Large Low Pressure, High Power RF Sources for Negative Hydrogen Ions for Fusion Applications

U. Fantz, P. Franzen, H.D. Falter, W. Kraus, M. Berger, S. Christ-Koch, M. Fröschle, R. Gutser, B. Heinemann, C. Martens, P. McNeely, R. Riedl, E. Speth, D. Wünderlich

Max-Planck-Institut fuer Plasmaphysik, EURATOM Association, 85748 Garching, Germany

The Max-Planck-Institut fuer Plasmaphysik (IPP) is developing a large RF ion source which meets the requirements of the neutral beam heating system for the ITER fusion experiment. High current densities of negative hydrogen ions (330A/m^2 and 230A/m^2, H^- and D^-, respectively) are achieved for a small extraction area (7.0x10^{-3}m^2) and for short pulses (4s). The development concentrates now on extending the pulse length to up to 1 hour and extending the size of the source (80x80cm^2). Key issues are the homogeneity of a large RF plasma and use of a modular RF source concept. Source and beam optimization are supported by an extensive diagnostic program and by source modelling.

1. Introduction

The international fusion experiment ITER [1] requires for its heating and current drive neutral beam injection (NBI) systems based on negative hydrogen ion sources. The ion source must deliver 40 A of D^- ions for up to one hour with an accelerated current density of 200 A/m^2. The extraction area is 0.2 m^2 at a source dimension of 1.5×0.6 m^2. In order to reduce the losses by electron stripping in the acceleration system and the power load to the grids, the source pressure is required to be 0.3 Pa at an extracted electron/ion ratio ≤1. The development of the source was initially concentrated on filamented arc sources, which are operational at the Japanese fusion facilities [2,3], however these sources operate in a different (limited) parameter range. In addition, filamented arc sources suffer from regular maintenance intervals due to the limited lifetime of the high current tungsten filaments which requires a remotely handled replacement few times a year in the case of ITER.

As a promising alternative, a high power RF driven negative ion source is being developed at the Max-Planck-Institut fuer Plasmaphysik (IPP) [4]. RF sources offer substantial advantages: they are cheaper to build as they have fewer parts, requiring just a source body, an RF coil, and a matching circuit and they are basically maintenance-free in operation.

2. The low pressure, high power IPP RF Source

The standard IPP RF source (f = 1 MHz, P_{max} = 150 kW) consists of three parts (figure 1): the so-called driver, where the RF is coupled to the plasma by a water-cooled RF coil, the actual source body into which the plasma expands, and the extraction region. The latter are separated by a magnetic filter field (≈10 mT). The driver is mounted on the back of the source body and consists of an alumina cylinder. A water-cooled copper Faraday screen protects the alumina cylinder from the plasma. Due to the Faraday screen that allows only inductive coupling, a starter filament is necessary in order to ignite the plasma together with a gas puff of a few 100 ms length.

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 10 eV, away from the extraction region, where electron temperatures below 1-2 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. In addition, the current of co-extracted electrons is drastically reduced by the magnetic filter field due to the reduction of the electron density. Further

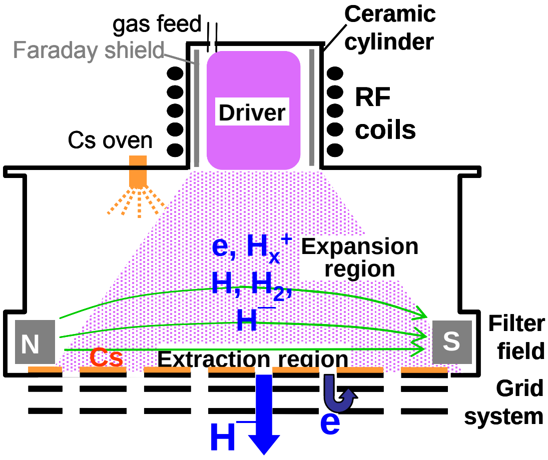

Figure 1: Schematic drawing of the standard size IPP RF source with a cylindrical driver (∅ = 24 cm, l = 20 cm) and a rectangular body (32×59 cm^2).

suppression of co-extracted electrons is achieved by biasing the plasma gird positive against the source body. In order to meet the ion current requirements, negative ions have to be produced by the surface process, i.e. the interaction of atoms or ions with materials of low work function: H, H_x^+ + surface e^- $\rightarrow H^-$. Currently evaporation of cesium is used to cover the surfaces with a thin layer of cesium, i.e. the work function is reduced to a value which depends on the thickness of the Cs layer. Since the survival length for negative ions is in the range of a few cm a coverage of the first grid, i.e. the plasma grid, is crucial. The negative ions produced at the plasma grid are accelerated into the plasma by the plasma sheath and have to bend back to the extraction system by collisions, charge exchange, or by the magnetic fields. In comparison to the production of negative ions by the volume process, i.e. the dissociative attachment process, approximately ten time higher current densities and drastically reduced electron currents (~factor 50) are achieved in this low pressure regime [4].

The extraction system consists of three grids (figure 2): (1) the plasma grid (holes with 14 mm size) which faces the plasma and is electrically insulated from the source body in order to allow for biasing; (2) the extraction grid with permanent magnets to prevent electrons to be fully accelerated; (3) the grounded grid. The source is on high potential (~20 kV). Extracted electron and ion current densities are measured electrically; however for the ion current density the value on the calorimeter is the parameter being of relevance for ITER.

Physical understanding of generation and destruction of the fragile negative hydrogen ions is mandatory. Thus, source optimisation is strongly supported by an extensive diagnostic program [5] and source modelling, which gives also an insight into the complex plasma chemistry of negative hydrogen ion sources caused by seeding the discharges with cesium. This understanding is of particular importance for stable long pulse operation and homogeneity of large sources. In a similar manner, extraction of negative ions and suppression of co-extracted electrons have to be optimised as well.

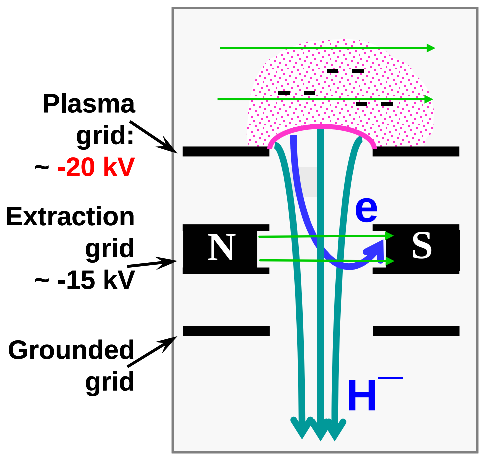

Figure 2: Schematic drawing of grid system. The permanent magnets for electron suppression are turned by 90°. The plasma grid can be biased against the source body (~15 V).

3. Results

Current densities of 330 A/m^2 and 230 A/m^2 have been achieved for hydrogen and deuterium, respectively, at a pressure of 0.3 Pa and an electron/ion ratio well below 1 for a small extraction area (7.0×10^{-3} m^2) and short pulses (< 4 s). Since in deuterium electron current are higher than in hydrogen, electron suppression is important and was done by using a higher magnetic filter field and an increased bias voltage. Reproducible and reliable operation was achieved by optimizing the Cs dynamics.

The development concentrates now on extending the pulse length to up to 1 hour and extending the size of the source - a large RF source with the width and half the height of the ITER NBI source. This source is dedicated to demonstrate the homogeneity

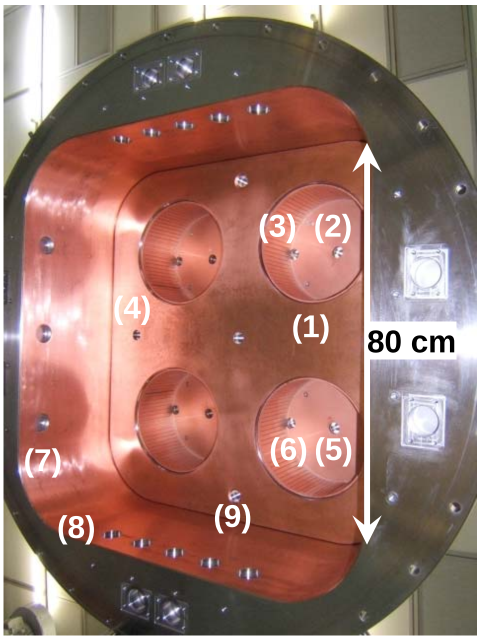

Figure 3: View into the large ion source: (1) source back plate, (2) drivers with back plate, (3) Faraday screen, (4) Cs oven ports, (5) feedthroughs for starter filaments and (6) gas, (7) three vertical, (8) five horizontal and (9) three axial diagnostic ports.

of large RF plasmas and to test the modular concept of the RF source (4 driver modules). The source is not equipped with an extraction system, however, to ensure the gas conductance a dummy grid is installed [4,6]. The RF power supply consists of two 180 kW, 1 MHz RF generators rated for a pulse length of up to 30 s. Each generator powers a horizontal pair of drivers.

Figure 3 shows the interior of the large source, being equipped with many ports for diagnostic access. The homogeneity is measured in front of the dummy grid by optical emission spectroscopy using several line-of-sights and Langmuir probes. The overlap of the plasma generated in the individual drivers is measured. First measurements of a 'pure' plasma, i.e. without Cs seeding, without magnetic filter field, and without bias, show that the plasma overlap is sufficient for a homogeneous illumination

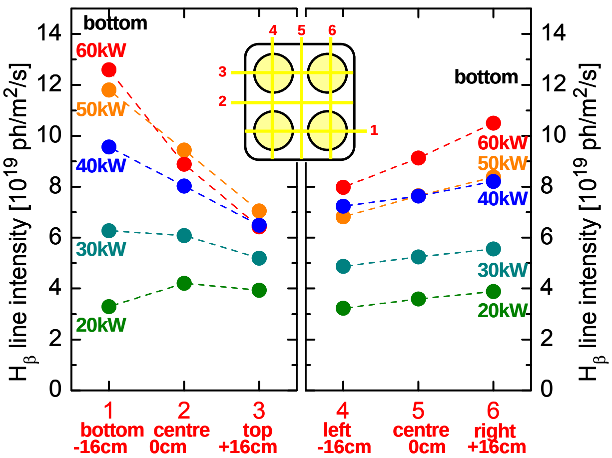

Figure 4: Balmer line intensity as measured in the large ion source (figure 3) at 0.38 Pa and 40 kW RF power for the upper pair of drivers. The power of the lower pair was varied as indicated. The six lines-of-sight at a distance of 2 cm to the grid are indicated in the sketch.

of the plasma grid. Possible plasma non-uniformities can be compensated for by varying the RF power levels across the source (figure 4).

Systematic investigations on the plasma symmetry, i.e. the ratio of the plasma light (H_β emission) in the upper half to the lower half of the plasma grid at 2 cm distance, are carried out in the standard size source. When a magnetic filter field is applied, a plasma asymmetry is observed. By applying a bias voltage between source body and plasma grid this asymmetry can be compensated for, indicating that an E×B drift causes the asymmetry. As shown in figure 5 symmetrical plasma is obtained in the typical working range, i.e. at still high ion currents but drastically reduced electron currents. The change in the plasma potential close to the grid

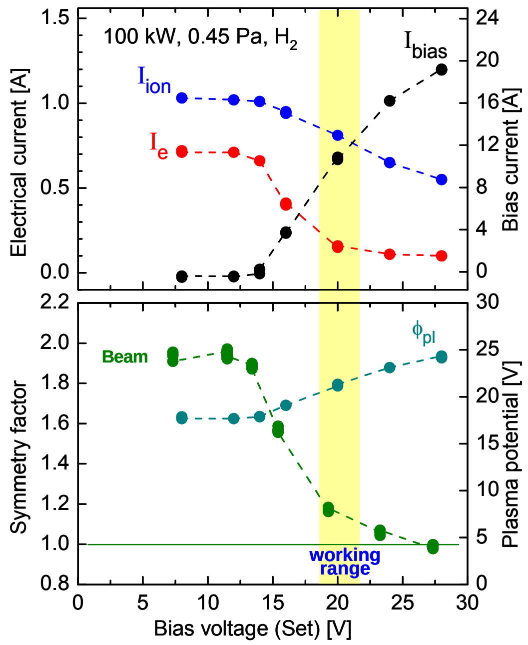

Figure 5: Symmetry factor defined as the ratio of H_β line intensity (in 2 cm distance to the grid) in the upper half to the lower half of the standard size source as a function of the applied bias voltage. Bias current, extracted electron and negative ion current as well as the plasma potential are shown.

by the biasing is measured by the Langmuir probe system. The achieved electrical ion current of 2 A corresponds to a calorimetrically measured ion current density of 80 A/m^2.

The other main challenge of a stable operation of a negative ion beam is the Cs dynamics and supply during long pulses. Hence, the long pulse test facility (standard size) is equipped with a remotely controlled Cs oven and a specially designed Cs monitor system. Time traces of a long pulse (800 s at 0.5 Pa and 40 kW) are shown in figure 6. The bias current was varied during the pulse in order to control the electron current.

Furthermore, the long pulse test facility is equipped with a spatially resolved beam emission spectroscopy system for measurements of the beam homogeneity. The temporal and spatial homogeneity of the ion beam can be determined by comparing the half width of the Doppler shifted H_α line being proportional to the local divergence and hence the local negative ion density in the source. First measurements showed that the beam inhomogeneity is less than 5-10% (RMS) - for an extraction area of 0.0188 m^2 - and improves with lower source pressure and increased RF power. In combination with optical emission spectroscopy this system gives the unique possibility of relating the beam homogeneity to the plasma uniformity in the source.

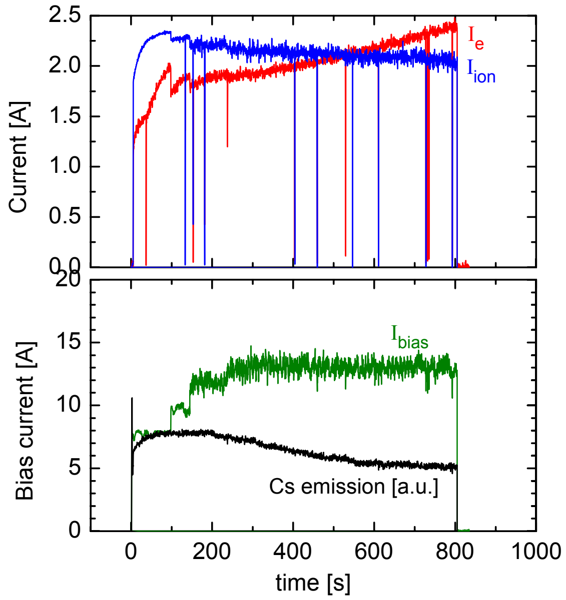

Figure 6: Time traces of the long pulse experiment. The intensity of the Cs line at 852 nm is measured at 2 cm distance to the grid.

The measurement of the negative ion density by the novel technique via the H_α/H_β ratio [7] indicates that negative ions are not a minority in front of the grid. Measurements show that even at a distance of 2 cm above the plasma grid, the negative ion density is about 20-30% of the electron density. This ratio is increased closer to the grid due the production of the negative ions at the grid and the resulting pushing back of the electrons. Measurements of the negative ion density by cavity ringdown spectroscopy and laser detachment agree rather well with the values obtained by optical emission spectroscopy. These diagnostics have been successfully installed in the noisy RF environment [8, 9]. Figure 7 shows the correlation between the negative ion densities measured with the cavity ringdown spectroscopy at

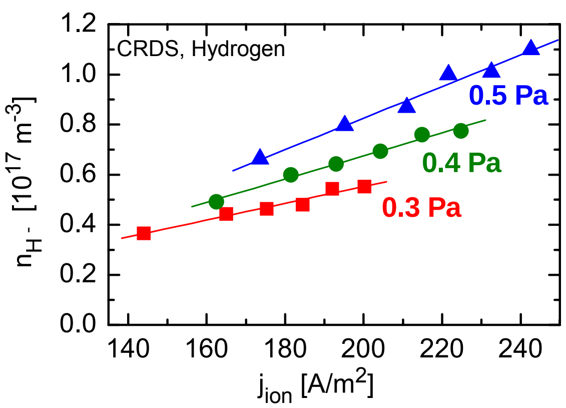

Figure 7: Correlation between the negative ion density (cavity ringdown spectroscopy) and extracted ion current density for three pressures at RF powers of 40-90 kW.

2 cm distance to the grid and the extracted current density of negative hydrogen ions. This correlation will be used for extrapolation of expected current density of negative ions in the large ion source where an extraction system is not available but the cavity ringdown and the laser detachment technique will be applied.

4. Conclusion

The development of an RF source for ITER NBI system is being successfully developed at IPP. The physical parameters, i.e. high ion current densities and low co-extracted electron currents at 0.3 Pa source pressure are achieved in a pulsed standard size source in hydrogen and deuterium. In the long pulse experiment stable operation is shown for 800 s at an extraction area of 0.0188 m^2. First measurements at the large size source (80×80 cm^2) indicate a homogeneous illumination of a 'half-size ITER' grid. The development is strongly supported by an extensive diagnostic and modelling program. One important issue is the understanding of the plasma asymmetry which could be compensated for by using different power levels in the large source and by applying a bias voltage, which is also a benefit for the suppression of co-extracted electrons. Second, negative ion densities close to the extraction systems show a strong correlation with the extracted ion currents. Third, the beam homogeneity is measured to be in the required range for ITER applications. Fourth, the long pulse experiment will give the unique possibility to correlate plasma homogeneity with beam homogeneity, which is one of the next tasks.

5. References

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