First Beam Extraction Experiments at BATMAN Upgrade

W. Kraus, L. Schiesko, F. Bonomo, U. Fantz, B. Heinemann, A. Hurlbatt and the NNBI Team

Max Planck Institute for Plasma Physics
Boltzmannstr. 2, 85748 Garching, Germany.

Corresponding author: kraus@ipp.mpg.de

Abstract. The design concept of the RF driven negative ion sources used in the NBI of ITER has been developed at the BATMAN test facility since 1997 [1]. It is based on the plasma generation with a 1 MHz RF power supply in circular drivers out of which the plasma expands in a large source volume. The negative ions are produced by surface conversion of atoms and ions on the caesium covered plasma grid. During the past two years Batman has been upgraded substantially by a new extraction system with a design closer to that of the ITER source allowing beam extraction with higher acceleration voltage and by a refined beam and source diagnostics. A further improvement concerns the magnetic filter field which was previously generated only by permanent magnets placed at the lateral walls of the source. It can now additionally be produced, like at the ITER source, by a current flowing through the plasma grid (PG). In the first beam extraction experiments significantly higher negative ion currents, much lower currents of co-extracted electron currents and nearly no beam shift was observed with the PG filter field. With the new extraction system a lower beam divergence is achieved by variation of the acceleration voltage up to 32 kV.

INTRODUCTION

RF driven negative ion sources will be used for the NBI systems of ITER and beyond that for DEMO. Tests of the ITER size source with eight cylindrical drivers for plasma generation have already been started at the SPIDER testbed at the NBTF (Neutral Beam Test Facility) in Padua [2]. With the ELISE source at IPP, which is half the size, the accelerated ion current densities required for ITER have been recently demonstrated in hydrogen for more than 1000s [3]. However, there are still difficult problems to be solved concerning the performance in deuterium, the beam divergence and homogeneity, the caesium dynamics in the source and the source efficiency. To accelerate the development the smaller BATMAN testbed (BAvarian Test MAchine for Negative ions) is being operated in parallel to ELISE using smaller sources. It is more flexible, has better access for diagnostics and allows testing new source concepts. Further goals are to improve the physical understanding and to benchmark the results of source and beam modelling.

Up to now BATMAN was equipped with an extraction system based on a positive ion extraction system, which resulted in a poor beam quality and a limited voltage holding capability. For BATMAN Upgrade a new extraction system with aperture geometry similar to that of ITER was designed in order to enhance the significance of the results and to improve the beam optics. A second important upgrade was to generate the magnetic filter field by a current through the plasma grid as it is foreseen for ITER. The self-excited RF generator has already been replaced by solid-state generators at BATMAN [4]. Technical improvements concerned all electrical circuits and the cooling system resulting in higher reliability of BATMAN Upgrade.

EXPERIMENTAL SETUP

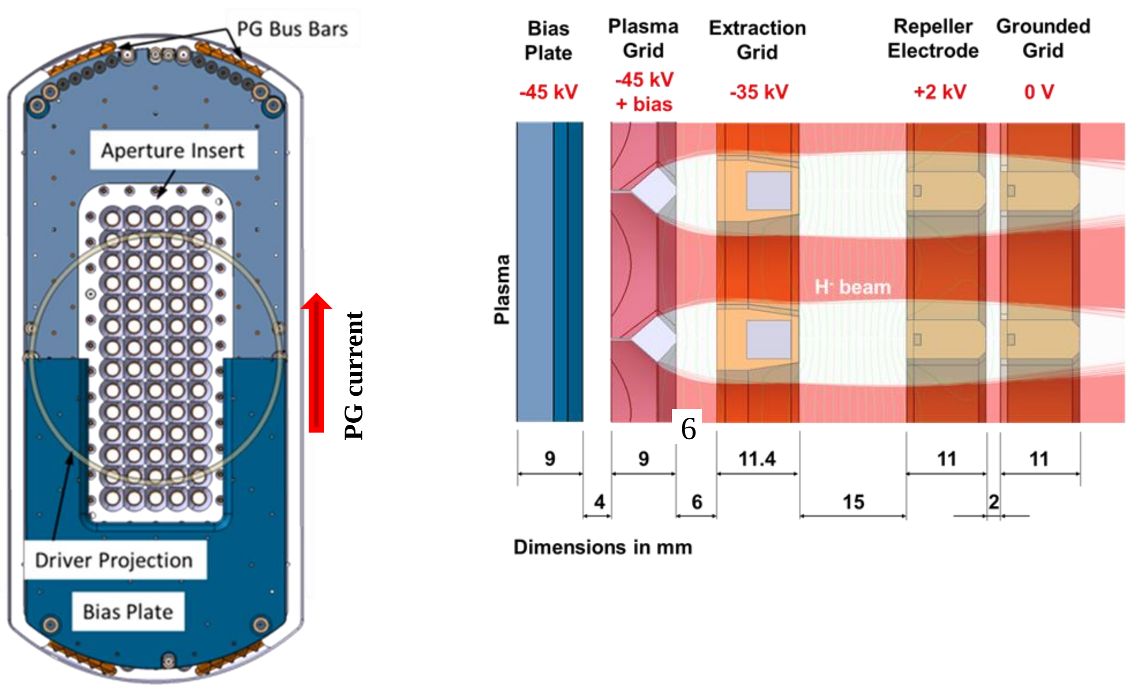
For the first experiments the small prototype source with b × l × d = 31 × 58× 23 cm^3 and one cylindrical driver of 24.5 cm diameter was used. Due to the limitation by the pumping system (Ti evaporation pumps) source plasma operation is only possible in short pulse up to 7 s with minimum 180 s interruption time between the pulses. A detailed description of all technical and design changes from BATMAN to BATMAN Upgrade can be found in [5]. Only general issues of the set-up are described in the following.

The ITER Like Grid System (ILG)

In the new extraction system 70 apertures of 14 mm diameter are arranged in a 5 x 14 pattern (see. Figure 1 (a)) like used in one segment of the ITER NBI (5 x 16 apertures). The cross sections of the apertures in the grids are similar to that of the ITER extraction system. Compared to the old system with 8 mm apertures the total extraction area was enlarged from 70 cm^2 to 108 cm^2. By new grid holder boxes with higher voltage holding capabilities, the maximum beam energy was raised from 23 kV (10 kV extraction (U_{ex}) and 13 kV acceleration voltage (U_{acc})) to 45 kV (10 kV U_{acc} and 35 kV acceleration voltage).

With the old BATMAN extraction system the beam divergence was optimal at U_{ex} < 5 kV and U_{acc} = 18 kV. But to extract high currents it was necessary to raise the voltage beyond that up to 10 kV, resulting in a high beam divergence, because the U_{acc} was too low to focus the beam. At ITER 10 kV are foreseen for U_{ex} The higher available acceleration voltage of the ILG will allow to extract of high ion currents with a well-focused beam.

A difference to the ITER extraction system is the fourth electrode, the “repeller grid” (RE) (see. Figure 1 (b)) which is located between the extraction grid and the grounded grid (GG). By application of a positive potential with respect to the grounded grid the repeller grid can be used for tests to reduce the space charge blow up of the beam and to suppress the current of back streaming positive ions. During the first experimental campaign the repeller grid was connected to ground potential.



(a) (b)

FIGURE 1. CAD drawing of the plasma grid of the ILG (a) and cross section of one beamlet (b).

The Magnetic Filter Field

The magnetic filter field at BATMAN could only be generated by six to eight rows of CoSm permanent magnets of a cross section of 9 x 13 mm^2 placed at the lateral sides of the expansion chamber (PM field). Many investigations have been performed about the effect of the number and the position of the magnets with respect to the plasma grid on the plasma and the beam properties [6]. However, due to their limited range permanent magnets cannot be used for large sources like the ELISE and the ITER source. For the first experiments on BATMAN Upgrade eighth rows of magnets have been mounted in 9 cm distance from the plasma grid. The magnetic field could be created alternatively by a current of up to 3 kA flowing vertically through the plasma grid (PG field) as indicated in Figure 1(a). The PG current returns in connectors which are located below the back plate at the lateral side of the expansion volume in order to keep the B field in the driver as low as possible.

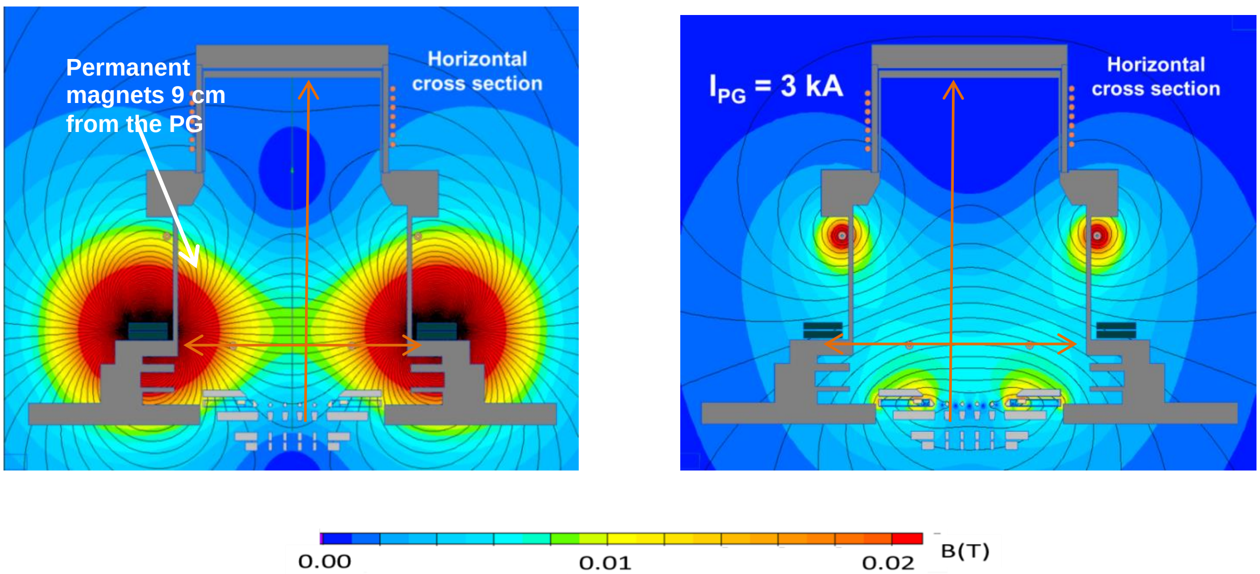


FIGURE 2. Horizontal cross section of the magnetic B field created by permanent magnets (left) and by a PG current of 3 kA (right), orange arrows indicate the position of the profiles shown in Figure 3.

The differences of the 2D field topology between the two filter fields are obvious (see Figure 2). The axial profiles in the center are not so much different, but the horizontal profile of the field of the permanent magnet shows from inside to outside a steep increase (Figure 3). This inhomogeneity of the field profile is expected to affect the plasma drift as well as the caesium dynamics in the source.

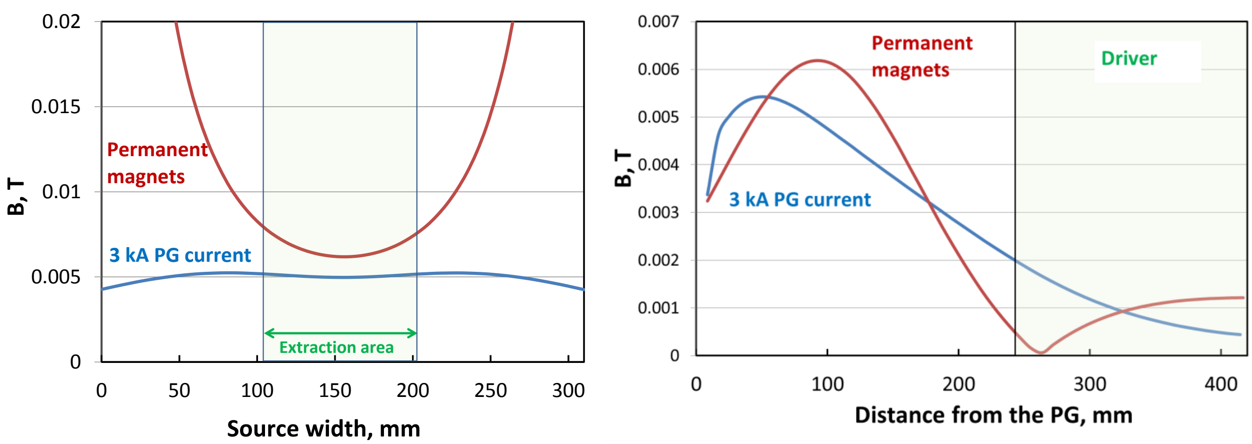


FIGURE 3. Axial B field profiles from the plasma grid to the back plate of the driver (right) and horizontal profiles in 9 cm distance parallel to the plasma grid over the entire width of the source (left)

Beam Diagnostics

An overview of the installed beam diagnostics is shown in Figure 4. Apart from the usual measurements of the extracted currents of ions and electrons and the currents on the GG and the RE, BATMAN Upgrade has been equipped with various new or upgraded beam diagnostics. For a quick visual image of the beam two wire calorimeters can be used consisting of an array of thin tungsten wires with a diameter of 0.3 mm [7]. One is located in 19 cm the other in 180 cm distance from the grounded grid. In the wire calorimeter close to the GG in front of each of the outer four vertical rows of apertures only one wire is spanned. The glow pattern of the 12 wires in front of the central row provides a rough resolution of the beamlets and visualizes the divergence of the single beamlets and the deflection by the field of the electron deflection magnets in the extraction grid.

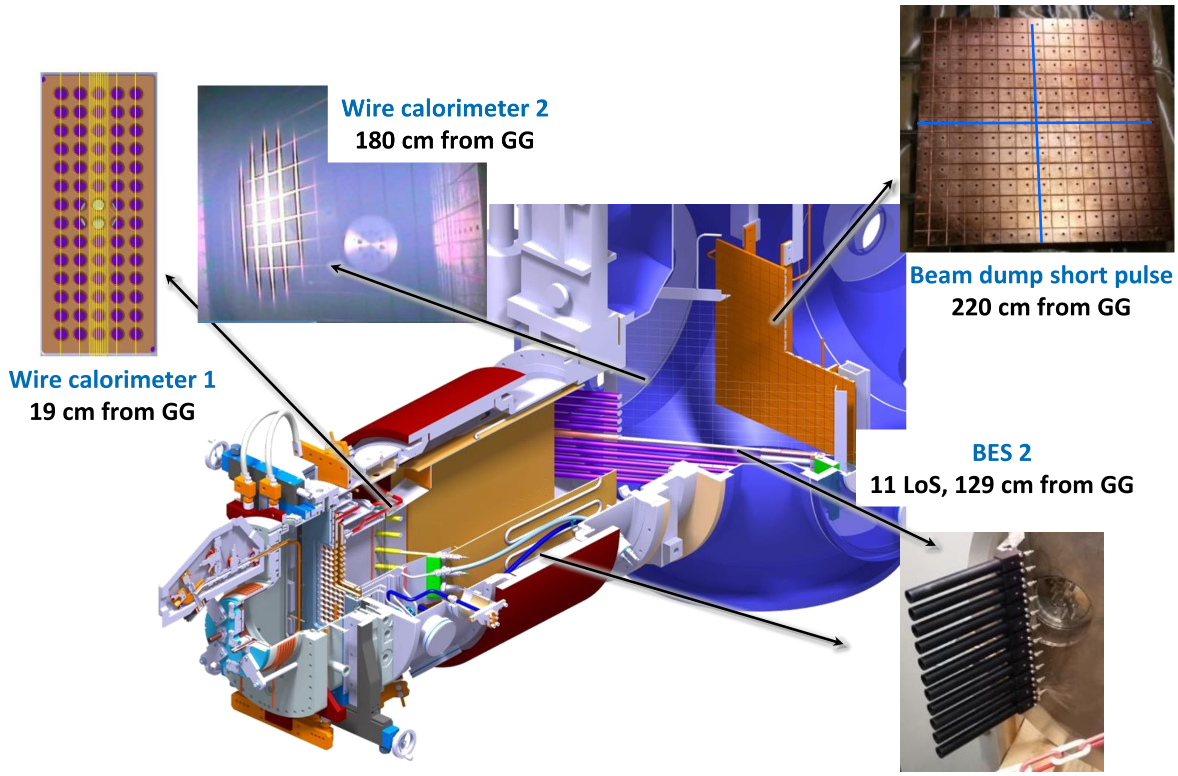


FIGURE 4. Beam diagnostic systems at BATMAN Upgrade

With two arrays of line of sights for the beam emission spectroscopy (BES), one in 26 cm the other in 129 cm distance from the GG, the local beam divergence can be determined. On the beam dump the beam profile and the total ion current can be measured by thermocouples. The current can also be measured by water flow calorimetry.

RESULTS

Ion and Electron Currents with Different Filter Fields

For the first beam extraction experiments the source has been conditioned in hydrogen by evaporation of caesium and by short plasma pulses to distribute it in the source. A level of 25 mA/cm^2 for the extracted current density was reached with 70 kW at 0.6 Pa after some days. Further improvement might be possible by long term conditioning.

Scans of the extracted ion currents and the ratio of electron to ion currents as a function of the PG current have been performed for 0.6 Pa and 0.4 Pa and comparative measurements carried out in the successive pulses with the field of the permanent magnets only. With permanent magnets the ion currents are about 20 % lower and the electron currents higher. The results shown in Figure 5 reveal that the electron currents can be suppressed efficiently with the PG field without reducing the ion current. With a PG current of more than 2.5 kA it is possible to reduce the I_{el}/I_{ion} ratio below 0.1.

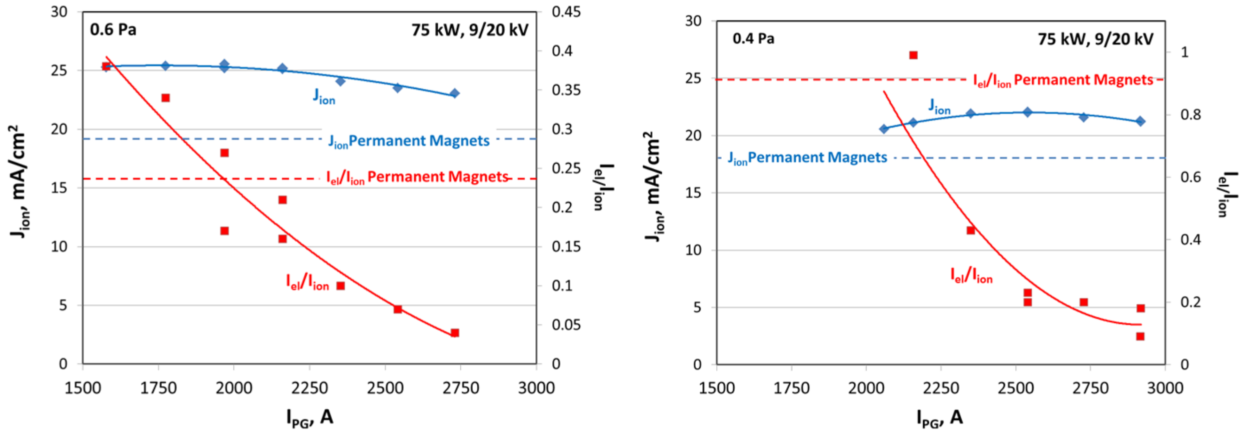


FIGURE 5. Extracted ion current densities and ratio of electron to ion currents as a function of the PG current for source pressures of 0.6 Pa (left) and 0.4 Pa (right), the results with the permanent magnet filter are indicated by the dotted lines.

Beam Quality

Figure 6 shows the electrically measured extracted current which is at least 25% higher than the current on the calorimeter measured by water flow calorimetry j_{WC}. This difference is significantly higher than observed with three grid extraction systems with the same aperture geometry as it is used on ELISE. There less than 20 % are measured mainly caused by stripping losses [3]. The reason for the difference between the two grid systems are the additional losses on the repeller grid in the ILG. The currents on this additional grid, which have been measured by water flow calorimetry, are of about the same order as the currents on the grounded grid j_{GG}.

The decrease of j_{GG} at high acceleration voltage corresponds to the simultaneously decreasing beam divergence shown in Figure 7 for both filter fields. Less than 1.5 degree has been achieved with the permanent magnets in the center of the beam. The divergence minimum at an extraction voltage of 6 kV has been achieved with an acceleration voltage of 28 kV. With the old extraction system the acceleration voltage was limited to 17 kV for the same extraction voltage and the beam divergence therefore higher than 3 degree [8].

With the single line of sights of the beam emission spectroscopy a very homogenous distribution of the divergence has been observed in case of the PG filter. An acceleration voltage, however, high enough to reach the divergence minimum was not available for this scan.

The different B field topology of the permanent magnets results in a much greater variation of the divergences.

The minimum divergence is achieved above the geometric centre which corresponds to a drift upwards of the beam caused by the deflection by the B field of the magnets. The direction of the PG field is opposite, but the drift is almost not visible.

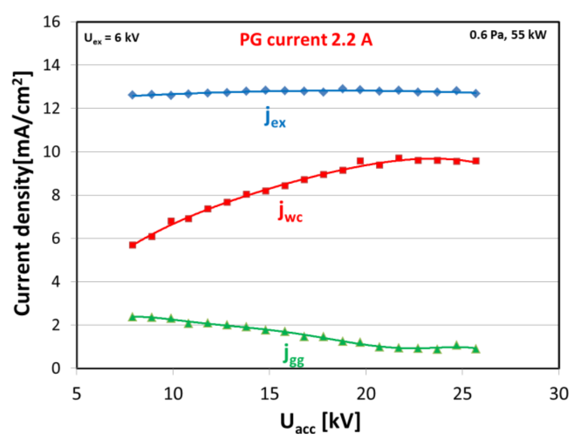


FIGURE 6. U_{acc} scan with PG filter of the extracted currents density j_{ex}, the current densities jwc and j_{tc} on the calorimeter and on the grounded grid j_{gg} at an extraction voltage of 6 kV.

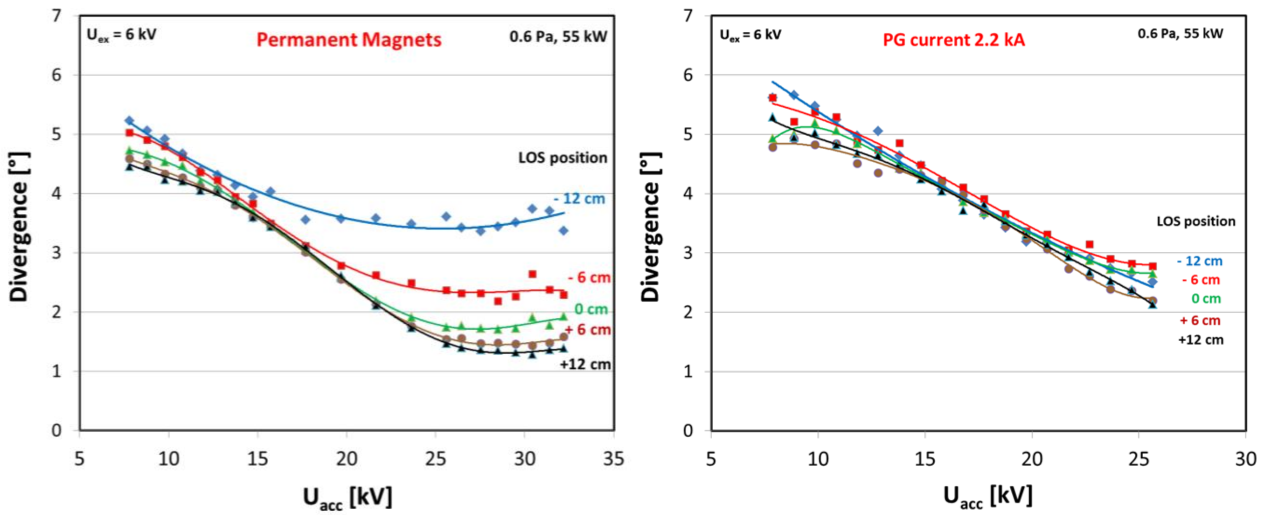


FIGURE 7 . U_{acc} scans of the beam divergence measured with the BES located 129 cm from the grounded grid at an extraction voltage of 6 kV, the positions of the lines of sight are given with respect to the horizontal center of the beam line + sign corresponds to + is up, - to bottom. .

SUMMARY

The major changes from BATMAN to BATMAN Upgrade are a new ITER like extraction system and the magnetic filter produced by a current flowing through the plasma grid.

In first extraction experiments a significant better source performance could be achieved by this filter compared to the previously used permanent magnet filter. The main difference of the beam profiles are a more homogenous beam divergence with the PG field and a beam shift only occurring with the permanent magnets. Compared to the old extraction system the beam divergence was in both cases much lower which is caused mainlyby higher achievable beam energy. All these observations have to be confirmed and refined after long-term conditioning of the caesium layers on the plasma grid.

The fourth grid, the repeller grid, caused additional current losses in the extraction system. The next experiments will concentrate on the effect of positive biasing the repeller grid on the beam quality. The next major step of the upgrade of the test facility will be replacing the Ti evaporation pumps by Cyro pumps. This will enable to operate the source in cw, but still with pulsed beam extraction. Beam extraction in cw will be possible after implementation of a long pulse calorimeter.

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