Status of RADI - a RF source size-scaling experiment towards the ITER source

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1. Introduction

IPP Garching is currently developing a RF source for the ITER neutral beam system. The principle suitability concerning current density (> 20 mA/cm^2 D^-), pressure (0.3 Pa) and electron content (j_e/j_{D^-} ~ 1) has been demonstrated with the test facility BATMAN [1], [2], [3], but with only small extraction area (~ 70 cm^2) and limited pulse length (< 6 s). The further development concentrates now on long pulse operation (at the test facility MANITU, operational this spring [4]) and source size extension.

Figure 1 shows the principle design of the IPP RF driven negative ion source. The details are given elsewhere [5],[6]. 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 10 mT, the so-called 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.

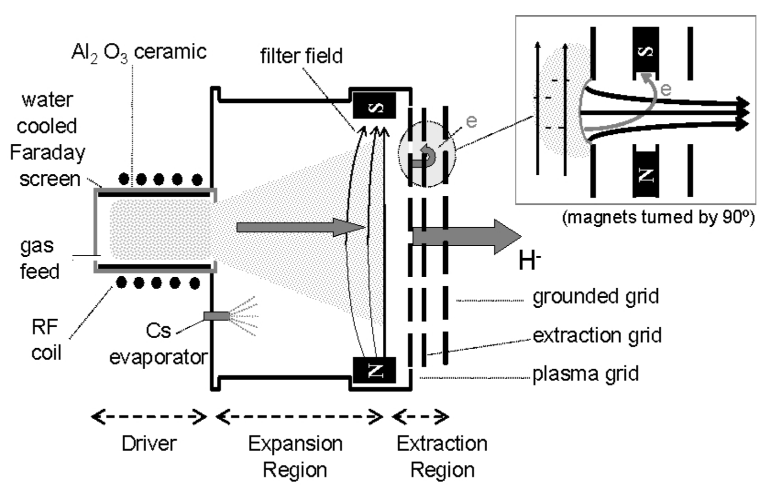
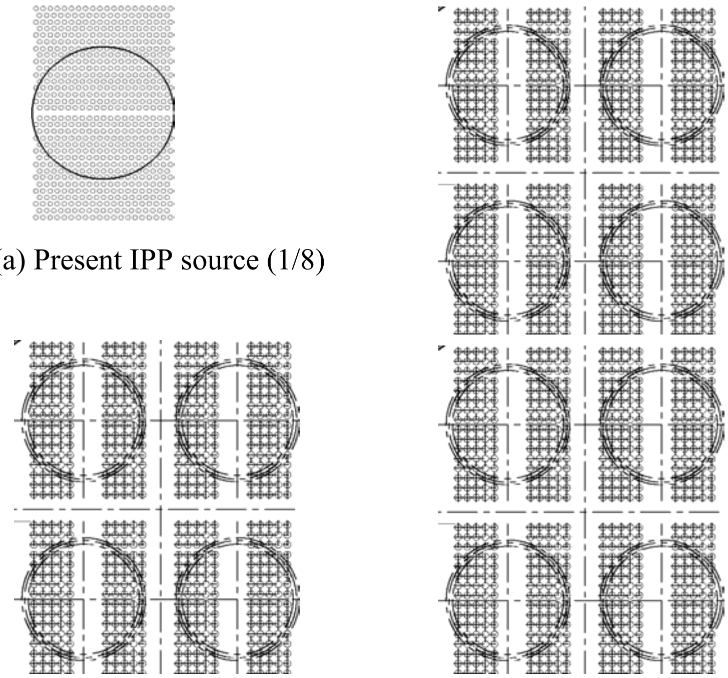


Figure 1: Schematic view of the IPP RF source with one driver. The extraction region is shown in detail; the magnets in the extraction grid are shown rotated by 90º.

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 eV are necessary for minimizing the destruction rate of the negative hydrogen ions by electron collisions; then mutual neutralization with positive ions takes over as the dominant destruction process.



(a) Present IPP source (1/8)

(b) half-size source

(c) ITER source

Figure 2: Size comparison of (a) the present IPP RF source, (b) the half-size source and (c) the ITER source. The circle indicates the standard RF driver with a diameter of 24 cm.

At present, the source body dimensions (32 x 59 cm^2) are those of the positive ion system presently installed at ASDEX Upgrade [7]. As an intermediate step (see Figure 2) between the present small source and the full size ITER source — with a height of 1.6 m and a width of 60 cm — the so-called half-size source is currently under construction. The source will roughly have the width and half the height of the ITER source; its modular concept will allow an easy extrapolation to the full size ITER source without any change of the source depth. The experience of the operation of this half-size source will then enter in the final design of the ITER full size source.

Due to technical limitations of the foreseen test bed large scale extraction is not possible. Hence, the half-size source is devoted to test the geometry and the optimum number of drivers as well as the required homogeneity of large plasmas. The performance of the negative ion sources is normally expressed by the source efficiency for ions and electrons, i.e. the ion and electron current densities divided by the RF power at sufficient low source pressure. Hence, IPP Garching is currently investigating and testing plasma diagnostic tools at the other test beds (BATMAN and MANITU). The measured plasma parameters — especially the negative ion density in front of the grid — are then related together with modeling to the source efficiency.

2. RADI Setup

A new test facility (called RADI) is being constructed in order to prepare this size-scaling demonstration. The new test facility will be using one of the injector boxes — the radial box — of the decommissioned W7-AS injectors. The half-size source is scheduled to be ready for commissioning in summer 2005; first results are expected after the summer break in October 2005.

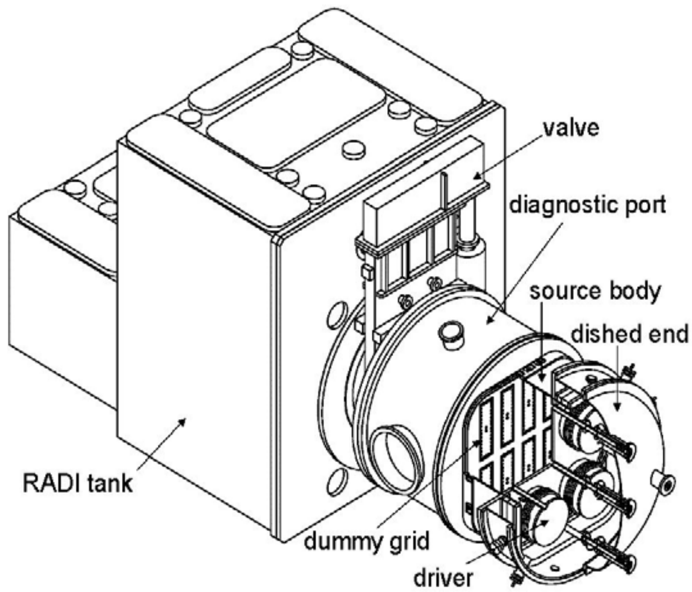


Figure 3: 3D sketch view of the RADI test bed with the half-size source. The ITER grid segmentation is indicated in the dummy grid.

Figure 3 shows a 3D-sketch of the whole test bed with the half-size source. Full size extraction will not be possible due to the lack of a big insulator, of a large size extraction system and of a beam dump. Hence, the whole source can be operated on ground potential. However, to get some insight of the current density distribution across the grid, local extraction using faraday cups is planned. An advantage of the plasma operation only is that RADI can be operated also with deuterium without radiation protection measures.

In the following we will describe in more detail the design of the half-size source, the RF circuits and the new RADI test bed. The main parameters are summarized in Table 1.

Isotope	H or D
Source size	800 x 760 mm^2
Equivalent Plasma Grid Size	1000 cm^2
Tank Volume	5 m^3
Pulse length	10 s
RF power	2x180 kW
Pumping System	Ti Getter
Pumping Capacity	2 x 60000 l/s, 1 x 40000 l/s
Extraction	none, local extraction only
PG bias	power supply 50 V, 500 A
Filter field	grid current 15 V, 5 kA or rod filter
Cs oven	2 ovens with 3 g each

Table 1: Main parameters of RADI

2.1. Source Design

The half-size source consists mainly 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 and (4) the driver back plates. Figure 4 shows the detailed design of the source. In contrast to the present NNBI sources at the various test beds, the source in the ITER NNBI system is kept in vacuum (VIBS --- vacuum immersed beam source [8]); furthermore, the source will not be part of the tritium containment. Hence, the back plates do not have to withstand the vacuum forces and the sealing of the source parts does not underlie the special tritium requirements. To simulate the VIBS of ITER, the drivers can be therefore enclosed by a dished end connected to the driver back plate. This vacuum is separated from the source vacuum and pumped via a bypass valve that is closed during plasma pulses. However, we enforced the source back plate, so that we can operate in principle the source in air; this may help for the commissioning but problems may arise with the voltage holding of the RF coils (see below).

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

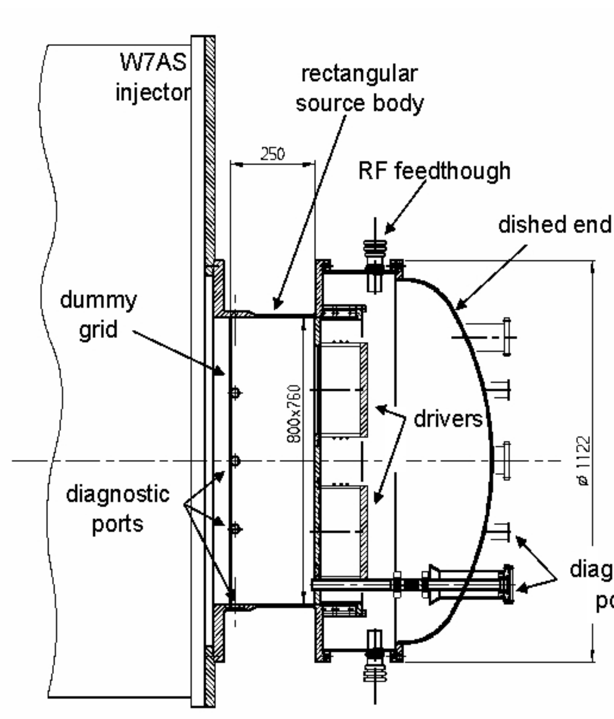


Figure 4: Sketch view of the half-size source. Details are given in Section 2.1.

In contrast to the large ITER-like filamented driven sources, a large RF source can be kept rather short due to its principle cuboidial form. This may be an advantage for the

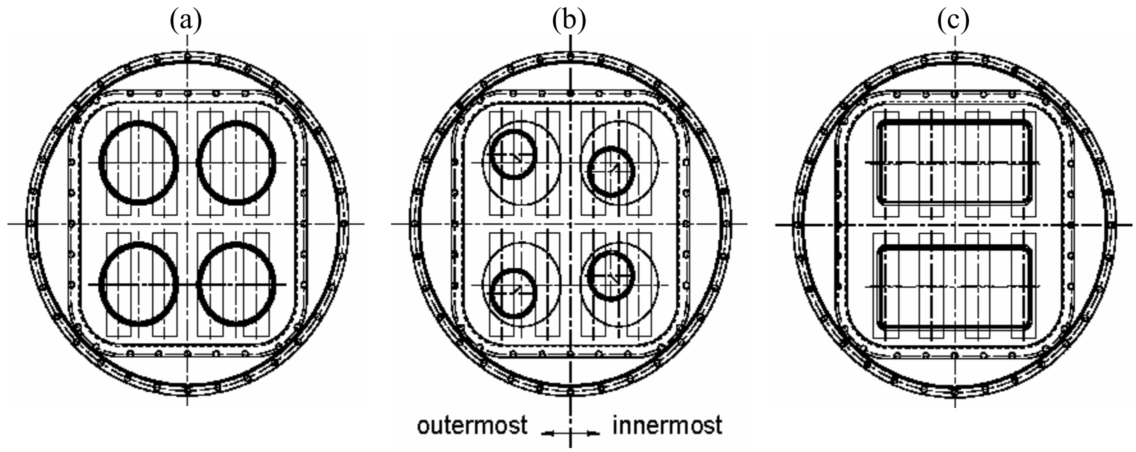


Figure 5: Driver configurations foreseen for RADI: (a) 4 drivers with 240 mm ∅ (start-up configuration); (b) 4 drivers with 150 mm ∅ on an eccentric flange; and (c) two race track drivers. The ITER grid segmentation is indicated by the 2x4 rectangles.

neutral hydrogen atom balance: the ratio of the grid area — where the extracted negative ions are created by the surface process — to the other source wall areas increases with increasing grid area, if the source depth is constant; this reduces the loss rate of neutral hydrogen atoms at the walls via recombination and increases therefore the neutral atom flux to the grid.

The RADI source body has a depth of 250 mm. The distance of the drivers to the grid however can be varied — if both sides are vented: the source back plate can be moved inside the source body by spacers. Hence the physical source depth can be varied between 150 mm and 250 mm. This possibility allows us, without major rebuilding of the test bed, to investigate the influence of the source depth on the source performance.

In order to optimize the number and geometry of the drivers, three different driver configurations are presently foreseen for RADI at it is shown in figure 5. Previous experiments at our test bed MANITU [1] showed that our standard RF driver with a diameter of 240 mm can illuminate a plasma grid extraction area of 150 – 200 cm^2 with sufficient homogeneity. Hence, 4 of these standard drivers might be sufficient for our case of an equivalent 1000 cm^2 extraction grid area taking a certain 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. This will allow an optimization of the driver position. The third approach is to use two race track formed drivers with the dimension of 510 mm x 250 mm. For this configuration a new source back plate is necessary; those drivers are similar in geometry as the one that have been used successfully for the positive ion RF source at ASDEX Upgrade [7].

The drivers have a depth of 14 cm and consist as our standard driver of an alumina cylinder pressed onto the source back plate via the driver back plate. Inside the cylinder, a tungsten-coated copper Faraday screen protects the quartz being sputtered by the plasma. However, due to this resulting inductive coupling of the RF to the plasma, a so-called starter filament for the plasma start-up is necessary in our RF source. This filament is switched-off when the plasma is ignited. RADI will be equipped with two starter filaments.

A large number of ports for diagnostics and for the RF power and gas and Cs supply are foreseen. For the 4 drivers configuration 5 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 5 vertical and 3 horizontal ports allow access for plasma diagnostics near the grid (~1 cm distance) and for possible filter field modifications (see below). The ports have a diameter of 40 mm; hence, axial profiles of the plasma parameters (see below) using 2 or 3 light fibers are possible. The port configuration is adjusted to the segmentation of the ITER source grid system.

2.2. Half-Size Source Test Bed

The existing pumping system consists of one turbo molecular pump (2000 l/s) and three Titanium getter pumps with a total pumping capacity of 160.000 l/s. The box dimensions are $1.3 \times 1.6 \times 1.8\ m^3$. This pumping system limits the possible pulse length to about 10 s.

The available circular port of the RADI test bed 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 conductance of the ITER grid system — 1280 holes with a conductance of 11.7 l/s each at is for the SINGAP system, including the grounded grid — and hence the gas flow conditions of the ITER source. For simplicity, this is achieved with small lengthy slits in the dummy grid. In order to have an at least limited control of the conductance without an 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.

The performance of a negative ion source depends very critically on the work function of the plasma grid and hence on the Cs coverage and the temperature of the plasma grid. Cs enhances the negative ion yield and reduces the amount of co-extracted electrons. Although RADI will not have extraction and hence no possibility to study the influence of Cs on the co-extracted electron current, Cs evaporation is still necessary for the influence on the local plasma parameters in front of the grid. The new work function measurement allows us to cor-

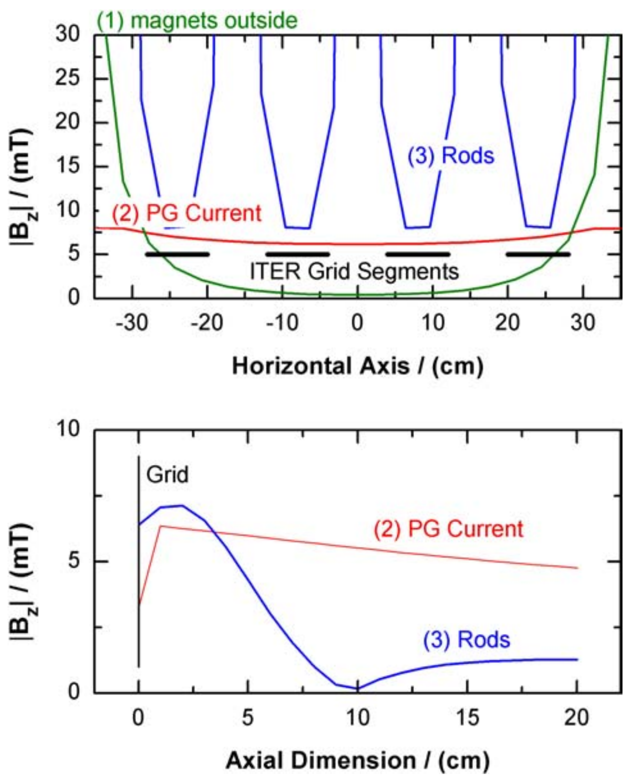


Figure 6: Profiles of the magnetic filter field by (1) permanent magnets outside the source at ±32.5 cm, (2) by a plasma grid current of 10 kA, and (3) by magnet rods inserted in the source with the magnets being located 1 cm above the grid. (Top) horizontal profiles 1 cm above the grid. The grid segments are indicated by the thick black lines. (Bottom) Axial profiles into the source at the centre of the grid segment.

relate those and the amount of evaporated Cs to the grid work function. This will help for the up to now limited understanding of the Cs dynamics and transport in an RF source. Cs will be supplied by two ovens, sitting on the source back plate; each oven is equipped with 3 ampoules containing 1 g of Cs each. The plasma grid will be heated by electrical heating wires to temperatures of 150 °C to 300 °C necessary to reduce the work function of the Cs covered grid sufficiently.

In order to reduce further the co-extracted electrons, the plasma grid is usually positively biased against the source body in negative ion sources. Although we don't have large scale extraction in RADI, bias is also foreseen on order to study the influence on the plasma parameter. First experiments at BATMAN [9] showed that the bias voltage should be similar to the plasma potential (~10 V) when the Cs effect is optimal and no electrons are present near the plasma grid. In this case the bias current is only small.

At large plasma sources permanent magnets outside the source cannot be used in order to create the necessary filter field in front of the grid. In the ITER reference source design the filter field is provided by a current flowing through the plasma grid. In order to test this "PG filter" method, RADI will be equipped with a 5 kA, 15 V power supply. For comparison, the filter field can also be produced by five water-cooled rods of magnets inserted vertically into the source according to the ITER grid segments. Figure 6 shows the resulting axial and horizontal profiles of the vertical magnetic field strength. It shows clearly that permanent magnets outside the source do not produce a sufficient field in the center due to the large distance. 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 here some variation across the single grid segments is produced. RADI will test both configurations, also in combination. Furthermore, the influence of the filter field change due to the magnets in the extraction grid can also easily simulated by attaching a dummy extraction grid.

2.3. RF circuit

Figure 7 shows the RF circuit(s) at RADI. The RF power supply of RADI consists of two 1 MHz RF generators rated for 180 kW each and 10 seconds. Both generators have already been commissioned at IPP. The generators have a typical electrical efficiency of 60%.

The principle as well as the technical layout of the RADI RF circuits is very similar to the system which is planned for ITER. The main difference is that in the ITER system the transmission line — at 1 MV potential — is split into two parts for accessibility reasons. In contrast to a design with only one RF generator supplying all drivers in series, our — and the ITER design — has the advantage that the RF power can be set individually and therefore plasma non-uniformities can be compensated. Experiments with large filamented sources [10] showed that the main non-uniformity is in the vertical, longer, dimension, most probable due to *ExB* drifts due the filter field; hence, in the case of the 4 driver configuration one RF generator will supply the two horizontal drivers in series.

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 of the plasma parameters and is of the order of a few Ohm. The matching and transforming is done via two capacitors — one parallel at the generator side and one in series near the source — and a transformer, typically 3:1. For the present RF sources at IPP both for negative and positive

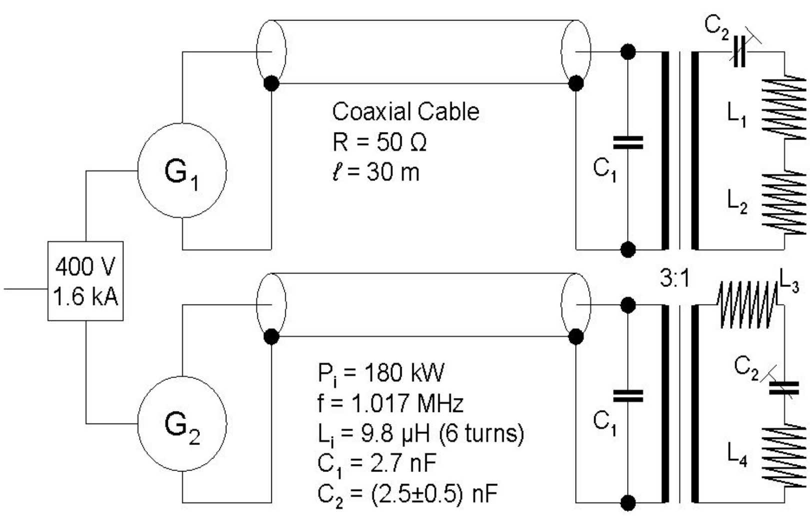


Figure 7: RF circuit for RADI for the 4 driver configuration (L_1 – L_4). The matching unit near the source is drawn in two possible arrangements to be tested ('CLL' or 'LCL', respectively); during operation only one arrangement for both circuits will be used.

ion production the transformer separates the source potential from ground. This is not necessary for ITER, where the RF generators are sitting at the 1 MV potential, and for RADI. Also in the present IPP sources the series capacitor — located near the source — is variable in order to adjust the plasma impedance. This is especially necessary when source operation is changed from hydrogen to deuterium and vice versa.

The experience with the RF system at RADI will have direct impact on the design of the ITER RF system (if the RF source is chosen, of course). Apart from the number and the arrangement of the drivers, open questions are:

- The distribution of the output RF power into the source including the Faraday screen, eddy currents in the back plates etc. This will determine the cooling requirements for cw operation.
- The optimum number of coil 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.
- The arrangement of the series capacitor with the drivers (‘CLL’ or ‘LCL’, see Figure 7).
- The insulation of the coil. For a maximum power of 90 kW at the driver, we expect a voltage of 4.5 kVpp between the turns and of 27 kVpp between the coil ends if our 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. If we operate the coil in air, organic insulation must be used. 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.
- The effect of possible different frequencies of the networks. The RF generators are equipped with self-exciting oscillators with a self-adjusting frequency to the matching circuit. Hence the frequency is not constant with variations of the order of 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 mean for a simpler variable matching is the control of the frequency, but this requires a change in the generator design.

Diagnostic	*Parameter*	*Profiles*	*Comments*
Optical Emission Spectroscopy	n_e, T_e, n_{H-}, n_{Cs}, $n_{H°}$, Impurities	yes	already working on BATMAN, non-invasive
Langmuir Probes	n_e, T_e	yes	problematic in RF environment, also installed in the plasma grid
Work Function	Cs-coverage	no	in preparation
Laser Detachment	n_{H-}	yes	in preparation, no absolute measurement
Cavity Ring Down Spectroscopy	n_{H-}	no	in preparation, absolute measurement
Local extraction with Faraday Cups	j_{H-}	yes	voltage too low for maximum performance

Table 2: Planned diagnostic tools for RADI

3. Source Diagnostics

Due to the lack of a large scale extraction system, the performance of RADI cannot be expressed in terms of overall extracted current density and beam uniformity. Hence RADI will be equipped with a bunch of more or less sophisticated diagnostic tools in order to measure the plasma parameters determining the performance of the source (see Table 2 and also Ref. [11]). Those are mainly the H^- and electron density profiles across the grid; they will be measured by optical emission spectroscopy, probes, laser detachment and cavity ring down. These methods are/will be actually calibrated to the extracted current density in BATMAN. First results showed a D^- density of 1×10^{17} m^{-3} in front of the grid (~ 1.5 cm) for an extracted current density of 22 mA/cm^2 [11], in accordance with theoretical expectations.

3.1. Optical Emission Spectroscopy

Optical emission spectroscopy was demonstrated at the past at our test beds [11], [12] to be a powerful tool for the non-invasive diagnostic of negative ion sources. With sufficient viewing ports this tool can provide spatial and time resolved measurements of plasma parameters and their profiles and for the monitoring of impurities in the source. Especially our new technique of measuring the negative ion density via the H_α/H_β ratio [11] together with modeling provides a simple and non-invasive access to this quantity.

RADI will be equipped in the first stage with two three-channel low resolution survey spectrometers ($\Delta\lambda_{FWHM} \approx$ 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 us to record the time traces of CsI at 852 nm, H_α and H_β at various line-of-sights (LOS, 1 cm diameter) in the source. The addition of small amounts of rare gases gives access also to the electron density and temperature. The determination of local quantities is possible via tomography by a proper arrangement of the LOS. The large ports (4 cm ∅) give access to axial profiles of the plasma parameters in front of the grid with a spatial resolution of about 1 cm.

3.2. Langmuir Probes

RADI will be equipped with two movable Langmuir probe systems for measuring time-resolved the electron density and temperature profiles perpendicular and parallel to the grid. The systems will be a copy of the Langmuir probe system that is currently adapted to our RF source at BATMAN in collaboration with the Charkov University, Ukraine. The main challenge is the compensation of the RF noise at around 1 MHz, where even the RF frequency is not constant but varies with RF power and plasma impedance.

The Langmuir probes are also essential for other diagnostic tools: they will provide basic input data for the evaluation of the spectroscopic data and for modeling, and are necessary for the Laser Detachment system (see below).

Fixed (simple) Langmuir probes — similar to the probes installed in the divertor of fusion experiments — inserted in the dummy grid will provide relative profiles of the plasma parameters near the grid.

3.3. Work function measurement

The negative ion yield from surface production depends very critically on the work function and hence on the Cs coverage of the extraction grid. Since the work function of Cs layers depends on the layer thickness, work function measurements can be used to optimise the coverage. The work function diagnostics is based on the photo effect, i.e. the Cs-covered surface is illuminated with a white-light Hg-lamp (P_{max}= 100 W). The photon energy is varied by using interference filters. The photo-emitted electrons are captured by a platinum grid positioned parallel to the surface in a few centimetre distance. Since the photocurrent is in the range of nA, the current measurement will be performed with a lock-in amplifier, combined with a light chopper.

Due to the RF noise, in-situ measurements during the pulse are not possible. Another drawback is the presence of magnetic fields at the grid which alter the electron trajectories and may alter the current of the capture grid. Hence we will use a lock which allows us to in-

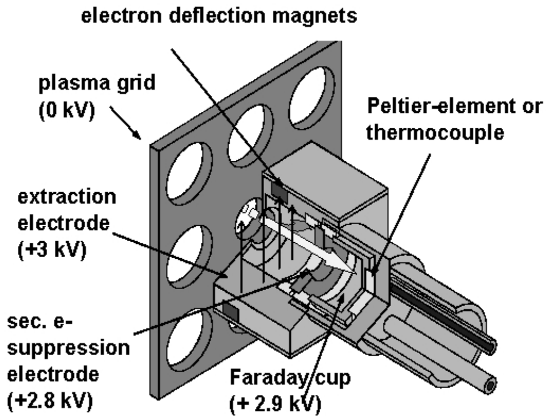


Figure 8: Local extraction system for RADI. The size is adapted to the size of the ITER extraction hole (14 mm diameter).

sert a probe sample to a position near the grid during the pulse and to perform the analysis after a pulse far away from the grid where the magnetic fields are zero.

3.4. Cavity Ring Down Spectroscopy

The Cavity Ring Down Spectroscopy (CRDS) method 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 the pulse of a Nd:YAG-laser. This leads to an intrinsic e-folding time of the transmitted ring-down-signal of about 50 µs. The additional attenuation of the signal by the photo detachment process of the negative hydrogen ions can easily be discerned against this background and yields the absolute line-of-sight-integrated negative ion density in the source while being insensitive to RF-interference. The laser fibre in use limits the pulse energy to 30 mJ, although a setup is conceivable which circumvents this limitation by setting up the laser within a direct line of sight to the source. The absolute power limit for operation is given by the damage threshold of the mirror coatings, which is roughly 500 mJ/cm^2.

3.5. Laser Detachment

The laser-detachment method [13] will be used to determine the spatial and time resolved relative change of the negative ion density distribution. The pulsed laser beam (Nd:YAG-laser at a wavelength of 1064 nm) detaches the electrons from the H^- ion. The electrons are detected with a Langmuir probe system working in the electron-saturation region. The probe tip is arranged to be coaxial to the laser beam, in which the length of the probe tip (1 cm) determines the spatial resolution of the system. The resolution in time is limited by the laser frequency of 15 Hz, resulting in a maximal time resolution of about 60 ms. Measured currents are expected to be in the order of mA using a pulse width of some µs. 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.

Since it is very difficult to calibrate the system absolutely, only relative measurements are planned. However, the combination with the cavity ring-down spectroscopy offers the determination of spatial and time resolved H^- densities.

3.6. Local Extraction

In order to get some information about the possible ion currents and the current density distribution, local extraction with a Faraday cup system from single holes is planned. A sketch design of the Faraday cup with typical voltages is shown in Figure 8. However, the maximum achievable extraction voltage (4-5 kV, due to the small distances) might be too low in order to demonstrate high H^-/D^- current densities.

With 15 to 20 of such Faraday cups properly distributed along the plasma grid, sufficient information of the negative ion density profile can be obtained.

4. Summary

IPP Garching is currently constructing a new test bed in order to demonstrate the scaling and modular concept of the IPP RF source. The source will have roughly the width and half the height of the ITER source. Due to the lack of a large size extraction system, only plasma operation is possible. The source will be equipped with 2 RF generators delivering 180 kW each for 10 s. Commissioning is foreseen in Summer 2005.

Several diagnostics including optical emission spectroscopy, Laser detachment and Cavity Ring Down Spectroscopy will provide the plasma parameters, especially the negative ion density, in front of the grid. These diagnostics will be/are currently commissioned and calibrated against the extracted current density at the other test beds at IPP.

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