Overview of the RF source development programme at IPP Garching

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Abstract

The development of a large-area RF source for negative hydrogen ions, an official EFDA task agreement, is aiming at demonstrating ITER-relevant ion source parameters. This implies a current density of 20 mA/cm^2 accelerated D^- ions at a source filling pressure of ≤ 0.3 Pa and an electron to ion ratio of ≤ 1 from a PINI-size extraction area for pulse lengths of up to 1 hour. The work is progressing along three lines in parallel: (i) optimisation of current densities at low pressure and electron/ion ratio, utilising small extraction areas (< 100 cm^2) and short pulses (< 10 s); (ii); investigation of extended extraction areas (< 300 cm^2) and pulse lengths of up to 3600 s; (iii) investigation of a size-scaling on a half-size ITER plasma source. Three different testbeds are being used to carry out those investigations in parallel. An extensive diagnostic and modelling programme accompanies the activities. The paper contains the recent achievements and the status of preparations in those four areas of development

1. Introduction

For heating and current drive ITER requires ion sources capable of delivering 40 A of D^- ions for up to one hour pulses with a current density of 200 A/m^2. The pressure in the source is required to be at or below 0.3 Pa and the electron / ion ratio ≤ 1. The development of these sources initially concentrated on arc sources as described in the ITER reference design [1].

RF sources for the production of positive hydrogen ions have been successfully developed at IPP for the AUG and the W7AS neutral beam heating systems [2], [3]. A collaboration on high frequency ion source development for negative hydrogen ions between CEA Cadarache and IPP Garching had been started in 1996 with first results reported in 1998 [2]. Compared to arc sources RF sources have less parts, requiring just a source body, an RF coil and a matching circuit. They are therefore cheaper to build and basically maintenance-free in operation. Those design features are potentially quite beneficial for ITER with its remote handling requirements, since the RF sources do not suffer from the limited filament lifetime of the arc sources. Furthermore it is being speculated, that the arc current of the arc sources might contribute to the plasma non-uniformity observed in the large arc sources [4]. In addition there may be an advantage with respect to Cs consumption, as in the RF source there is no filament material that is evaporated and might bury the Cs layer on the walls. Provided RF sources can match the ITER requirements they would therefore be an interesting alternative to the arc sources.

Since September 2002 the development of the RF source is being supported by an EFDA contract aimed at demonstrating that the ITER requirements can be met. The work is progressing along three lines in parallel: (i) optimisation of current densities at low pressure and electron/ion ratio, utilising small extraction areas (< 100 cm^2) and short pulses (< 10 s) on the small testbed “BATMAN”; (ii) investigation of extended extraction areas (up to 300 cm^2) and pulse lengths of up to 3600 s on the large testbed “MANITU”; (iii) a size-scaling experiment on a half-size ITER plasma source on a dedicated plasma source testbed (“RADI”). An extensive diagnostic and modelling programme is accompanying those activities.
The paper is structured as follows: in the next section the experimental set-ups are described with respect to testbeds, source and grid configurations. The third section contains the experimental results with emphasis on hydrogen and deuterium operation, low pressure operation, variation of extraction area and first results with >10 s pulses. The fourth section is devoted to the accompanying diagnostics and modeling work. In the last section an outlook into the next months is presented concerning the extension of the pulse length and the study of the size-scaling characteristics.

2. Experimental Set-up

2.1 Test Facilities

At present two test facilities are being used: “**BATMAN”** (Bavarian Test Machine for Negative Ions) mainly devoted to reach or exceed the ITER requirements with respect to current density, operating pressure, and co-extracted electron current. The extraction area on BATMAN is limited to <100 cm^2, the pulse length to <10 seconds. Operation with deuterium is possible for a limited number of pulses. The calorimeter is a water-cooled copper panel which has specially designed thermally isolated areas which are read by thermocouple. Software allows for an evaluation of the power on the calorimeter both from the change in water temperature and from a fit to the thermocouple profiles. Recently added is an array of optic fibres, which allow for H□ spectroscopy of the negative ion beam. The ion source has a number of diagnostics mounted on it either specifically for an experimental campaign or routinely in operation [2]. In addition the walls of the expansion body are designed to accept external magnet holders so that the effect of magnetic confinement can be studied easily. Control of the test facility is via a computer controlled Simatic S7 system and the data is collected via a CAMAC based DAQ and analysed and displayed via in house developed software.

The second test facility **MANITU** (Multi Ampere Negative Ion Test Unit) is used for scaling up the extraction area and for increasing the pulse length to ITER requirements. The standard diagnostic equipment that has been used so far, is similar to that on BATMAN. For the increased pulse length and for hardening the system for deuterium operation major modifications are being made, as shown later. The main parameters of the test facilities are shown in table I together with the data of a third test facility **RADI** earmarked for tests of a half size ITER source.

	BATMAN	MANITU		RADI
operational	1996	08/2003	5/2005	2005
vacuum pumps	Ti Getter	Ti Getter	Cryo-sorption	Ti Getter
pumping speed	120 m^3/s	1500 m^3/s	700 m^3/s	160 m^3 /s
Isotope	H, D (limited)	H	H, D (limited)	H, D
RF power	< 150 kW	< 100 kW	< 180 kW	< 2x180 kW
HV	22 kV, 10 A	32 kV, 20 A		none
Source	Type 6/1	Type 6/1, 6/2, and 5		1/2 size source
Grid *)	CEA, LAG	LAG		modified LAG
Extraction Area	< 100 cm^2	< 390 cm^2		≈1000 cm^2
Pulse Length	< 6 s	< 10 s	< 3600 s	< 10 s

**) for terminology see 2.3*

Table 1   Parameters of the IPP test facilities

2.2 RF ion sources configurations

The RF source used for producing negative hydrogen ions at IPP (fig. 1) 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 two are separated by a magnetic field parallel to the plasma grid of the order of 10 mT, the so-called filter field. This field also helps to reduce the co-extracted electron current. The driver is mounted on the back of the source body and consists of a 245 mm id alumina cylinder with a

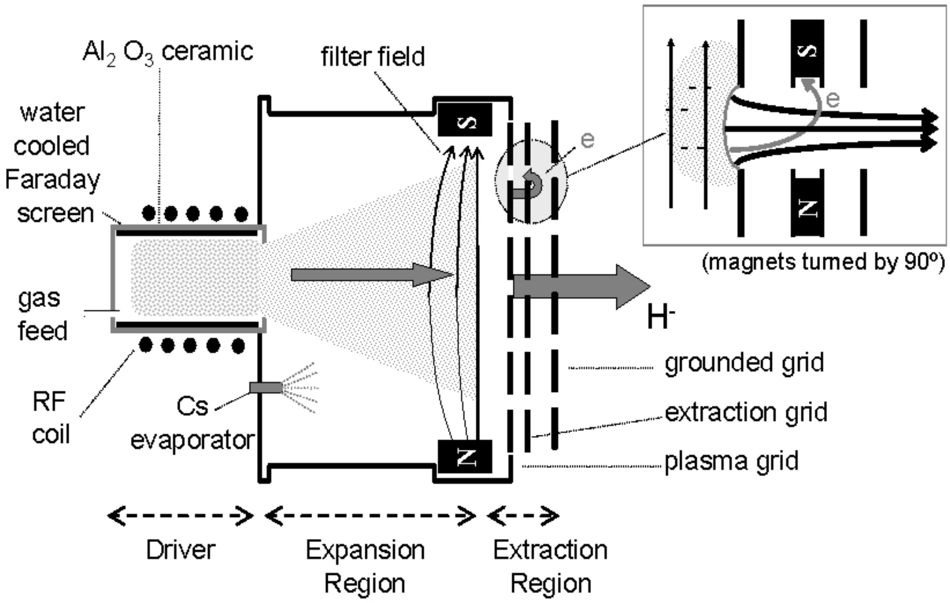
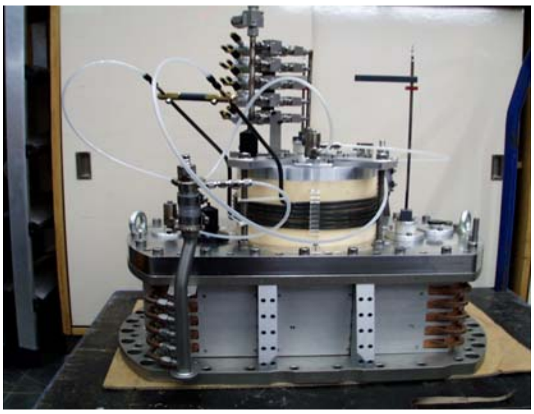


Fig. 1: Schematic of the RF source for negative ions

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 around 10 eV, away from the extraction region. There electron temperatures below 2 eV are necessary for minimizing the destruction rate of the negative hydrogen ions by electron collisions.



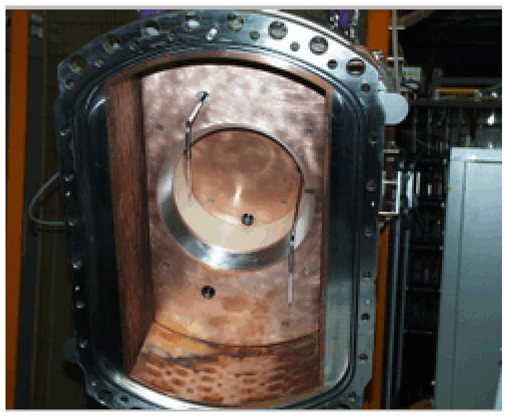


Fig.2: The negative ion RF source type 6/1

The cool-down from the expansion is further assisted by magnets in the extraction electrode which are primarily there to deflect the co-extracted electrons. To save time and money com ponents from the RF sources for positive ions are, as far as possible, also used for negative ions. This is the reason why at present the the expansion volume has a racetrack shaped cross section with 310 mm internal width, 580 mm internal length, and 250 mm height. Its dimensions are those of the positive ion system presently installed at ASDEX Upgrade [2]. The source volume is approximately 50 litres.

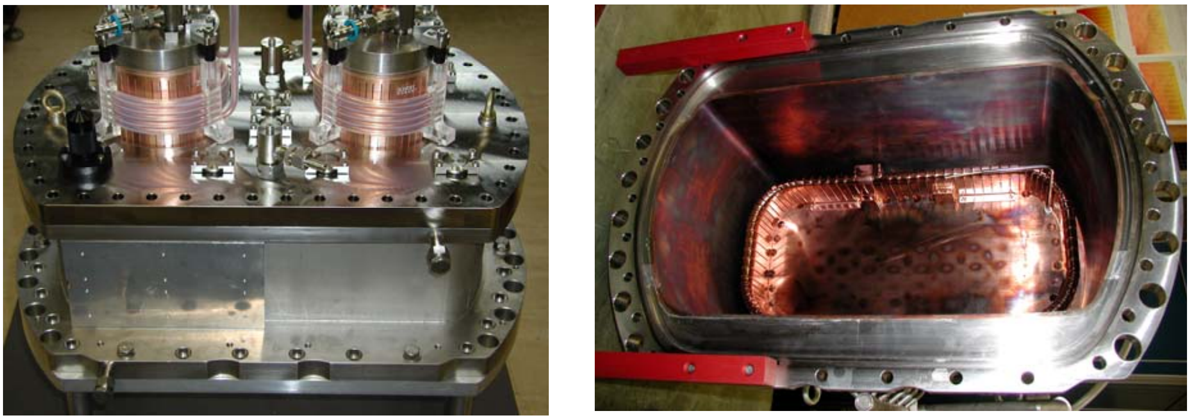


Fig.3 (a) Type 6/2 source (left) with two cylindrical drivers, quartz insulator and Faraday screen visible inside the quartz cylinde;r; (b) Type 5 source (right) with internal coil and Faraday shield

Apart from the earlier experiments reported in [2] the so-called source 6.1, shown in fig. 2, has been mainly used so far. The RF source concept is modular and can readily be adjusted to requirements by changing the number of drivers (source type 6.2 in fig.3a) or the shape of the driver (source type 5 in fig.3b). A large source with either 4 cylindrical drivers similar to those of source 6.1 or two drivers with the shape of source type 5, is under manufacturing (see section 5.2). The drivers of the large ITER half size source have a common vacuum enclosure and are mounted on a remotely adjustable back-plate. The cross section of the source corresponds to half an ITER source with numerous ports on the expansion volume to allow for diagnostics access and for the installation of internal magnets.

2.3 Accelerator configurations

Two different triode accelerators have been used so far. The experiments started with the so-called CEA accelerator with an extraction area of 67 cm^2 from 44 holes with 14 mm diameter in the plasma electrode, comparable to the ITER reference design. A second accelerator, called **L**arge **A**rea **G**rid (LAG) is derived from the IPP positive ion accelerator used for AUG injection. The total injection area is 390 cm^2 and consists of 776 holes of 8 mm diameter in

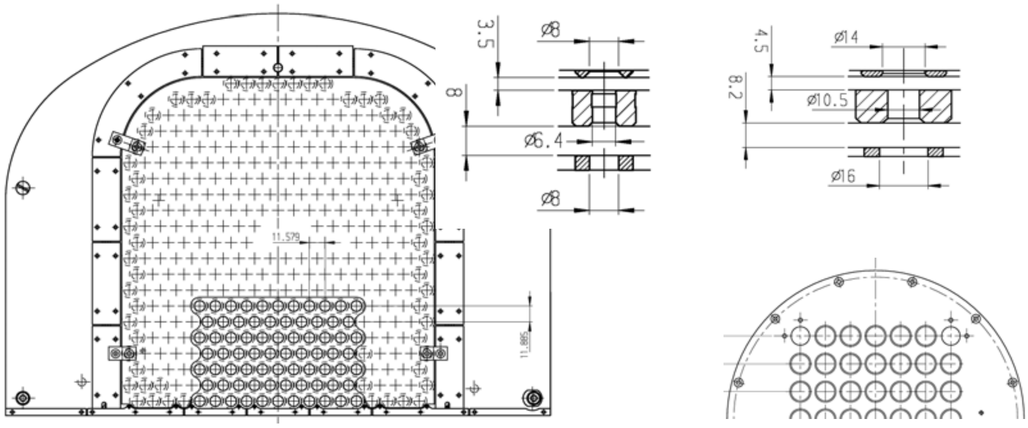


Fig. 4: Drilling pattern and spacing of the accelerators used at IPP for negative ion extraction. Left: LAG masked, right: CEA.

the plasma electrode. Both accelerators have edge cooled and electrically heated plasma grids made of 2 mm thick molybdenum and actively cooled copper extraction grids with electron deflection magnets. In BATMAN the large area grid is masked down to an extraction area comparable to that of the CEA grid because of the limited pumping speed. The drilling pattern and the grid geometry are shown in fig. 4. The plasma grids can be biased against the source body in order to enhance the negative ion yield and suppress co-extracted electrons. This biasing requires in the case of the LAG the addition of a so-called bias plate to enhance the surface area on source potential. At the LAG further modifications, shown in fig. 5, were introduced in November 2004: (i) the cut out of the bias plate is increased, (ii) the mask on the plasma grid was modified from a plate covering the unused holes in the plasma grid to a plate where the selected holes in the plasma grid where opened by a chamfered hole, and (iii) the clearance between extraction holes used and other components in the source was increased.

3. Experimental results

3.1 Hydrogen Experiments in BATMAN with CEA Grid and Cesiated Source

Experiments in 2002 and the first part of 2003 were performed in a Cesium free source to study H^- volume production in an RF source. The calorimetric current densities were only up to 4 mA/cm^2 and consequently irrelevant for neutral beam heating. With the introduction of Cesium the calorimetric current densities gradually increased to 26 mA/cm^2. This increase was particularly strong in early 2004 based on a better screening of the beam in the drift space, improvements of the filter field configuration, and by benefiting from good

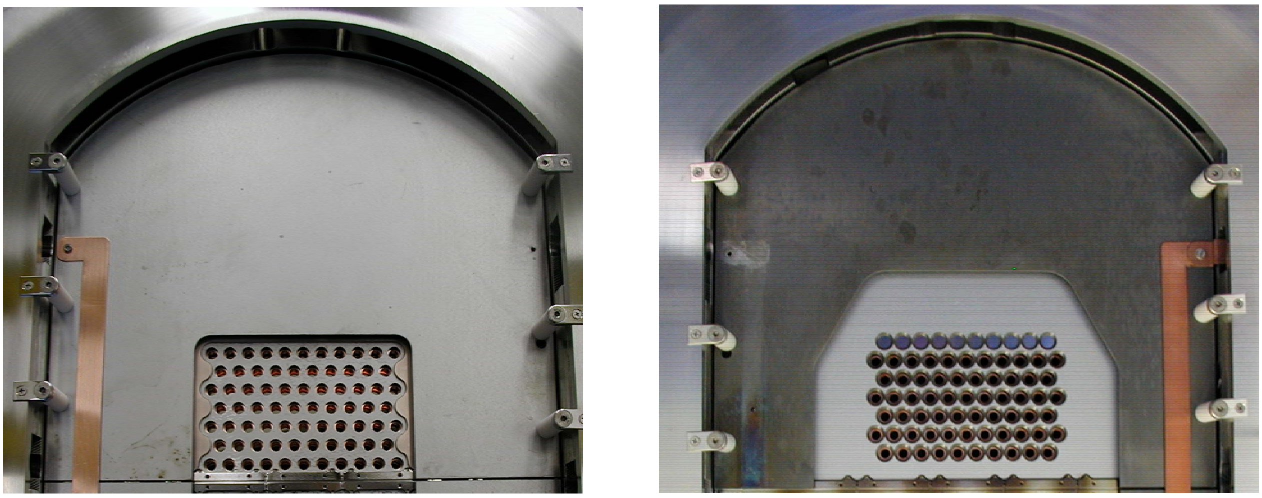


Fig. 5: View on one half of the large area grid from the plasma side showing the plasma grid, the mask on the plasma grid and the bias plate in the 2004 configuration (left) and in the configuration from November 2004 onwards (right).

surface production efficiency. The experiments had to be interrupted in March 2004 due to a water leak in the extraction grid.

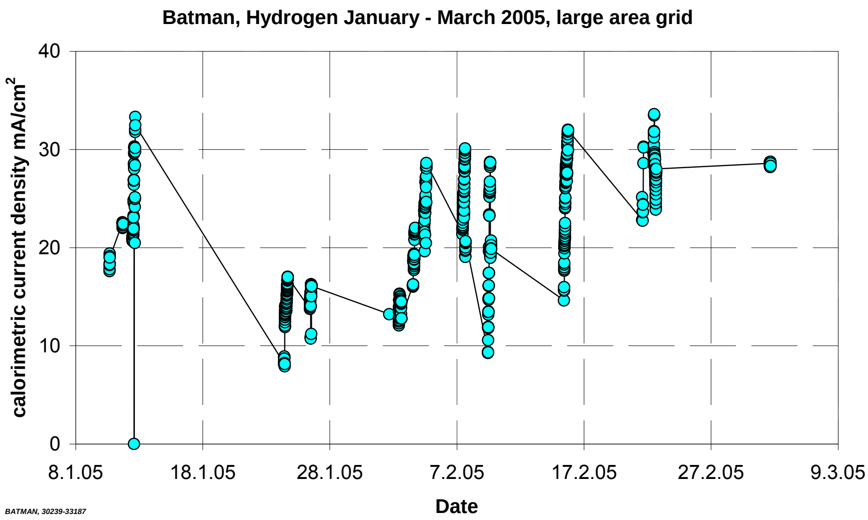


Fig. 6: Evolution of the calorimetric current densities in BATMAN January – March 2005 for discharges with hydrogen, cesiated source, RF power ≥100 kW and ≤ 0.4 Pa driver pressure.

In 2005 the calorimetric current densities could be increased from 27 to 33 mA/cm^2. The good performance of the source could be maintained over 2 month. Within this two month there was also an opening of the source beginning of February after which the previous performance could be regained with roughly one week. Fig. 6 shows the calorimetric current density of all beam pulses with hydrogen with an RF generator power of 100 kW and above and a driver pressure of 0.4 Pa or less.

Assuming that the source is cesium- free at the start of the campaign it has been found that it will take a few days of conditioning to achieve the best results. Conditioning is a process of slow cesium evaporation coupled with normal beam or plasma shots. The key issue seems to be slow but steady introduction of cesium coupled with plasma shots to distribute the cesium in the source. Once the source is conditioned it will take a few hours to achieve those best results again each and every day of operation.

By observing various source parameters the degree of conditioning can be monitored. The key signals are the negative ion current and the electron to ion ratio. It is generally irrelevant whether the calorimetric or electric value of negative ion current density is used though often insight in beam quality is gained by monitoring both. The first sign that the cesium amount that has been introduced has reached the point where surface production begins to dominate the extracted negative ion current is an increase in extracted negative ion current in conjunction with a fall in co-extracted electrons. This trend will then continue with continued cesium evaporation until after appropriate adjustments to extraction voltage and RF power the best source performance can be reached.

The primary requirement to achieve a high level of negative ion production appears to be patience. There is lack of any direct control over the exact rate of deposition of cesium on the plasma grid. The optimal performance requires the achievement of a dynamic balance of cesium on the plasma grid. This equilibrium is on the one hand given by deposition of cesium from the Cs vapour / ion density in the volume. This is either fed by evaporation from the source body surfaces, which serve as a reserve to maintain the cesium on the plasma grid or from cesium introduced during the pulse from the oven. The equilibrium on the other hand is determined by the rate of evaporation / desorption of Cs from the grid, given by grid temperature and plasma bombardment. Al those aspects preclude any faster or more rigorous procedure.

3.2 Deuterium experiments in BATMAN

MANITU has always been, BATMAN has mainly been operated with hydrogen. Experiments in deuterium have up to end of 2004 been limited to six days total. The general observation is:

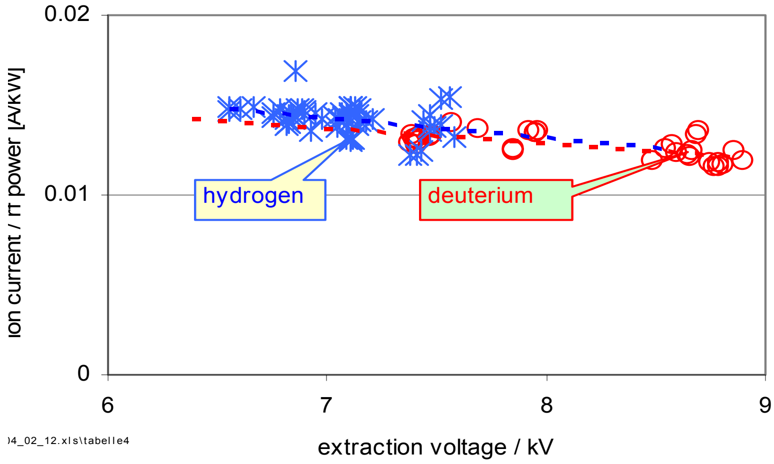


Fig. 7: Source efficiency for hydrogen and deuterium as a function of the extraction voltage

(a) The source efficiency is almost identical for hydrogen and deuterium (fig. 7).

(b) Deuterium ions require higher extraction voltages and the co-extracted electron current is also higher for deuterium, probably a mass effect.

Both, higher electron current and higher extraction voltage increase the risk of overpowering the extraction grid. For this reason the system could not yet be optimised for deuterium. The highest current density in 2004 was 16.5 mA/cm^2 calorimetric. Up to 15 mA/cm^2 the co-extracted electron current could be kept at or below the level of the ion current.

With the new setup of the plasma grid the performance with Deuterium beams improved substantially in 2005. Calorimetric current densities of 20 mA and above could be obtained in a regular basis as fig. 3 shows. The best values were just above 26 mA/cm^2. Also remarkable is that source efficiency for ion production shows a slight improvement with time, reaching top values of 0.4 mA/cm^2 kW, i.e. 20 mA/cm^2 of calorimetric current have been obtained with an RF generator power below 70 kW. This means that the performance was not limited by the RF power, but rather by the power deposition of the co-extracted electrons on the extraction grid. Fig.10 shows a subset the data with the highest source efficiency. The electron to ion ratio for this subset was in the range between 1.1 and 1.35. From these results we conclude that current density obtained in the RF source with deuterium has scope for further improvement.

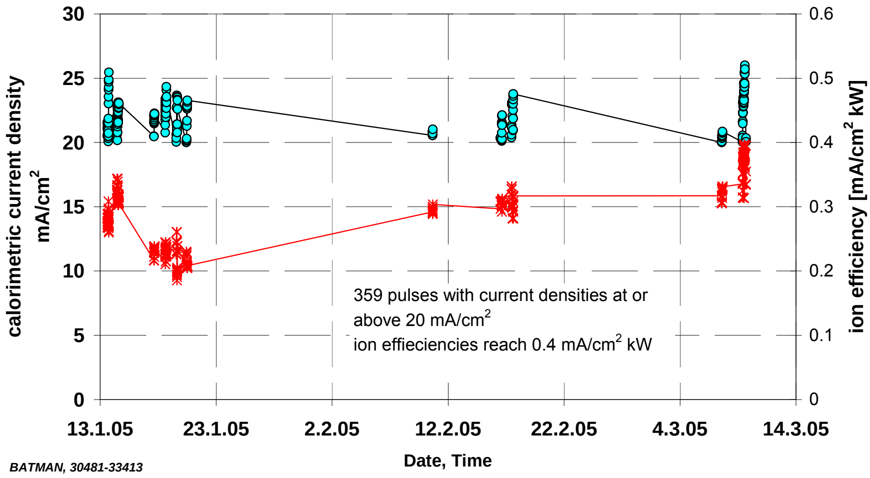


Fig. 9: Calorimetric current density (blue circles) and source efficiency (red circles) for ions for all deuterium pulses with current densities at 20 mA/cm^2 and above for the period January to March 2005.

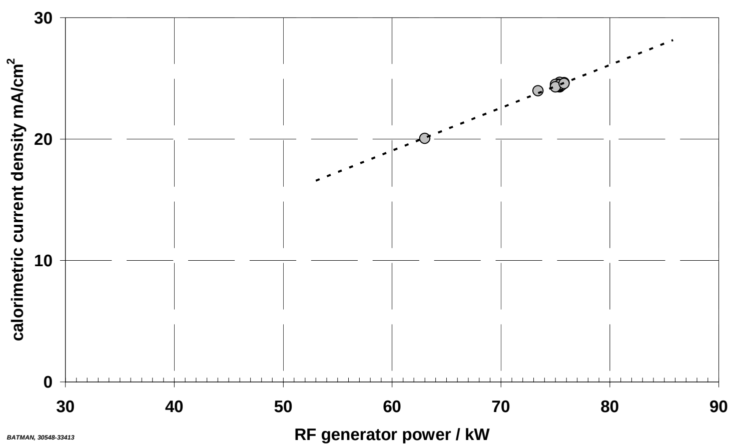


Fig. 10: Calorimetric current density for deuterium. BATMAN beam pulses with the highest source efficiency taken in the period between January and March 2005

3.3 Scaling experiment in MANITU

The extraction area has been increased from 70 via 150 to 306 cm^2 in the 6.1 source without significant loss in electrically measured ion current density yielding a maximum electrical ion current of close to 10 A. For the largest extraction area, the extracted electric current still

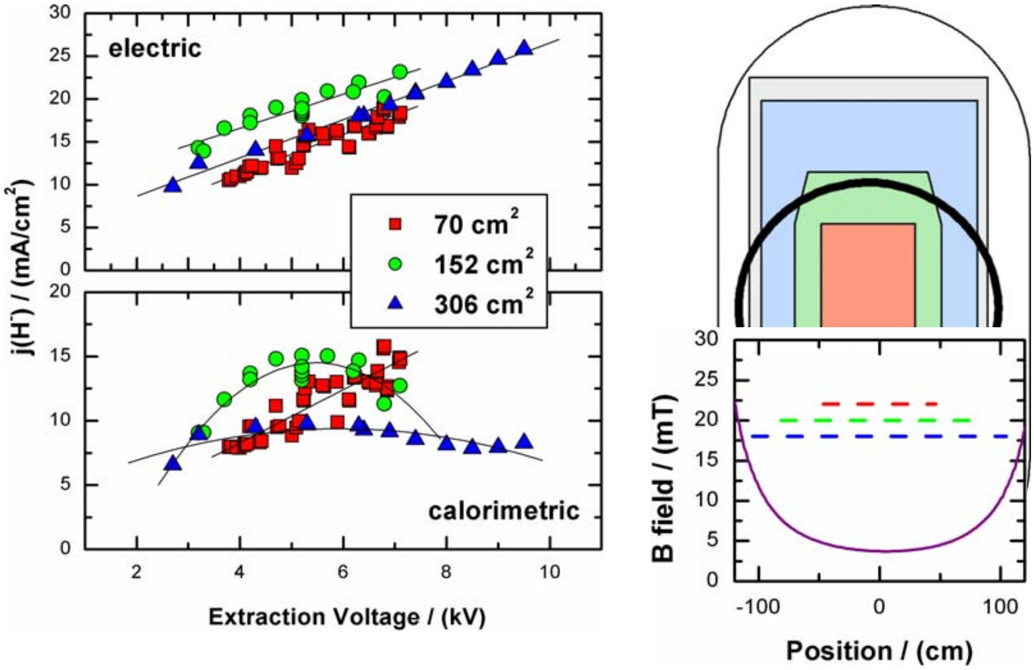


Fig. 11: Electric and calorimetric ion current density in MANITU for an extraction area of 75, 150, and 306 cm^2. The shape of the extraction area is indicated in the insert. The second insert shows the strength of the filter field together with the width of the extraction area as dashed lines.

increases with extraction voltage (fig. 11). On the other hand the calorimetric current is essentially independent of extraction voltages and at higher voltage significantly lower than the electric current. This is caused by an increasing fraction of the beam hitting the ground electrode. One obvious reason for that is the magnetic filter field increasing by a factor 4 from the centre to the edge of the plasma electrode. A 220 mm wide extraction area is obviously too large for the given filter field using external magnets.

3.4 Operation at low source filling pressure

In its present configuration the IPP RF source type 6.1 suffers from a gas pump out effect in the driver driven by the plasma flow from the driver into the expansion volume [5]. This pump out will be less significant when the extraction area and proportionally the gas flow is being increased . With a small extraction area in BATMAN pulses at a source filling pressure of 0.3 Pa have already been obtained as fig. 12 shows. The pressure in the driver is below 0.1 Pa and the source efficiency fall with falling driver pressure. Nevertheless the calorimetric current density of the pulse in fig. 12 was 19 mA/cm^2 and it is expected that operation at 0.3 Pa and below will be no problem once the extraction area has been increased.

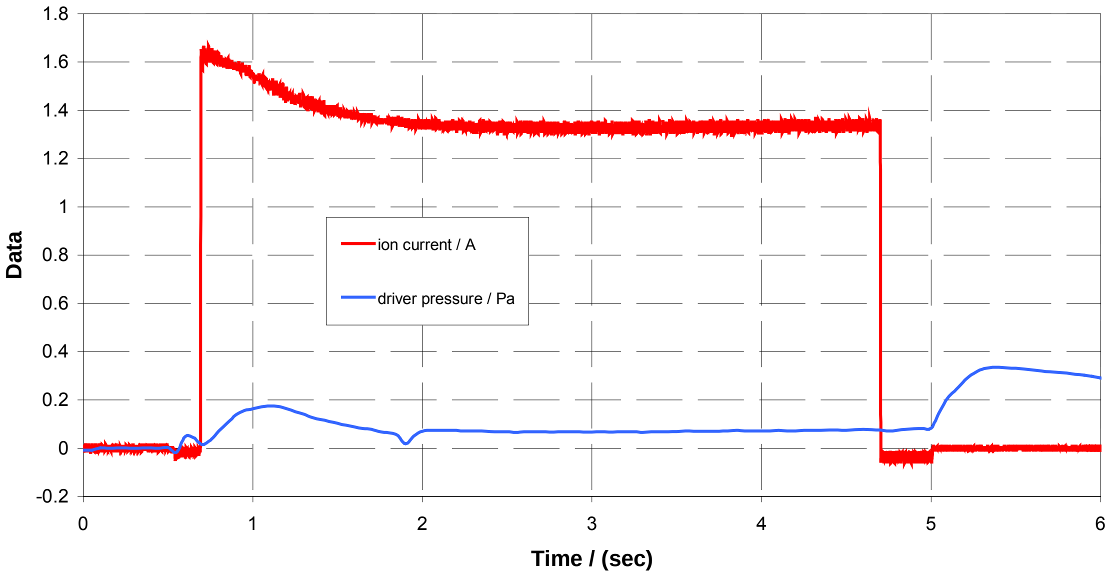


Fig.12:Ion current source driver pressure vs. time

3.5 First attempts of long pulse operation

The MANITU test bed is being set-up for a pulse duration of up to one hour. At present several components required for these long pulses are not yet operational. Nevertheless the pulse length could already be extended to 20 seconds (fig.13). At the time of taking this pulse the source was not fully cesiated, which is probably responsible for the slight decay in ion current with time. It is expected that all components for long pulses will become available in May 2005.

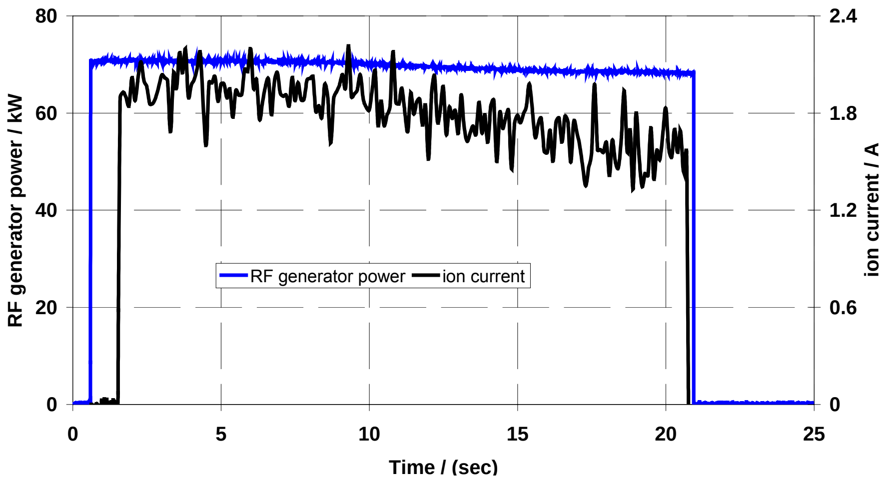


Fig. 13: Time traces fort he RF generator power and the ion current in Manitu for a hydrogen pulse.

4. Diagnostics development and modelling

4.1 Diagnostics

Table 2 shows an overview of typical diagnostics, partly still under development, as e.g. foreseen on the half size source.

4.1.1 Optical Emission Spectroscopy

Optical emission spectroscopy is used as a standard diagnostic tool in both teststands and is planned for RADI. The following parameters in the driver and the expansion region are obtained in hydrogen and deuterium discharges:

- Atomic hydrogen density and molecular hydrogen density
- Vibrational population of molecular hydrogen in its ground state
- Gas temperature
- Electron temperature and electron density by using diagnostic gases (He, Ar)
- The presence of impurities (oxygen, water, copper, …)
- Neutral and singly ionized cesium densities and fluxes
- Variation of negative ion densities in the plasma volume

With sufficient viewing ports this tool can deliver spatial and time resolved measurements of plasma parameters and their profiles and of impurities in the source. Especially the new technique of measuring the negative ion density via the H_α/H_β ratio together with modeling provides a simple and non-invasive access to this quantity. Details are presented elsewhere [6]. The discussion within the frame of this overview will be restricted to two examples.

The first example is an innovative technique to measure the line-averaged H- density is the analysis of the Balmer line ratio (H_α / H_β) supported by a collisional radiative model. For details see [6]. This allows for a the first time a correlation to be established between the H- number density n- in the plasma in front of the grid and the H- current density j- in the beam (see fig. 14). The result (n_{H^-} = 10 11 cm-3 for j_{H^-} =20 mA/cm2) agrees roughly with a 0-D simulation [11].

The second example is illustrated in fig. 15 which shows the line intensity of the Cs I light is increasing steadily during the discharge, whereas the H- current remains constant. Clearly H- formation is not a process related to the Cs volume density. The implicit conclusion apparently is surface production being responsible.

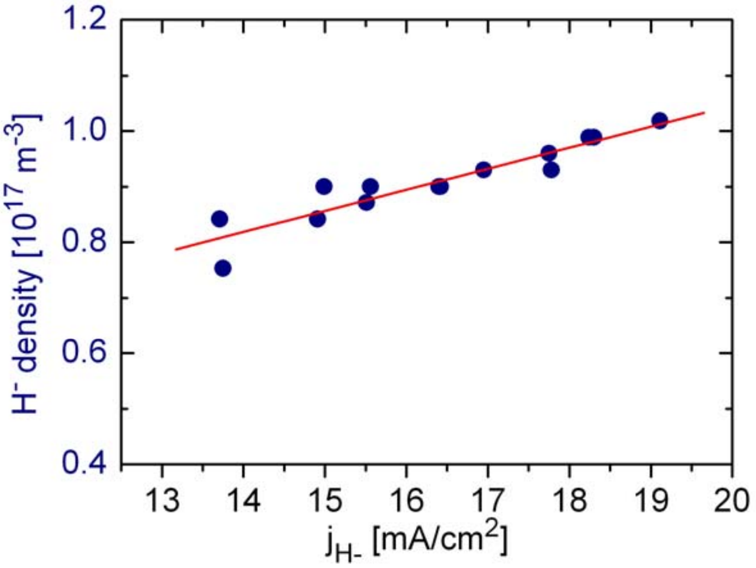


Fig.14: H- density (as measured via the line ratios H_α / H_β) vs. measured H- current density

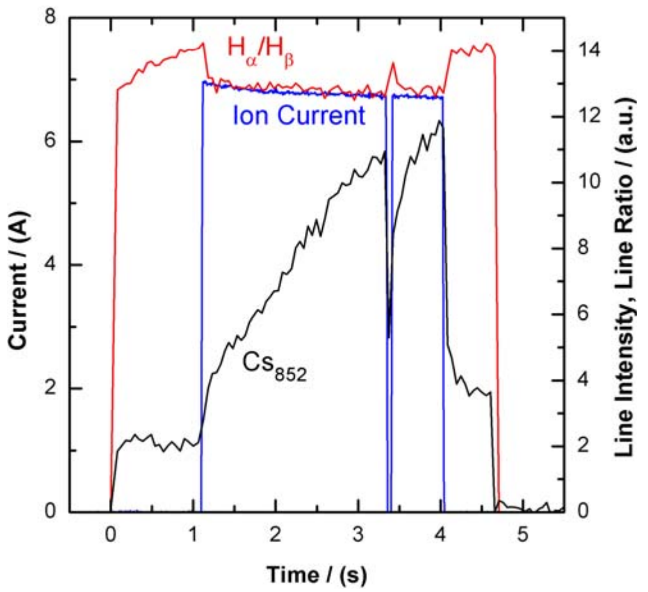


Fig.15: Temporal evolution of the Cs I line in comparison with the H^- yield

Emission spectroscopy is planned to be a standard diagnostic in all testbeds. The half- size source in particular will be equipped in the first stage with two three-channel low resolution survey spectrometers. 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.

4.1.2 Langmuir Probes

The main challenge with Langmuir probes 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. In collaboration with Charkov University, Ukraine a system has been developed for BATMAN, that is operational in the hostile environment of the RF noise. 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).

Two movable Langmuir probe systems, copies of the BATMAN probe, will be installed on the half- size source for measuring time-resolved the electron density and temperature profiles perpendicular and parallel to the grid. Furthermore locally fixed (simple) Langmuir probes inserted in the dummy grid will provide relative profiles of the plasma parameters near the grid.

4.1.3 Work function measurement

Since the work function of Cs layers depends on the layer thickness, work function measurements can in principle be used to optimise the Cs 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). Using interference filters varies the photon energy. The photo-emitted electrons are captured by a platinum grid positioned parallel to the surface at a distance of a few cm. 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, since this alters the electron trajectories and may alter the current of the capture grid. It is envisaged to use a lock that allows to insert 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. Alternatively, in the half-size source the analysis will be performed after the pulse, when the current through the PG filter is switched off.

The method is still under development.

4.1.4 Cavity Ring Down Spectroscopy

A further diagnostic under development is the Cavity Ring Down Spectroscopy (CRDS). This 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 [12]. This leads to an intrinsic e-folding time of the transmitted ring-down-signal of about 50 µs. Due to the photo detachment of the negative hydrogen ions the signal undregoes an additional attenuation, that can easily be discerned against the back-ground and yields the absolute line-of-sight-integrated negative ion density in the source. This is insensitive to RF-interference. The pulse energy is presently limited to 30 mJ by the laser fibre in use. The power density of 500 mJ/cm^2 is limited by the damage threshold of the mir-ror coatings.

4.1.5 Laser Detachment

Laser-detachment [7]. will be used in the half-size source to determine the spatial and time resolved relative change of the negative ion density distribution. A pulsed Nd:YAG-laser at a wavelength of 1064 nm will be used. The spatial resolution of the probe is about 1 cm, given by the size of the probe tip. The resolution in time is limited by the laser frequency of 15 Hz, resulting in a maximal time resolution of about 60 ms. In order tocompensate 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.

4.2 Modelling

Modelling work mainly covers three areas:

- negative ion production and transport in the source considering volume processes
- negative ion production and extraction
- negative ion production and transport in the source considering surface processes

The first topic is the subject of a thesis [8] and consists of three Monte-Carlo codes, one for the transport of the excited molecules, the second one for the formation of H- the third one for the transport of H- to the grid. The work is concluded and its essential results show that for typical source parameters the H- density is about 10^{10} cm^{-3} leading to a current density of a few mA/cm^2. This is in agreement with the Cs-free experiments. Interesting also that the sur-vival length of the H- is 1-2 cm only, as confirmed by previous studies [13]. This emphasises again, that only H- generated in the immediate vicinity of the plasma grid have a finite chance of being extracted.

The second topic is the subject of an ongoing collaboration with Prof. J. Sielanko from the University of Lublin, Poland. The extraction of H- from an arc or RF source is much more complicated than for positive ions due to the various additional electric and magnetic fields, such as filter-, bias, and electron suppression field, the two-step acceleration and the presence of electrons. In particular in the case of surface production with Cs at the plasma grid the extraction physics are not well understood. Ions crated at the plasma grid surface are initially accelerated back into the plasma chamber away from the plasma grid and have then to be bent back towards the extraction holes. Possible candidates are charge exchange, scattering and the magnetic fields near the grid. Hence a more detailed understanding of all these processes is highly desirable.

In 2002 the collaboration mentioned above was started, addressing the development of a code that contains all the elements of H- extraction. In the final stage the code will include:

- grid geometry, also multi-holes
- all magnetic fields
- extraction and acceleration potentials
- plasma grid bias
- all species in the plasma, like H-, H+, e-, Cs+ etc.

The code ("TRQR") is 3-D Monte-Carlo particle-in-cell program. It solves the Poisson equation for the potential distribution with the presence of all charged particles. In the next step the motion of the particles is calculated in the previously obtained potential distribution and then the new potential distribution is obtained etc.etc. Implementation of all physics proceses and increasing the number of particles to get into the relevant density regimes requires code parallelisation in order to reduce CPU time. First results for low densities have been obtained, but work is ongoing along the lines described above.

The third topic is subject of a new activity, was started only recently by a Post-Doc. This work is aiming at including surface production into a negative ion production and transport code. In a second step this code will be coupled together to the beam extraction code, described above.

5. Future Experiments

5.1 Extension of the pulse length towards 1 hour

The extension to deuterium operation with pulse lengths of up to one hour requires a number of modifications and replacements both in the mechanical and electrical parts:

- actively cooled Faraday shield and grids
- c.w. power supplies for high voltage and RF including transmission line and matching
- cryo pumps instead of Titanium pumps
- an actively cooled calorimeter
- a neutron shielding

5.1.1 The long pulse source

As described in setion 2, the driver consists of an alumina cylinder of 245 mm i.d. and is protected from plasma erosion by an internal copper Faraday shield. This part of the source is exposed to a high heat load and hence for c.w. operation has to be replaced by an actively cooled version. The source body is water cooled, the plasma grid, which has to be on a temperature of 150 – 250°C for optimal Cesium surface conditions, is gas cooled. The temperature of both will be made controllable during long pulses in order to optimize the H^-/D^- yield and minimize the Cesium consumption.

5.1.2 The testbed MANITU

Since on MANITU the RF generator is on ground potential, an insulation transformer in the RF circuit is necessary. During longer pulses overheating the ferrites of this transformer has occurred in the past. A dedicated development has resulted in a choice of ferrites with low losses and high Curie temperature, an optimized mechanical set-up and appropriate RF matching. This way the temperature increase has been reduced from 10°C/s to 0.2°C/s at 100 kW. Further developments concerning coaxial transformers are ongoing.

The previous RF generator for 120 kW / 10 s has been replaced by a more powerful one (180 kW) suitable for c.w. operation. The new generator is equipped with two tetrodes in push-pull arrangement. Furthermore new high voltage power supplies for extraction (15 kV, 35 A) and acceleration (35 kV, 15 A) have been purchased, both for c.w. operation. A completely new HV circuit and voltage regulation system using two tetrodes has been commissioned.

The former titanium evaporation pumps of MANITU, capable of pulse length up to 10 – 15 s only, have been replaced by a pair of cryosorption pumps with a pumping speed of 7×10^5 l/s and a pumping capacity of 1×10^6 mbarl. The complete cryo system was designed and built within a collaboration with FZK and includes a cryo supply which partly uses the He liquefier of the ASDEX-Upgrade cryo pump system.

Fig.16: Cryosorption pups for MANITU (details see[9])

An actively cooled beam calorimeter with a diameter of 800 mm has been designed for c.w. operation with 350 kW total power capability and a maximum power density of 6 MW/m^2. It consists of four ASDEX-Upgrade calorimeter panels. Space resolved calorimetric measurements using a separate water-cooled array of thermocouples in front of the calorimeter are envisaged for providing the beam profiles in horizontal and vertical direction.

The deuterium operation requires neutron shielding: the source and the extraction system are enclosed in a cabinet with 20 cm thick polyethylene walls, a sliding door and a removable roof slab. The calorimeter is shielded by 30 cm thick double walled water tanks which are placed inside the vacuum chamber. The shielding allows Deuterium operation. at 30 kV, 8A for total pulse duration of 6 hours per calendar year.

A new control system including HF and HV power supply, gas and vacuum system as well as a improved data acquisition system compatible with long pulses has been commissioned.

During a provisional commissioning phase the system has been run on extended pulses up to 20 s without cryopumps. The latter are being commissioned at present. More details about the long pulse project can be found in [9].

5.2 Size scaling

As an intermediate step between the present PINI-size (32 x 59 cm^2) 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 half-size source is devoted to optimize the shape, arrangement and number of the drivers in order to demonstrate the required uniformity of large plasmas. Furthermore the operation of a multi-driver arrangement with the associated rf generators and matching circuitry will be optimized. The experience of the operation of this half-size source will then enter in the final design of the ITER full size source.

5.2.1 The testbed RADI

In order to prepare this size-scaling demonstration a new test facility (called RADI) is being constructed, because those investigations will have to run at least partly in parallel to the activities on BATMAN and MANITU. The new test facility will be using one of the injector boxes — the radial box — of the decommissioned W7-AS injectors. Fig.17 shows a 3D-sketch of the half-size source. Full size extraction will not be possible due to the lack of a big

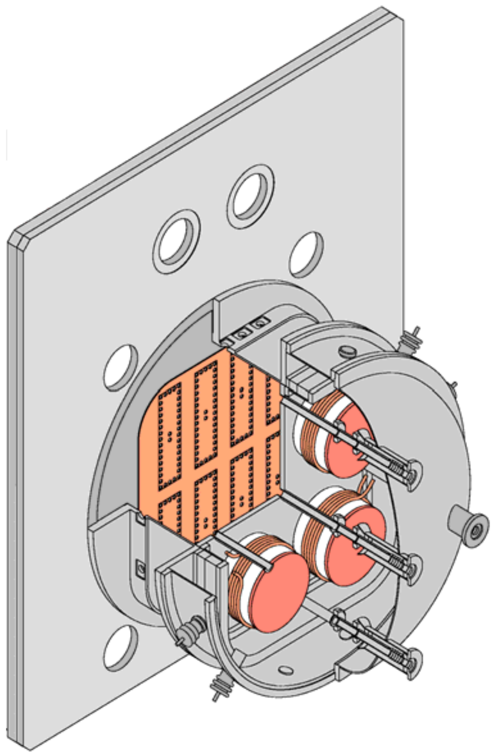


Fig.17: Schematic view of the half-size source

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 only a brief summary of the source design and the diag nostics will be given. Details on the design of the half-size source, the RF circuits and the new RADI test bed are described in [10].

5.2.2 The half-size source

In contrast to the large ITER-like filamented driven sources, a large RF source can be kept rather short (orthogonally to the grid plane) due to its principle rectangular cross-section. This may be an advantage for the 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 source body has a nominal depth of 250 mm. The distance of the drivers to the grid however can be varied between 150 mm and 250 mm. This possibility allows the investigation of the influence of the source depth on the source performance.

A large number of ports for diagnostics and for the RF power and gas and Cs supply are foreseen as well as for possible filter field modifications. 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.

Due to the pumping system limitations (Titanium evaporators) the maximum pulse length will be about 10 s. 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 as for the SINGAP system, including the grounded grid — and hence the gas flow conditions of the ITER source. There will be some limited control of the conductance.

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. Cs vapor 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 produce a “PG filter”, 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. On RADI both configurations will be tested, also in combination.

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 principle as well as the technical layout of the RADI RF circuits is very similar to the system which is planned for ITER. Apart from the number and the arrangement of the drivers, open questions concerning the features of the RF are e.g.: the distribution of the output RF power into the source including the Faraday screen, the optimum number of coil turns, the possibility to omit the transformer in the matching circuit (because HV separation is not necessary), the insulation of the coils, the mutual influence of the matching networks, the effect of possible different frequencies of the networks, the exploration of other means for a variable matching in order to compensate the variable plasma impedance.

5.2.3 Diagnostics on RADI

Due to the lack of a large-scale extraction system, the performance of the 1/2 size source cannot be expressed in terms of an average extracted current density and a beam profile. Hence it will be equipped with a number of diagnostics in order to measure the plasma parameters that determine the performance of the source. Those are mainly the H^- and electron density profiles across the grid; optical emission spectroscopy, probes, laser detachment and cavity ring down will measure those. These methods are presently being or will be calibrated to the extracted current density in BATMAN.

Furthermore, 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. Due to the limited available extraction voltage (4-5 kV, due to the small distances) moderate H^-/D^- current densities are accessible only. 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.

The half-size source, the supplies and some basic diagnostics are scheduled to be ready for commissioning in summer 2005; first results are expected after the summer break in October 2005.

6. Summary

Calorimetric current densities have been increased to 330 A/m2 in hydrogen and 230 A/m2 in deuterium with simultaneously achieved electron/ion ratios ≤ 1 and a source filling pressure equivalent to 0.3 Pa. The source has been operated reliably for more than 350 pulses in deuterium above the ITER requirement of 200 A/m2. The D- current density is limited by the electron power that can be safely absorbed by the extraction grid. The main modifications that are supposed to be responsible for the increases yield were a slow conditioning process and a chamfered mask above the plasma grid..

Gas filling pressure: The driver requires a pressure in excess of 0.1 Pa. In the present configuration in BATMAN with reduced extraction area the gas flow is just a few mbar l/s and a filling pressure of 0.5 Pa is required to keep the driver pressure above 0.1 Pa. With increasing extraction area this pressure drop decreases and operation at 0.3 Pa filling pressure becomes realistic.

Plasma uniformity: from the first scaling experiments in MANITU it can be concluded that one driver (245 mm) can illuminate an extraction area without loss in beam optics. At an extraction area of 300 cm2 the beam quality is clearly deteriorated, most like ly due to the effect of the steeply rising filter field strength at the periphery of the grid. At present it is therefore not possible to assess the uniformity limits of the H- yield. This question will be further addressed in an experiment with an intermediate extraction area of 220 cm2.

Cesium consumption: So far there is no indication of an excessive Cesium consumption. For a meaningful assessment operation with long pulses has to be awaited.

Diagnostics and modelling: There has been an extensive diagnostics and modelling development to study Cesium inventory and distribution, H- density in the plasma, plasma flow in the source and plasma parameters by spectroscopic methods. Modelling activities are focused on studying negative ion surface production and extraction from the plasma.

Long pulse operation: This requires upgrades of the HV and RF power supplies, the source components, vacuum pumping, neutron shielding and diagnostics. A first step was an extension to 20 s, presently limited by the cooled faraday screen and the cryopumps not being operational yet. The remaining components will become available in the next few weeks and the subsequent extension of the pulse length towards one hour is consequently expected.

Half-size ITER source: 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. For simplicity plasma operation for 10 s pulse length only is possible. Numerous diagnostics are foreseen being currently commissioned and calibrated against the extracted current density at the other test beds at IPP. Commissioning of the entire system is foreseen in Summer 2005.

In essence an integrated development program is being carried out demonstrating, that the RF source equals or surpasses the ITER requirements. As soon as the long- pulse characteristics and the size-scaling properties have been shown, the RF source will no longer be a simple alternative. Its potential for maintenance-free operation will make it an option hard to be ignored for ITER.

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