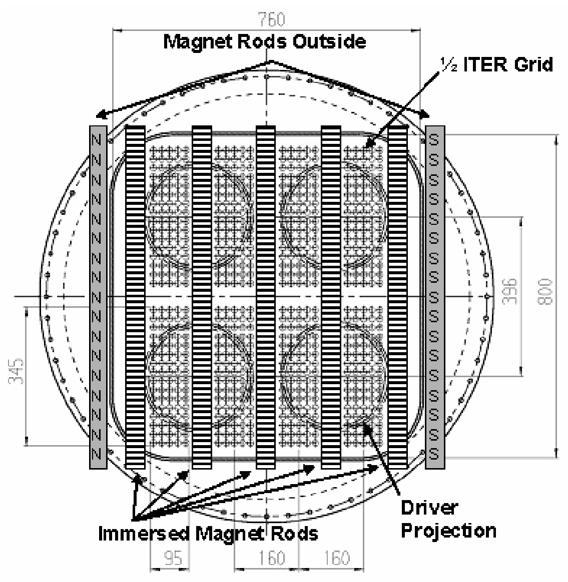

Figure 10: Possible magnetic configurations at RADI for the filter field by permanent magnets outside the source or localizing the field by water-cooled magnetic rods immersed into the source and adapted to the ITER grid segmentation.

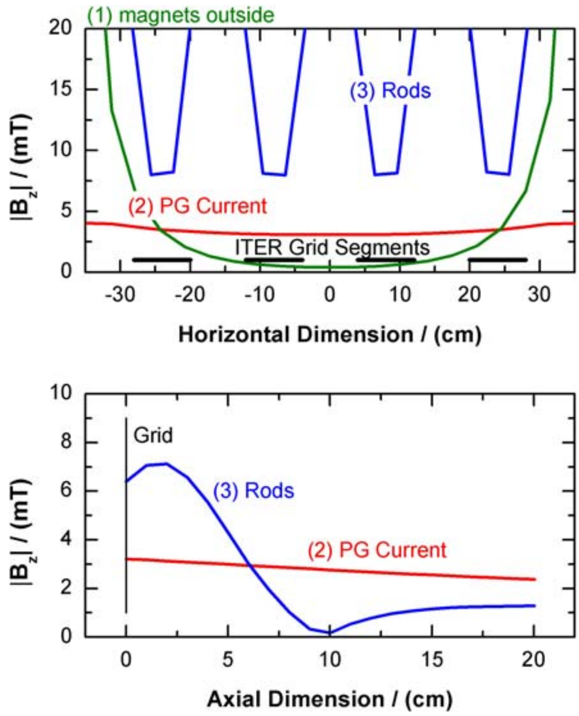

Figure 11: Calculated magnetic filter field by (1) permanent magnets outside the source, (2) by a plasma grid current of 5 kA, and (3) by magnet rods inserted in the source with the magnets being located 1 cm above the grid. Top: Horizontal profiles 1 cm above the grid. The grid segments are indicated by the thick black lines. Bottom: Axial profiles into the source at the centre of the grid segment. The respective profile for the permanent magnets is not shown since it is nearly zero in the center of the plasma grid.

field (see section 2) is in the horizontal direction — across the shorter source dimension — and is generated by permanent magnets mounted outside the source. For a large plasma source this method cannot be used to create the necessary filter field in front of the grid solely.

In the ITER reference source design [1] the external permanent filter field is augmented by a current flowing through the plasma grid. In order to gain experience with this so-called “PG filter” method, RADI is equipped with a 5 kA, 15 V power supply. For the required homogeneity of the plasma a homogeneous current flow through the grid is required. This is ensured by a thick copper bus bar on top and bottom of the dummy grid (see Figure 8)

In order to explore alternatives, the diagnostic ports allow for the mounting of five water-cooled rods of magnets inserted vertically into the source according to the ITER grid segments (see Figure 10). Figure 11 shows the calculated axial and horizontal profiles of the vertical magnetic field strength. It is obvious that permanent magnets outside the source alone do not produce the sufficient field of some mT in the center due to the large separation of the magnets. The field produced by the plasma grid current is rather uniform across the plasma grid, but reaches far into the source. This is not the case for the magnet rod filter field, but

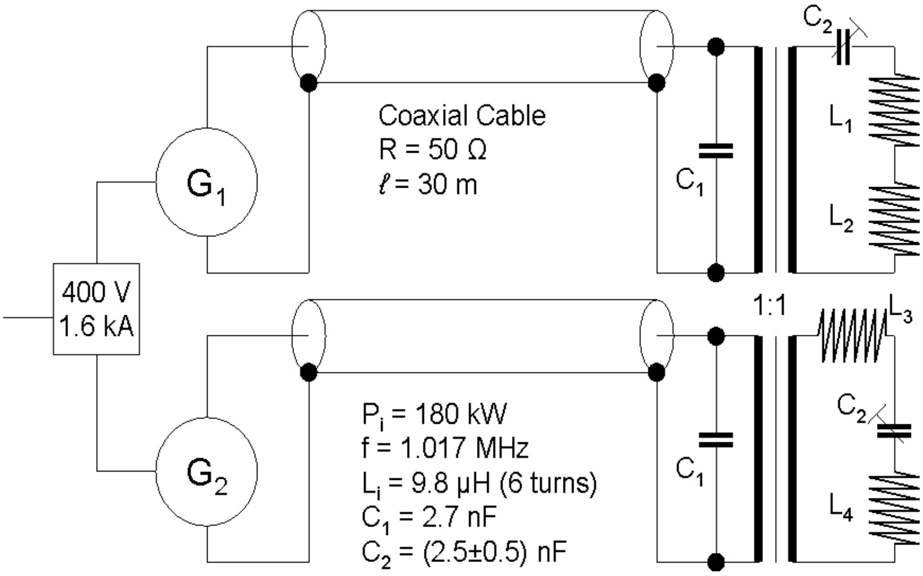

Figure 12: RF circuit for RADI for the 4 driver configuration (L_1 – L_4). The matching unit near the source is drawn in two possible arrangements to be tested ('CLL' or 'LCL', respectively); during operation only one arrangement for both circuits will be used.

here some variation across the single grid segments is produced. RADI will test both configurations, and also various combinations. Furthermore, the influence of the change on the filter field due to the magnets in the extraction grid can also easily simulated by attaching a dummy extraction grid.

3.3. RF circuit

Figure 12 shows the RF circuit at RADI. The RF power supply of RADI consists of two 1 MHz RF generators each rated for 180 kW and 30 seconds pulse duration and a typical electrical efficiency of 60%[1]. The RF generators are equipped with self-exciting oscillators which adjust their frequency to the load impedance.

The output impedance of the RF generator of 50 Ohm has to be transformed to the impedance of the plasma (together with the coil) by a proper matching unit. The plasma resistance depends on the plasma parameters; typical values are in the range of a few Ohm. The transformation is done via two capacitors, one parallel at the generator side and one in series near the source. In order to adjust the plasma impedance the series capacitor that has to be located near the source is variable. This flexibility is especially necessary when changing the source operation from hydrogen to deuterium and vice versa. Figure 13 shows the assembled matching unit near the source. Most of the space is needed for the remote adjustment of the

[1] Manufacturer: Himmelwerk GmbH, 72006 Tübingen, Germany; www.himmelwerk.com

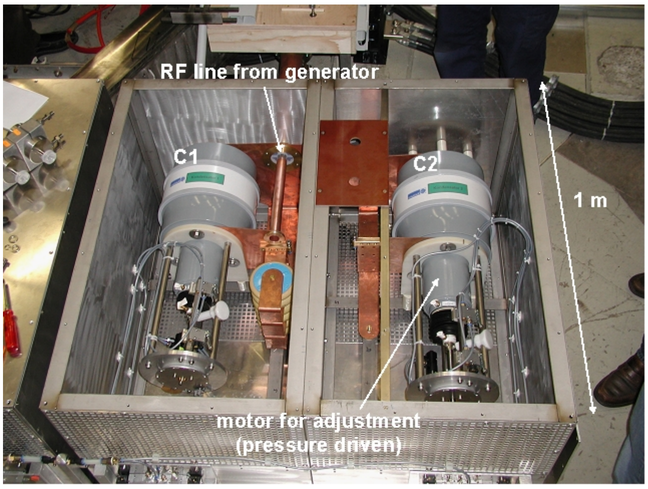

Figure 13: Matching unit with the C1 and C2 capacitors for the supply of 2 drivers at RADI. Most of the space is needed for the remote adjustment of the vacuum capacitors by a pressure driven motor.

capacitors. The parameters of the vacuum capacitors C_1 and C_2 as well as the respective frequency are given in Figure 12 for coils with 6 turns each.

In contrast to a design with only one RF generator supplying all drivers in series, the RADI design has the advantage that the RF power can be set individually and therefore possible plasma non-uniformities can be compensated for. Experiments with large filamented sources [6] showed that the main non-uniformity is in the vertical, longer, dimension, most probably due to drifts of the charged plasma particles and/or of the primary electrons caused by the horizontal filter field (via $B \times \nabla B$ and/or $E \times B$ drifts); therefore, in the case of the four driver configuration an arrangement is chosen where one RF generator supplies the horizontal drivers in series.

For the present RF sources at IPP a 3:1 transformer separates the source potential from ground. This is not necessary for RADI — as it is operated without extraction — and is not relevant for ITER, where the RF generators are at the source potential in order to avoid a 1 MV transformer. However, the experience during the commissioning showed that a transformer reduces significantly the RF breakdown probability at the coils as it separates the coil potential from ground. Therefore, a 1:1 transformer is presently installed. In contrast to the single driver sources at MANITU and BATMAN, the impedance of the matching unit — and hence the voltage at the coils — is larger (by about a factor of 2 if the same number of turns per driver is used).

The experience with the RF system at RADI will have direct impact on the design of the ITER RF system presently being carried out by RFX Padua in collaboration with IPP. Apart from the number and the arrangement of the drivers, open questions which will be addressed by RADI are:

- The distribution of the output RF power into the source (the Faraday screen, eddy currents in the back plates etc). This knowledge is critical in order to determine the cooling requirements for cw operation.

- The optimum number of coil turns. The impedance of the matching circuit and hence the peak-to-peak (pp) voltage to ground are proportional to the number of turns.
- The possibility to omit the transformer in the matching circuit because HV separation is not necessary. The proof of principle has already been demonstrated at MANITU for one driver per generator, but as mentioned above, in the present stage, the RADI setup suffers from RF breakdowns without transformer.
- The insulation of the coil. For a maximum power of 90 kW at one driver, a peak voltage of 4.5 kVpp between the turns and of 27 kVpp between the coil ends is expected if the standard 6 turn coil is used in the 'CLL' configuration. In vacuum — the tank pressure being of the order of 0.01 Pa — a distance of some mm between the coils should be sufficient.
- The arrangement of the series capacitor with the drivers ('CLL' or 'LCL' configuration, see Figure 12). The 'LCL' arrangement of the series capacitance with the drivers reduces the pp-voltage to source potential by a factor of 2.
- The mutual influence of the matching networks — directly or via the plasma.
- The effect of possible different frequencies of the networks. Due to the self-exciting oscillators in the RF generators the frequency varies on the order of few 10 kHz.
- Exploration of other means for a variable matching. In order to compensate the variable plasma impedance, the variable capacitor — which is rather large — has to be located near the source. This may be a problem in ITER not only for space but also for accessibility problems. A possible tool for a simpler variable matching is the control of the frequency, but this requires a change in the generator design. The proof of principle has been demonstrated at MANITU [17], where only one generator has to be modified.

4. Source Diagnostics

RADI is very well equipped with diagnostic tools and has sufficient operation flexibility for the (expected) final demonstration of the required plasma homogeneity for an ITER source. The profiles of the negative hydrogen ion and electron density near the dummy grid as well as the Cs neutral and ion density are measured by a combination of optical emission and cavity ring down spectroscopy, Langmuir probes and laser detachment. Due to the lack of a large scale extraction system, the performance of the half-size source cannot be measured in terms of the overall extracted current density, the amount of co-extracted electrons or the

Table 3: Planned diagnostic tools for RADI

Diagnostic	Parameter	Profiles	Comments
Optical Emission Spectroscopy	n_e, T_e, n_{H^-}, n_{Cs}, n_H, Impurities	yes	operational on BATMAN and MANITU, non-invasive, several line-of-sights [14], [16], [19]
Cavity Ring Down Spectroscopy	n_{H^-}	no	operational on BATMAN, absolute measurement [23], [24]
Langmuir Probes	n_e, T_e	yes	problematic in RF and magnetic environment, limits in the distance to the plasma grid [25]
Laser Detachment	n_{H^-}/n_e, n_{H^-}	yes	first signals on BATMAN, no absolute measurement [25], [26]
Local extraction with Faraday Cups	j_{H^-}, j_e	yes	in the final design phase [18]

beam uniformity. Hence the measured plasma parameters have been calibrated to the extracted current density in BATMAN.

The experience with these diagnostics tools at the other two IPP test facilities BATMAN and MANITU give confidence that the performance of RADI can be well extrapolated with respect to the current density. However, the experimental results of RADI will be of limited value with respect to the amount of co-extracted electrons expected in operation. The co-extraction of the electrons depends obviously on the electron density just above the plasma grid but much more critically on the detailed electrical and magnetic field distribution [18]. The electron density can be obtained in principle by optical emission spectroscopy, but only line-of-sight averaged, and with Langmuir probes, but they are limited in the distance to the plasma grid.

In the following the different diagnostic tools will be discussed; an overview is given in Table 3; details can be found in the references there.

4.1. Optical Emission Spectroscopy

Optical emission spectroscopy was demonstrated in the past at the IPP test facilities BATMAN and MANITU [14], [16] to be a powerful and non-invasive diagnostic for negative ion sources. With sufficient line-of-sights this tool can provide spatial and time resolved measurements of plasma parameters and for the monitoring of Cs (and impurities) in the source. The new technique of measuring the negative ion density via the H_α/H_β ratio [19] — developed at IPP — provides an extremely simple way to determine this quantity. Figure 14 shows the correlation of the negative ion density 3 cm in front of the plasma grid with the calorimetric current density as measured by optical spectroscopy at MANITU [14]. The H^-

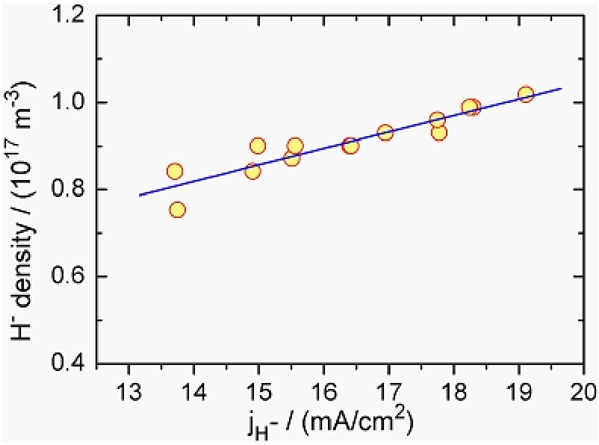

Figure 14: Correlation of the extracted current density with the negative ion density in a distance of 3 cm from the plasma grid, measured by optical emission spectroscopy at MANITU for hydrogen pulses and a cesiated source at a pressure of 0.44 Pa and 70 kW RF power. For comparison: the electron density for these pulses is about $3x10^{17}$ m^{-3}.

density of $1x10^{17}$ m^{-3} in front of the grid for an extracted current density of 22 mA/cm^2 is in accordance with theoretical estimations [20], [21].

RADI is presently equipped with two three-channel low resolution survey spectrometers[2] ($\Delta\lambda_{FWHM} \approx$ 1-1.8 nm, λ = 200-870 nm, 100 ms time resolution). The multiplicity of diagnostic ports perpendicular and parallel to the grid will allow recording the time traces of the Blamer lines as well as Cs lines at various line-of-sights in the source. The light is collected via a lens with a diameter of 6 mm and transferred by a quartz fibre with a length of 30 m and a diameter of 0.4 mm to the spectrometers. By different analysis techniques [14] one can obtain the neutral hydrogen density, the electron temperature and density, and the gas temperature. The determination of local quantities is possible via tomography by a proper arrangement of the line-of-sights. The large ports (40 mm diameter, see Figure 7) give access to axial profiles of the plasma parameters in front of the grid with a spatial resolution of about 1 cm.

4.2. Cavity Ring Down Spectroscopy

The Cavity Ring Down Spectroscopy (CRDS) method [22] measures the decay of radiation leaking out of a high-finesse optical cavity (f ~ 60000 for a reflectivity of 99.995% using special dielectric mirrors) after being excited by a pulse from a Nd:YAG-laser at a wavelength of 1064 nm. The empty cavity has an intrinsic e-folding time for the ring-down-signal of about 50 µs. The attenuation of the vacuum background signal by the photo detachment process due to the presence of negative hydrogen ions can easily be discerned and yields the absolute line-of-sight integrated negative ion density in the source. The method has the significant advantage of being insensitive to RF-interference. The laser beam is transported to the source via a shielded mirror system. There is an absolute power limit for operation given by the damage threshold of the mirror coatings, which is approximately 500 mJ/cm^2.

[2] Plasus EmiCon System. Contact: Plasus Ingenieurbüro, 86343 Königsbrunn, Germany; www.plasus.de

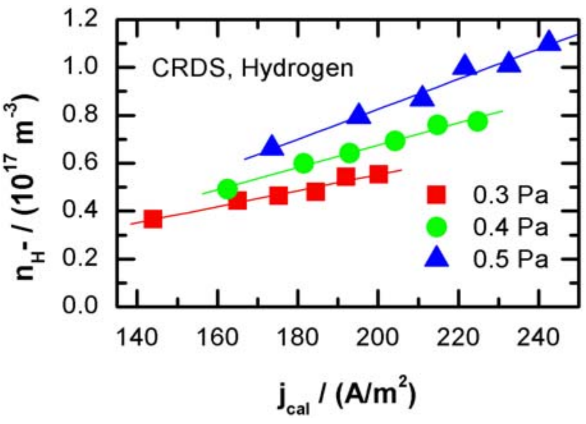

Figure 15: Correlation of the negative ion density in front of the plasma grid with the electrically measured ion current density as measured by Cavity Ring Down Spectroscopy at BATMAN [24]. The RF power varies in all three cases from 40 to 74 kW in steps of 6 - 7 kW.

The CRDS system was recently successfully commissioned at the BATMAN test facility; the measured values of the negative ion density agree rather well with those of the optical emission spectroscopy [23], [24].

Figure 15 shows an example of a good correlation of the measured negative ion density in front of the plasma grid and the calorimetric current density at BATMAN. The different dependence for the different source pressure is most probable caused by the different survival length of the negative ions.

4.3. Langmuir Probes

RADI will be equipped with two movable Langmuir probe systems for a time-resolved measurement of the electron density and temperature profiles perpendicular and parallel to the grid. The systems are a copy of the SMARTPROBE™ Langmuir probe system that was adapted to the RF source at BATMAN in collaboration with the Charkov University, Ukraine[3] and was successfully commissioned there [25]. Spatial profiles can be obtained by a motor-driven positioning system with a maximum distance of 400 mm from the source edge. The main challenge of the hardware, apart from the operation at high potential, is the compensation of the RF noise at around 1 MHz. A further complication is the fact that even the RF frequency is not constant but varies with RF power and plasma impedance and that there exist strong harmonic components to the main RF signal.

As the presence of the Langmuir probe locally influences the plasma parameters the interpretation of the Langmuir probe data is not straight forward. Additionally, the minimum distance of the probe tip to the plasma grid is limited due to the interaction of the wall sheath and the probe sheath. A further complication is the presence of various superimposed magnetic fields near the grid. This problem can be addressed due to the flexibility of the half-size source that allows a comparison of the Langmuir probe measurements with and without any magnetic fields.

[3] Contact: Prof. V. Dudin, University of Charkov, Ukraine

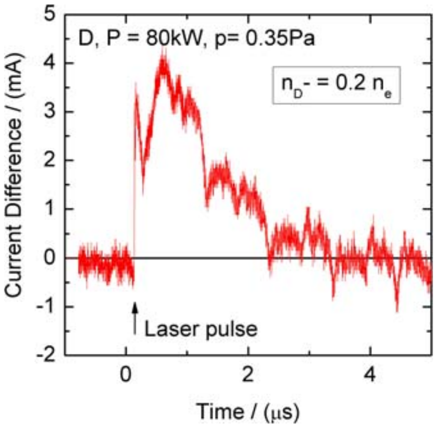

Figure 16: Example of a first laser detachment measurement of the negative ion density 3 cm above the plasma grid at BATMAN. The increase in current after the laser pulse is due to the detached electrons which are collected on the probe tip.

The results of the Langmuir probe measurements are also required as input for other diagnostic tools. They provide the basic input data for the evaluation of the spectroscopic data and for modeling. The Langmuir system is also the basis of the Laser Detachment system (see below).

4.4. Laser Detachment

The laser-detachment method [26] will be used for a relative spatially and temporally resolved measurement of the negative ion density distribution. In brief, the principle is the detachment of the electrons from the negative hydrogen ion by a pulsed laser beam. These additional electrons are detected by a Langmuir probe system biased in the electron-saturation region. At RADI, the same laser is used both for the CRDS system and the laser detachment. The probe tip is planned to be coaxial to the laser beam; hence the length of the probe tip (10 mm) determines the spatial resolution of the system. The temporal resolution is limited by the laser pulse frequency of 15 Hz, resulting in a maximal time resolution of about 60 ms. For the measurement, it must be assured that all negative hydrogen ions are detached within the sheath area around the probe tip; this is guaranteed by a sufficient laser beam power (200 mJ) and a laser beam diameter (6 mm) being much larger than the probe tip diameter (50 μm). Due to the magnetic fields an absolute calibration of the system itself is difficult; this can be done however by using the same line-of-sight as the cavity ring-down spectroscopy.

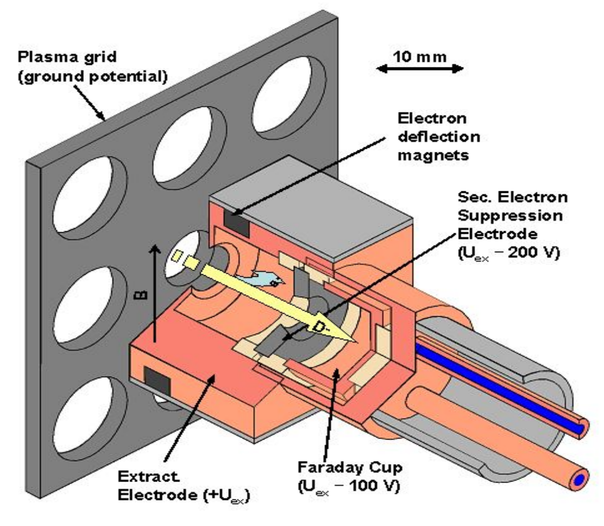

Figure 17: Local extraction system for RADI. The size is adapted to the size of the grids used at the IPP test facilities (8 mm diameter of the aperture). The extraction voltage is planned to be in the 7 – 10 kV range.

The Laser Detachment method in both a noisy RF environment and during beam extraction was demonstrated at

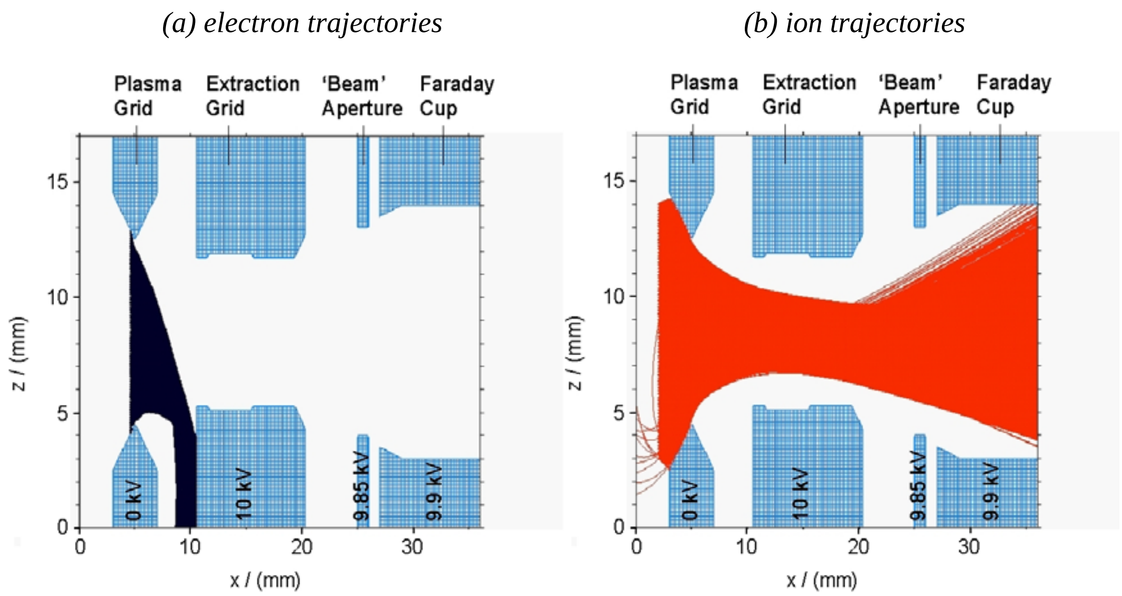

Figure 18: Calculated trajectories of electrons (a) and ions (b) for deuterium extraction with 200 A/m^2 at 10 kV and an electron/ion ratio of one. The extracted current densities of ions and electrons are derived from the currents on the extraction grid and the Faraday cup. The 'beam' aperture is on a slightly negative potential with respect to the Faraday cup in order to suppress secondary electrons; furthermore, a current on that aperture indicates bad beam optics.

BATMAN [25]. A first example is shown in Figure 16. The probe tip currents are in the order of some mA. In order to compensate periodic changes of the plasma parameters with the oscillating RF power, the laser is triggered in phase with the RF power.

4.5. Local Extraction

Local single aperture extraction with a Faraday cup system will be used in order to get some information about the possible ion and electron current density and the beam homogeneity. The Faraday cup system is currently in the final design phase. A conceptual design sketch with typical voltages is shown in Figure 17. The geometry and the magnetic configuration in the extraction grid are adapted from the geometry of the large area grid (LAG), which is presently used at the test beds BATMAN and MANITU [27], with a diameter of the plasma grid aperture of 8 mm; the electrons are deflected by permanent magnets to specially designed electrodes similar to the deflection in actual extraction grid systems. Both electron and ion currents are measured electrically; secondary electrons are suppressed by a small negative (~100 V) potential difference between the cup and the electron deflection electrode (see Figure 17). A design goal is to achieve similar voltages (8 – 9 kV) as in a 'real' grid system.

Figure 18 shows the calculated trajectories of ions and electrons for deuterium extraction at 10 kV and 200 A/m^2 with an electron to ion ratio of one [18]. The calculations have

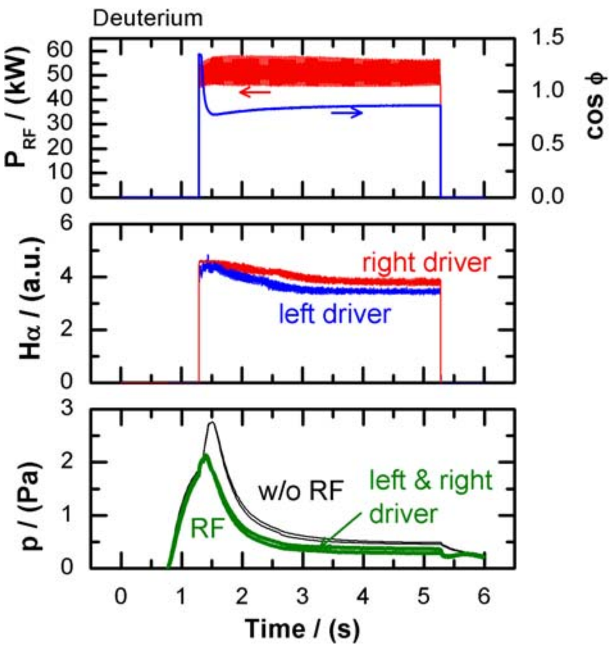

Figure 19: First example of a 50 kW discharge at RADI with deuterium. Only the two lower drivers are powered.

been done with the KOBRA-3D code. Whereas all the ions pass through to the Faraday cup, the electrons are deflected onto the grid, however not to the pockets in the extraction grid, but onto the grid surface. This is consistent with the damage patterns of the extraction grid at BATMAN [18].

With 10 to 15 of such Faraday cups distributed downstream on the dummy grid, sufficient information on the negative ion current profile as well on the profile of the amount of co-extracted electrons should be obtained.

5. First Results

Figure 19 shows time traces of a first 50 kW RF discharge in deuterium with the lower two drivers (see Figure 6a) powered. The oscillations of the RF power signal is most probable due a RF pick up of the signal transmission line. The matching unit of the RF circuit regulated the cosine of the phase angle between RF current and voltage to a value of roughly 0.8. As it is the case for the “standard“ IPP RF source, the plasma ignition is supported by a starter filament — which is switched off after ignition — and a so-called gas puff, that can be seen in the time traces of the driver pressure in Figure 19. In the case of the drivers in series, only one filament is necessary. In order to determine the filling pressure of the source, the gas valve is closed about 600 ms after the RF is switched off.

The plasma intensity (see the time traces of the H_α line emission in Figure 19. measured in the drivers) and hence the RF coupling in both drivers is almost identical. The small differences of the plasma light in both drivers are most probably due to small differences in the driver pressure, apart from possible small differences in the coil geometry and/or position. The temporal evolution of the H_α line emission may be a consequence of the decreasing driver pressure due to the gas puff, somewhat compensated by the increasing coupling.

The pressure during the plasma discharge in the lower drivers where the RF is coupled in is lower than the pressure in the (upper) drivers without plasma. This effect was already

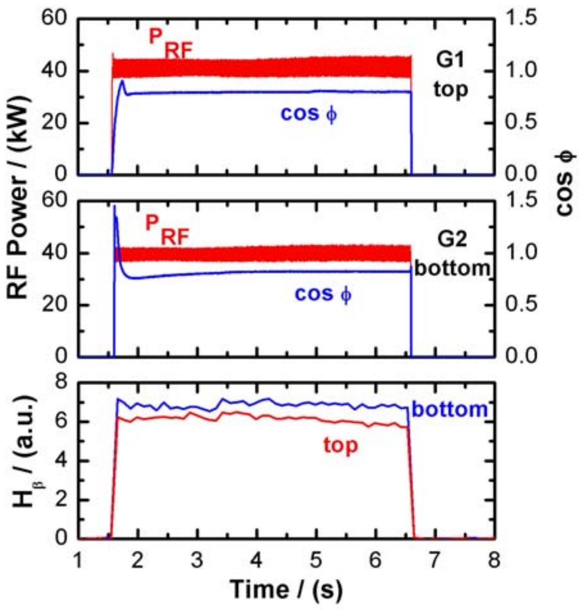

Figure 20: First example of a 2x40 kW discharge at RADI with deuterium. The bottom graph shows the plasma light emission parallel to the (dummy) plasma grid in a distance of about 1 cm.

observed in the smaller IPP test beds and can be explained by the plasma flow out of the drivers into the source.

Figure 20 shows an example of a first discharge in deuterium with all four drivers powered, but still without magnetic fields, bias or Cesium evaporation. The matching of each RF circuit was changed slightly for the simultaneous operation compared to the operation with one pair of drivers only. Nevertheless, a four driver operation is possible; furthermore, the RF plasma itself seems to be more or less homogeneous as can be seen in the plasma light emission (uncalibrated H_β signal) in front of the plasma grid. The further exploration of the plasma homogeneity and the dependence on the various source parameters is part of the upcoming physics experiments.

6. Summary

IPP Garching has constructed a ½-size ITER source in order to demonstrate the scaling and modular concept of the IPP RF source. A new test facility RADI was successfully commissioned with first plasma pulses. The source is equipped with two RF generators supplying two drivers in series and rated for 180 kW for 30 s each.

RADI has the primary goal of demonstrating the required plasma homogeneity of large RF sources as well as testing the operation of an ITER-like RF circuit. The dependence of the homogeneity on the various plasma parameters and the magnetic fields will be measured by several diagnostics including optical emission spectroscopy, Laser photo-detachment, Langmuir probes, and Cavity Ring Down Spectroscopy.

References

[1] "ITER Technical Basis", ITER EDA Documentation Series No. 24, Plant Description Document, Sec. 2.5.1. International Atomic Energy Agency (IAEA), 2002

[2] E. Speth, H. Falter, P. Franzen, U. Fantz, M. Bandyopadhyay, S. Christ, A. Encheva, M. Fröschle, D. Holtum, B. Heinemann, W. Kraus, Ch. Martens, P. McNeely, S. Obermayer, R. Riedl , R. Süss , A. Tanga, D. Wünderlich. *Overview of the RF source development program at IPP Garching.* Nuclear Fusion 46(6) 2006, S220

[3] E. Speth, P. Frank, B. Heinemann, W. Kraus, R. Riedl, et al. *RF sources for fusion applications: Design, development and performance.* In: B. Beaumont, P. Libeyre, B. deGentile, G. Tonon (Eds.), Proceedings of the 20th Symposium on Fusion Technology, Marseille, 1998. Association EURATOM-CEA, Saint Paul Lez Durance, 1998, p. 27.

[4] O. Vollmer, A. Stäbler, E. Speth, M. Ciric, P. Franzen, et al. *Commissioning and performance of the new ASDEX Upgrade neutral beam injector.* In: B. Beaumont, P. Libeyre, B. deGentile, G. Tonon (Eds.), Proceedings of the 20th Symposium on Fusion Technology, Marseille, 1998. Association EURATOM-CEA, Saint Paul Lez Durance, 1998, 449

[5] E. Speth, NBI Team. *Development of powerful RF plasma sources for present and future NBI systems.* Plasma Science and Technology 6, 2004, 2135

[6] A. Krylov, D. Boilson, H.P.L. de Esch, U. Fantz, R.S. Hemsworth, O.Provitina, S. Pontremoli, L. Svensson and B. Zaniol. *Caesium and Tungsten behaviour in filamented arc driven Kamaboko-III beam source.* Nuclear Fusion 46 (2006) S324

[7] K. Ikeda, Y. Takeiri, O. Kaneko, K. Nagaoka, Y. Oka, M. Osakabe, K. Tsumori, M. Sato, E. Asano, and T. Kawamoto. Review of Scientific Instruments 75(5), 2004, 1744

[8] N. Umeda, L.R. Grisham, T. Yamamoto, M. Kuriyama, M. Kawai, et al. *Improvement of beam performance in the negative-ion based NBI system for JT 60U.* Nucl. Fusion 43 (2003) 522–526

[9] P. Franzen, H. D. Falter, E. Speth, W. Kraus, M. Bandyopadhyay, A. Encheva, U. Fantz, Th. Franke, B. Heinemann, D. Holtum, C. Martens, P. McNeely, R. Riedl, A. Tanga, R. Wilhelm**.** *Status and plans for the development of an RF negative ion source for ITER NBI.* Proceedings of the 23rd Symposium on Fusion Technology, Venice, 20-24 Sept. 2004. Fusion Engineering and Design 74 (2004) 351

[10] P. Franzen, H. D. Falter, U. Fantz, W. Kraus, M. Berger, S. Christ, M. Fröschle, R. Gutser, B. Heinemann, S. Hilbert, S. Leyer, A. Lümkemann, C. Martens, P. McNeely, R. Riedl, E. Speth, D. Wünderlich. *Progress of the Development of the IPP RF Negative*

Ion Source for the ITER Neutral Beam System. Proceedings of the 21st IAEA Fusion Energy Conference, Chengdu, China, 2006. To be published in Nuclear Fusion.

[11] W. Kraus, B. Heinemann, H. D. Falter, U. Fantz, T. Franke, P. Franzen, D. Holtum, Ch. Martens, P. McNeely, R. Riedl, E. Speth, R. Wilhelm. *RF-Source Development for ITER: Large Area H- Beam Extraction, Modifications for long Pulse Operation and Design of a half Size ITER Source.* Proceedings of the 23rd Symposium on Fusion Technology, Venice, 20-24 Sept. 2004. Fusion Engineering and Design 74 (2004) 337

[12] W. Kraus, P. Franzen, B. Heinemann, E. Speth, O. Vollmer. Fusion Engineering and Design, 56-57 (2001) 499

[13] O. Vollmer, B. Heinemann, W. Kraus, P. McNeely, R. Riedl, E. Speth, R. Trainham, R. Wilhelm. Fusion Engineering and Design, 56-57 (2001) 465

[14] U. Fantz, H. Falter, P. Franzen, S. Christ, B. Heinemann, A. Lorenz, W. Kraus, P. McNeely, R. Riedl, E. Speth, A. Tanga, D. Wünderlich. *Spectroscopy – a powerful diagnostic tool in source development.* Nuclear Fusion 46 (2006) S297

[15] W.G. Graham, Proc. 2nd Int. Symp. on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven National Laboratory, Upton, New York, 1980, p 126

[16] U. Fantz, M. Bandyopadhyay, H. D. Falter, P. Franzen, B. Heinemann, W. Kraus, P. McNeely, R. Riedl, E. Speth, A. Tanga, R. Wilhelm. *Diagnostics of the Cesium Amount in an RF Negative Ion Source and the Correlation with the Extracted Current Density.* Proceedings of the 23rd Symposium on Fusion Technology, Venice, 20-24 Sept. 2004. Fusion Engineering and Design 74 (2004) 299

[17] W. Kraus. Meeting of the Coordinating Committee on Neutral Beams, Naka, 12-16 Dec. 2006; to be published.

[18] R. Gutser. Diploma Thesis, University of Augsburg, 2006

[19] U. Fantz, D. Wünderlich. *A novel diagnostic technique for H^-/D^- densities in negative hydrogen ion sources.* New Journal of Physics 8, 2006, 301

[20] R. Wilhelm, Max-Planck-Institut für Plasmaphysik, Garching, Germany. Private communication, 2003

[21] M. Bandyopadhyay. *Studies of an Inductively Coupled Negative hydrogen Ion Radio Frequency Source through Simulations and Experiment.* Ph.D. Thesis, Technische Universität München, 2004.

[22] A. O'Keefe and D.G. Deacon. Rev. Sci Instrum. 59(12), 1988, 2544

[23] M. Berger, U. Fantz. To be published

[24] M. Berger. PhD Thesis, University of Augsburg, 2006

[25] S. Christ, U. Fantz. To be published

[26] M. Bacal, G.W. Hamilton, A.M. Bruneteau, H.J. Doucet, J. Taillet. *Measurement of H- density in a plasma by photodetachment.* Rev. Sci. Instrum. 50(6), 1979, 719

[27] B. Heinemann, J. Bucalossi, P. Frank, R. Riedl, A. Simonin, et al.. *Large-Area, High-Transparency Extraction System for Negative Ions.* In: B. Beaumont, P. Libeyre, B. de-Gentile, G. Tonon (Eds.), Proceedings of the 20th Symposium on Fusion Technology, Marseille, 1998. Association EURATOM-CEA, Saint Paul Lez Durance, 1998, p. 433

[28] L. Svensson et al. Nuclear Fusion 46 (2006) S369