Status and Plans for the Development of an RF Negative Ion Source for ITER NBI

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Abstract

Inductively coupled RF ion sources are being developed at IPP for the production of negatively charged hydrogen ions. The source volume is approximately 50 litres. The extraction area varies between 70 and 300 cm^2. With an extraction area of 70 cm^2 current densities of 26 mA/cm^2 for hydrogen and 16 mA/cm^2 for deuterium have been achieved. Experiments in deuterium have so far been very limited and the system is not yet optimised for deuterium. The RF source requires a pressure of at least 0.1 Pa in the driver. It is expected, that the ITER requirement of 0.3 Pa filling pressure can be met in a source with a relevant extraction area and gas flow. The co-extracted electron current can be kept at or near the level of the ion current.

The extracted current scales almost linearly with extraction area and a current of 7.5 A has been extracted from a 306 cm^2 area. Due to the strong variation in filter field over the width of the grid so far only part of this current passes through the accelerator and is detected on the calorimeter.

One of the test beds is at present being upgraded to allow one hour pulses and deuterium operation with approximately 250 cm^2 extraction area. A third test bed is being assembled to house a half size ITER source with approximately 1000 cm^2 extraction area. This so-called half size ITER source is being manufactured and will be used to demonstrate scalability of the RF source concept.

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. The development of these sources was 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 transformer and are therefore cheaper to build and basically maintenance free in operation. The simple design is potentially quite beneficial for ITER with its remote handling requirements. In contrast to the arc sources RF sources do not require regular maintenance to replace worn out filaments. Furthermore it is being speculated, that the arc current of the arc sources might contribute to the plasma non-uniformity observed in the large arc sources [4]. 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.

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 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. 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:

Table I: Selected data of the IPP test facilities for RF source development

	BATMAN	MANITU		RADI
operational	1996	08/2003	11/2004	2005
vacuum pumps	Ti Getter	Ti Getter	Cryo-sorption	Ti Getter
pumping speed	2 x 60000 l/s	2 x 750000 l/s	2 x 350000 l/s	160000 l/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*

2.2. RF ion sources for negative ions at IPP

The RF source used for producing negative hydrogen ions at IPP consists of a circular driver and a PINI[1] size expansion volume (fig. 1). The plasma is produced in the driver and expands into the expansion volume. The cool-down from the expansion is further assisted by a magnetic filter field parallel to the plasma grid, which also helps to reduce the co-extracted electron current. Magnets in the extraction electrode deflect co-extracted electrons. To save time and money components from the RF sources for positive ions are, as far as possible, also used for negative ions. 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 driver is a 245 mm id aluminium oxide

[1] PINI refers to the ion source used in most European fusion devices (JET, AUG, Textor).

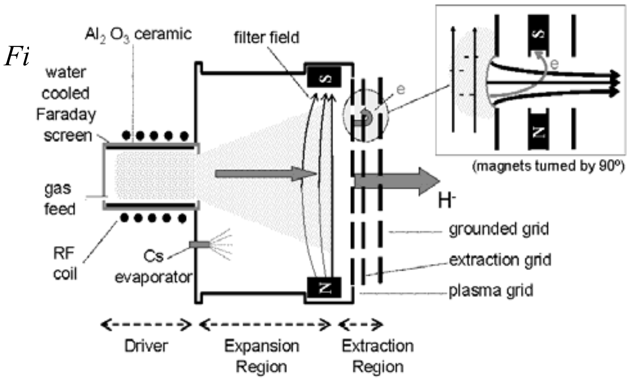
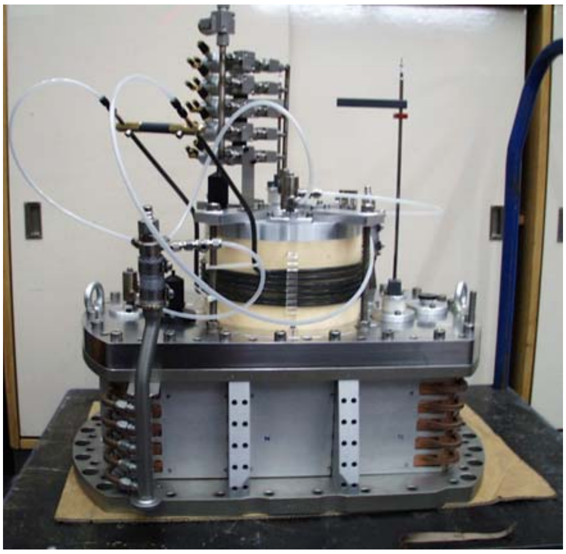
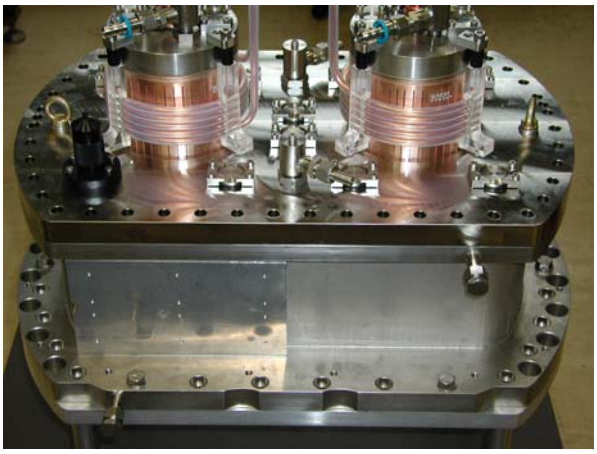


Fig. 1: Schematic of the RF source for negative ions.





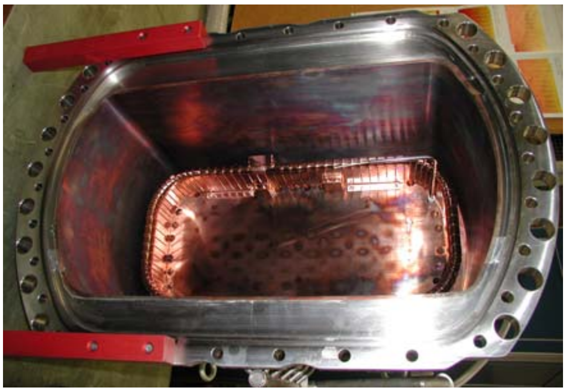
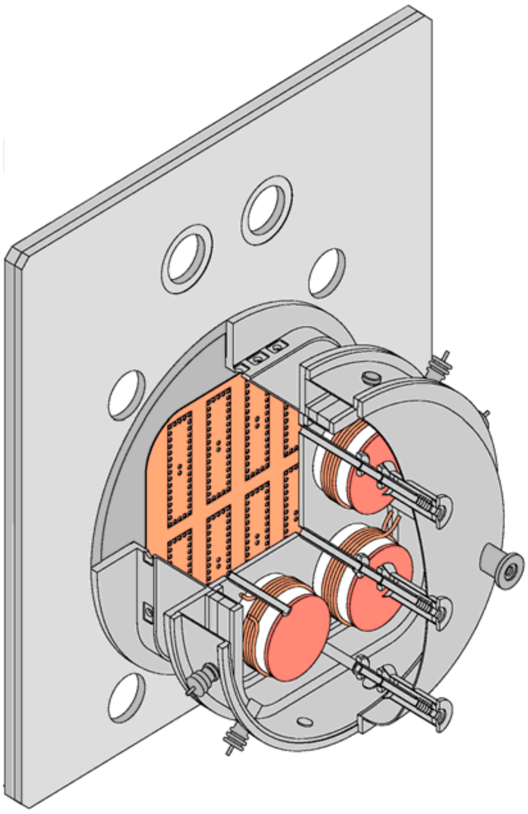


Fig. 2: Source types used at IPP for producing negative ions: Top: type 6.1 with one cylindrical driver of 245 mm id, left: type 6.2 with two cylindrical drivers, quartz insulator and Faraday screen visible inside the quartz cylinder, right: type 5 with internal coil and Faraday shield.



cylinder with an external coil and an internal Faraday shield. The expansion volume has a racetrack shaped cross section with 310 mm internal width, 580 mm internal length, and 250 mm height. The source volume is approximately 50 litres.

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.2) or the shape of the driver (source type 5 in fig.2). 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 (fig. 3). 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

Fig. 3: Schematic of the ITER half size source.

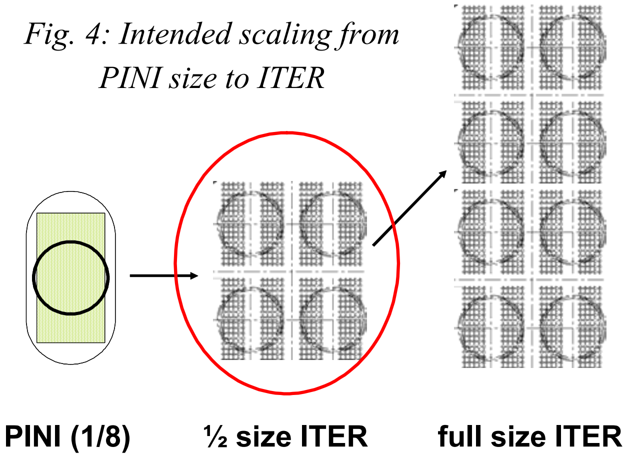


Fig. 4: Intended scaling from PINI size to ITER

(fig. 4) with numerous ports on the expansion volume to allow for diagnostics access and for the installation of internal magnets.

2.3. *Acceleration grid configuration*

Two different three grid 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 the plasma electrode. Both accelerators have edge cooled plasma grids made of 2 mm thick molybdenum and actively cooled copper extraction grids with electron deflection magnets. The large area grid in BATMAN is masked down to an extraction area comparable to that of the CEA grid. The drilling pattern and the grid geometry are shown in fig. 5. The plasma grids are heated and can be biased against the source body in order to enhance the negative ion yield and suppress co-extracted elec-trons.

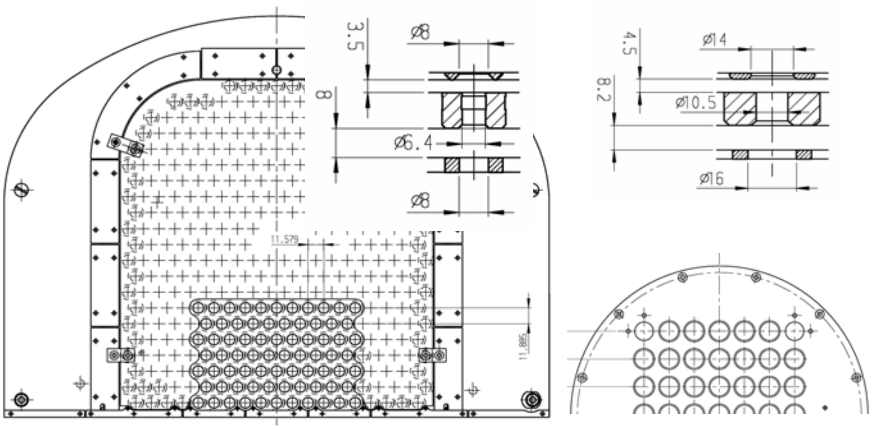


Fig. 5: Drilling pattern and spacing of the accelerators used at IPP for negative ion extraction. Left: LAG masked, right: CEA.

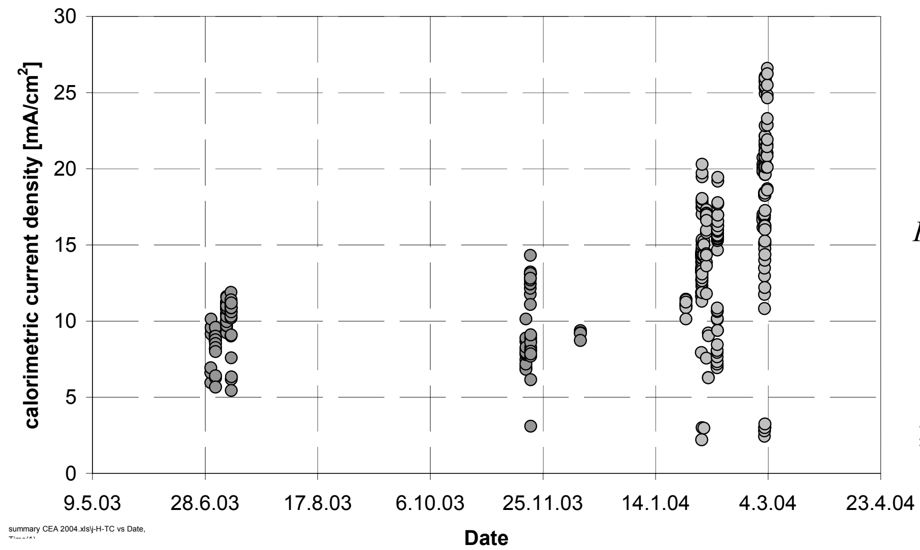


Fig. 6: Evolution of the calorimetric current densities in BATMAN for discharges with hydrogen, cesiated source, RF power ≥100 kW and ≤ 0.4 Pa driver pressure.

3. Experimental Results

3.1. Hydrogen Experiments in BATMAN with CEA Grid and Cesiated Source

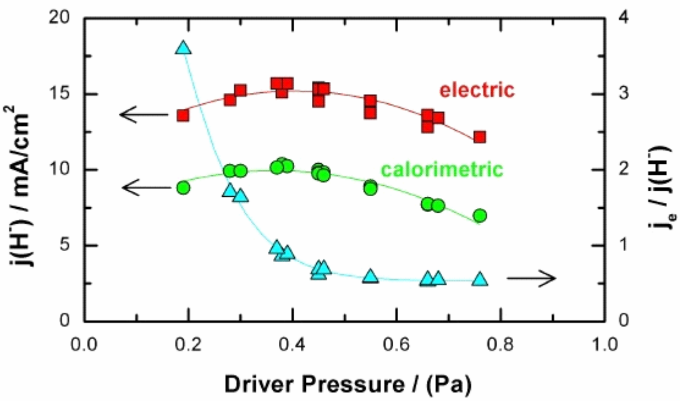


Fig. 7: Current densities and electron/ion fraction as a function of the driver pressure

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 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 (fig. 6). 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 surface production efficiency. The experiments had to be terminated in March 2004 due to a water leak in the extraction grid. The H^- current density is essentially independent of the source pressure (fig. 7) as long as the pressure in the driver is larger than 0.1 Pa. However there is a strong increase in co-extracted electron current at lower pressures, probably due to an increase in local electron temperature requiring additional effort in electron suppression by biasing and filtering. At present low pressure operation is limited by a pump-out effect in the driver from the plasma flow. This effect reduces when the extraction area is increased [5]. Magnetic shielding of the source wall so far had little effect on the source efficiency.

3.2. Deuterium experiments in Batman with CEA grid.

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

- The source efficiency is almost identical for hydrogen and deuterium (fig. 8).
- 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

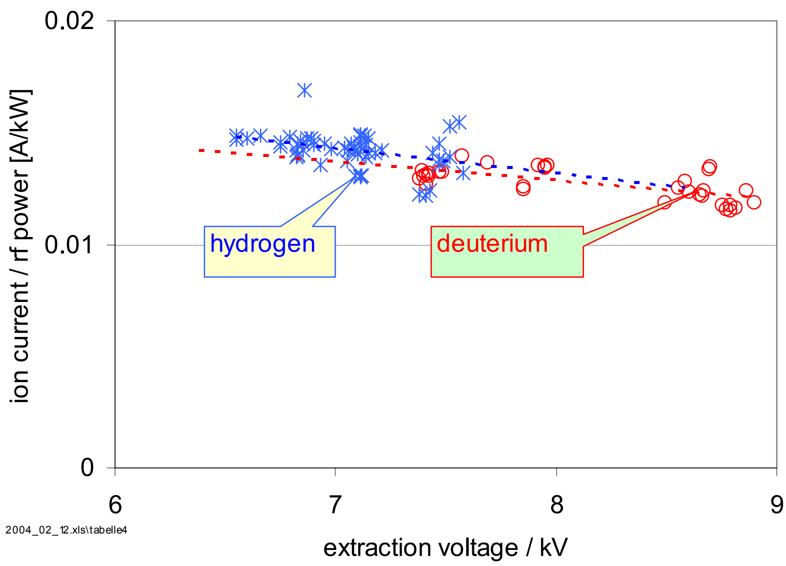
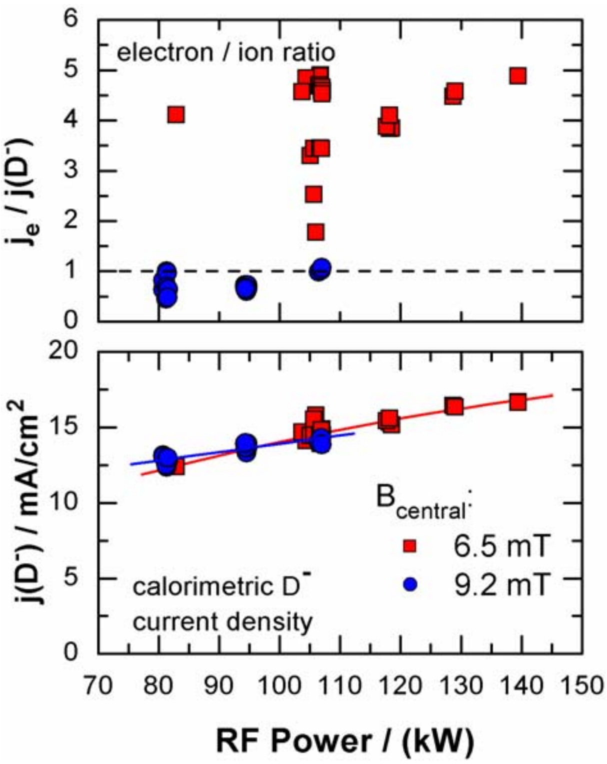


Fig. 8: Source efficiency for hydrogen and deuterium as a function of the extraction voltage



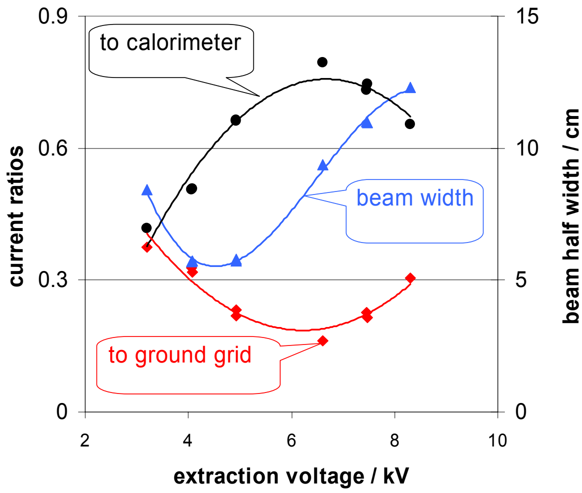


Fig. 10 (top): Current fractions to the calorimeter and ground grid normalised to the electrical current to ground. Also shown is the vertical beam half width on the calorimeter

Fig. 9 (left):Calorimetric D^- current and electron/ion fraction for two different filter fields in BATMAN.

system could not yet be optimised for deuterium. The highest current density was 16.5 mA/cm^2 calorimetric (fig. 9). Up to 15 mA/cm^2 the co-extracted electron current could be kept at or below the level of the ion current.

3.3. Role of the extraction voltage

Increasing the extraction voltage initially increases both calorimetric- and electrical ion current, however above 7 kV (fig. 10) the calorimetric current passes through a maximum and an increasing fraction of the ion current flows to the ground grid. The best beam optics is obtained just below 5 kV, demonstrating that the extraction voltage required for ion extraction can be quite different from the voltage required for transporting the beam through the accelerator. A high extraction voltage leads to a beam waist near the extraction electrode und a subsequent beam blow-up. This could be overcome by using a higher acceleration voltage, which unfortunately is not available, as the systems at IPP are set-up for source development only. At IPP the currents flowing to ground potential and to the ground grid are routinely recorded together with the calorimetric current. The calorimetric current is calculated from the power deposition and the beam voltage. Particles neutralised in the accelerator do not have the full energy and the

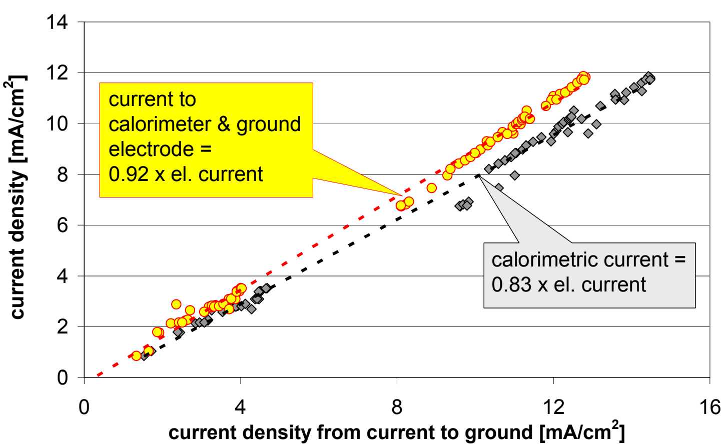


Fig. 11: Calorimetric current and current to ground electrode as a function of the current between HV and ground potential.

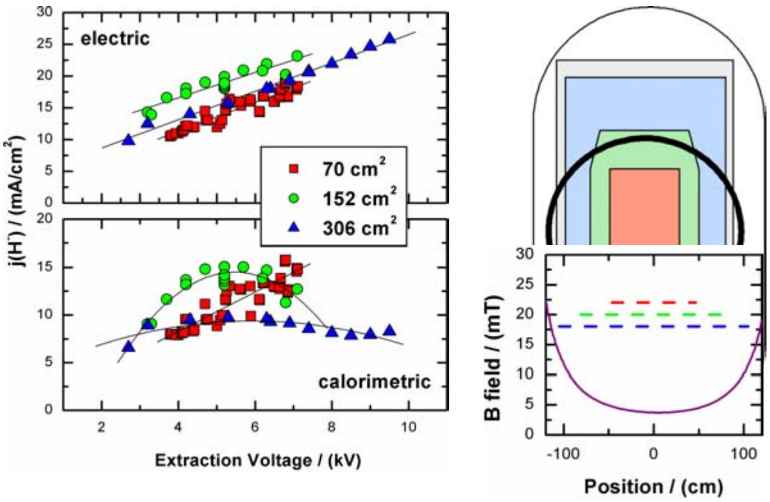


Fig. 12: Electric and calorimetric ion current density in MANITU for an extraction area of 75, 150, and 306 cm^2. The shape of the extraction area is indicated in the insert. The second insert shows the strength of the filter field together with the width of the extraction area as dashed lines.

calorimetric current is therefore a lower limit. 92% of the electrical current flowing between high voltage- and ground potential is either found on the calorimeter or on the ground electrode (fig. 11) with little scatter. In cases as in 3.4 below were the beam optics is not suitable for particle transport to the calorimeter the electrical current between high voltage and ground is a reasonable substitute for the calorimetric current, representing 80 – 85% of the calorimetric current.

3.4. *Scaling experiments 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 7.5 A. For the largest extraction area, the extracted electric current still increases with extraction voltage (fig. 12), while 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.

3.5. *Comparison LAG and CEA accelerator*

It could be expected that the LAG accelerator would yield higher ion currents than the CEA accelerator as the distance between plasma grid material, where negative ions are produced, and extraction hole is smaller. The first experimental results do not support this assumption. At lower RF power the current densities were essentially identical, at higher power the currents obtained with the LAG fall tend to fall below those obtained with the CEA accelerator (fig. 13). So far it can not be decided, whether this is caused by the grid design or if the source is not sufficiently optimised (experiments were terminated by a water leak).

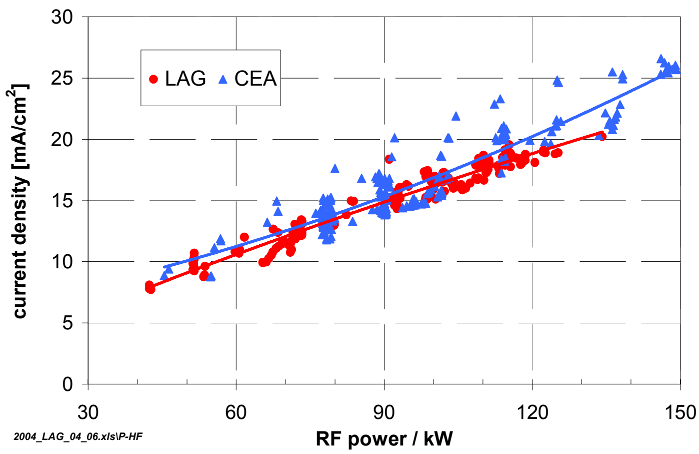


Fig. 13: Calorimetric H$^-$ current densities as a function of RF power for the CEA- (blue triangles) and the LAG accelerator (red dots). The dataset covers all 2004 pulses with heated plasma grid (>150 C), well caesiated and efficient source, grid bias (>8V) and low pressure (>0.4 Pa).

4. Outlook

At present MANITU is being upgraded for one hour pulses with the installation of a dc 180 kW RF power supply and dc HV power supplies rated for 15 kV, 35A for extraction and 35 kV, 15 A for acceleration. To enable deuterium operation a radiological shield is being added to MANITU. Additionally cryo pumps, beam dumps for steady state load, and source cooling for steady state operation are being installed. Details of the upgrade can be found in [5], [6].

The scaling of the extraction area is further being studied by introducing an intermediate step on the way to ITER: the so called half size ITER source to be installed in the RADI test bed, made up from parts of the previous W7AS radial injector. This source can be equipped with up to 4 circular drivers similar to those of the source 6.1, or with two race track shaped drivers similar to source 5. The distance between driver and plasma grid can be varied by means of a movable back plate. The filter field can be varied by inserting magnet bars or coils. Details of the source are given in [5, 6]. The test stand will be equipped with two 180 kW 1 MHz RF oscillators. Beam extraction is not foreseen, but there will be diagnostics to measure the plasma uniformity. Power supplies for biasing the plasma grid and for driving a current through the plasma grid to produce a so-called pg filter will also be provided. Recent developments in optical plasma diagnostics give reasonable confidence, that it will be possible to measure the negative ion density near the plasma grid [7], [8].

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