A new tungsten wire calorimeter for the negative ion source testbed BATMAN Upgrade

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Within the framework of the ion source development for the ITER and DEMO Neutral Beam Injection (NBI) systems, IPP Garching has recently upgraded the radiofrequency-driven negative ion source testbed BATMAN. One of the requirements for the ITER NBI system is to produce a beam power density homogeneity above 90% over its large beam size extracted from an ion source of 1 x 2 m^2. The beam uniformity is going to be investigated, on a smaller scale, in BATMAN Upgrade with the new ITER-like beam optics. The testbed is equipped with several beam diagnostic tools to measure beam power, uniformity and divergence. A new tungsten wire calorimeter (TWC) has recently been developed to characterize the beam quantitatively and with an improved spatial and temporal resolution. The TWC consists of an array of thin tungsten wires with a diameter of 0.3 mm, placed in the beam path. The wires are heated by the beam up to 3000 °C and emit visible light, which is observed by an optical camera. While the existing TWC provides a qualitative impression of beam power characteristics and is placed at a distance of almost 2 m from the beam extraction system, the new TWC is positioned only 19 cm downstream from the extraction system and allows observation of the single beamlets for the first time in this testbed. In order to determine the correlation between the pixel intensity measured by the camera and the power density impinging on the wires, one wire is equipped with an ohmic heating system which allows heating up the wire with a known power, thus enabling calibration of the diagnostic tool.

In this paper the design, including FEM simulations of the wire thermal behavior, manufacturing and installation of the new TWC inside the BATMAN Upgrade testbed are described and the first, very promising, observations of beamlet intensities are presented.

Keywords: *ITER, NBI, Negative Ion Source, RF Source, Beam Calorimeter*

1 Introduction

For heating and current drive in the fusion experiment ITER two Neutral Beam Injectors (NBIs) will be used with a total power of 33 MW [1]. These systems rely on radio frequency (RF) driven ion sources which must deliver 46 A of accelerated H^- current for 1000s and 40 A of accelerated D^- current for 3600s. The ITER NBI will use RF sources, which are based on the design developed at IPP over the last two decades at the testbeds BATMAN [2], MANITU [3], RADI [4] and ELISE [5]. The test facility BATMAN has recently restarted operation after an extensive renewal and will be called from now on BATMAN Upgrade [6]. In particular the prototype ion source at BATMAN Upgrade, which has one RF driver and has roughly the dimension of 1/8 of the ITER ion source, has been equipped with a new extraction system and new beam diagnostics. The new ITER-like extraction system has the same aperture design as in ELISE and an additional "Repeller electrode" i.e. a 4-grid extraction system. The first grid, the plasma grid (PG), is equipped with 70 apertures of 14 mm diameter with 20 mm x 20 mm spacing, arranged in a 5 (H) x 14 (V) pattern, just two rows shorter than one beamlet group of the ITER extraction system, for a total 108 cm^2 of extraction area. Caesium is evaporated into the source to reduce the surface work function and increase (by a factor of 10) the H^- extraction. A magnetic filter field, which is necessary to reduce the amount of co-extracted electrons and to lower the electron temperature to below 2 eV in front of the PG and therefore reduce H- destruction, can be produced by a strong electric current (up to 3 kA) flowing inside the PG, as in ELISE and ITER, and/or by permanent magnets placed on the side of the source. The second grid is the extraction grid (EG), which is equipped with strong electron suppression permanent magnets (ESM) to filter the co-extracted electrons, by deflecting them onto the EG surface. The impinging electrons cause a strong heat load on the EG, which is actively cooled by means of an embedded water circuit. The third grid is the Repeller electrode (RE) and the fourth grid is the grounded grid (GG). The RE can be positively charged against the GG (+2 kV) to reduce the back-streaming positive ions originating downstream of the GG. An extraction voltage U_{ex} up to 10 kV is applied, as in previous IPP test beds. The total voltage U_{HV} has been increased from 23 kV in BATMAN to 45 kV in BATMAN Upgrade, which, together with the new aperture design, considerably improves the beam optics.

The first experimental campaign of BATMAN Upgrade was started in June 2018 with up to 10 s plasma pulses including up to 4.5 s beam pulses repeated every 3 min. Currently the beam duration is limited by the titanium sublimation pumps and the inertially cooled copper calorimeter, which are designed for short beam pulses. New cryo-pumps and a new actively cooled diagnostic calorimeter will be installed over the next months, to allow for longer beam pulses, up to 1 h.

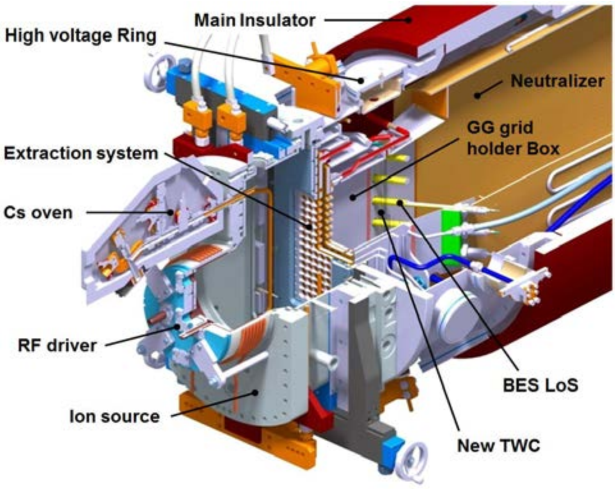

Figure 1 Section of the BATMAN Upgrade ion source

In ITER it will be very important to produce a large beam with the required intensity, a low divergence (e.g. to reduce losses in the beam transmission from the accelerator to the vacuum vessel) and low non-uniformity: maximum 10% deviation of the H^- current extracted from each beamlet with respect to the average value. To fulfill such a requirement it is first of all necessary to measure the single beamlet intensity and this is difficult in an ITER relevant source with a large multi-aperture extraction system (grid area ~ 1 m^2) and beam duration up to 1 h. Arc source testbeds at NIFS and QST have beamlet monitor capability for short time scales (~ 1 s) [7][8]. At the ITER full-size RF source testbed SPIDER in Consorzio RFX (Padoa, Italy) the beamlet diagnostic tool STRIKE is also foreseen to characterize the beam for short pulses (< 10 s) [9]. Up to now the beam homogeneity at the IPP prototype source testbeds could only be measured more globally by either absolutely calibrated Doppler-shift beam emission spectroscopy (BES), positioned at 26 cm and 1.3 m downstream from the GG, or at the diagnostic calorimeter positioned at about 2.1 m from the GG. In ELISE a 2D beam power map can be obtained via IR measurements of the diagnostic calorimeter placed at 3.5 m distance from the GG. Tungsten wire calorimeters have been successfully used at BATMAN and ELISE to obtain a qualitative impression of the beam, albeit with spatial resolution of 20 mm and 40 mm, respectively and at a distance of about 1.8 m from the GG. In BATMAN Upgrade new beam diagnostic tools have been introduced or upgraded in the beamline [10]. Among them a new tungsten wire calorimeter (TWC), has been installed only 19 cm downstream from the GG, as shown in Figure 1. This calorimeter has to withstand a high heat load, but can give insight on the beam uniformity across one column of apertures. This TWC has been equipped for the first time with a calibration system to perform quantitative analyses of the beamlet power density distribution along the W wires [11].

2 Tungsten wire calorimeter

The working principle of the TWC is based on the heating up of tungsten wires caused by the energetic H^- ions (tens of keV) impinging on the wire surface. When the wires are heated up to a temperature above 600°C they emit radiation in the visible spectrum. Wires with 0.3 mm diameter are used, which result in very short heating up time (down to about 1 s), which in turn allow to observe the temporal evolution of the beam in short time scales. For such thin wires, at high temperature (> 1000°C), little heat is transported via conduction along the wires with respect to the thermal radiation cooling; therefore the wire emissivity profile is very close to the beam power density profile. The use of thin wires also results in a minimal blocking of the beam, which can pass through the TWC almost undisturbed and can be further analyzed by the other diagnostic tools placed downstream. The intercepted beam portion is less than 5% of the total, which means that a few kW of power are thermally irradiated to the surrounding water-cooled components, i.e. GG, grid holder box and neutralizer, during the beam-on time.

The wires are arranged vertically in a horizontal array and are fastened onto a metallic frame by tension springs, to compensate for thermal expansion, as shown in Figure 2. A simplified calculation shows that with a uniform H^- ion beam accelerated at 50 kV and an extracted ion current of 300 A/m^2 (typically reached at BATMAN) and divergence of less than 1°, a wire temperature of about 2800°C can be reached in less than 1 s. At this temperature the 300 mm long wire elongates about 3.6 mm. The springs have been specified to allow for this elongation and also to exert a minimal force on the wires. Although tungsten is mechanically very strong at room temperature, the tensile strength is greatly reduced at a very high temperature, therefore the springs have been designed to produce just a few tens of MPa of tensile stress on the wires. The estimated maximum spring temperature is about 700 C at one extremity, therefore heat resistant INCONEL X750 alloy has been chosen as spring material.

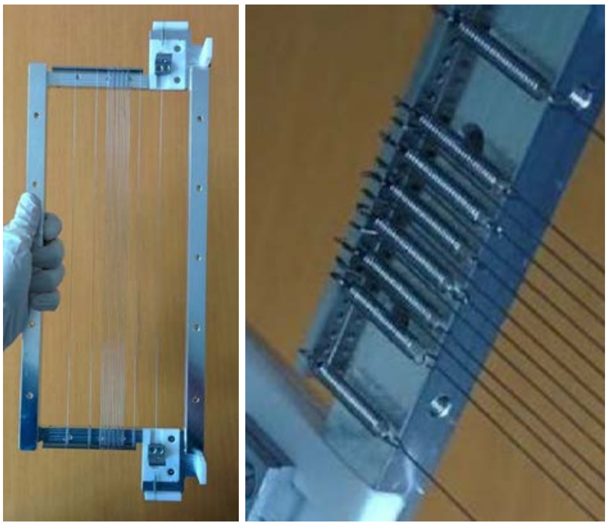

Figure 2 *Left*: assembled tungsten wire calorimeter ready for installation; *right*: detail of springs and wire fastening.

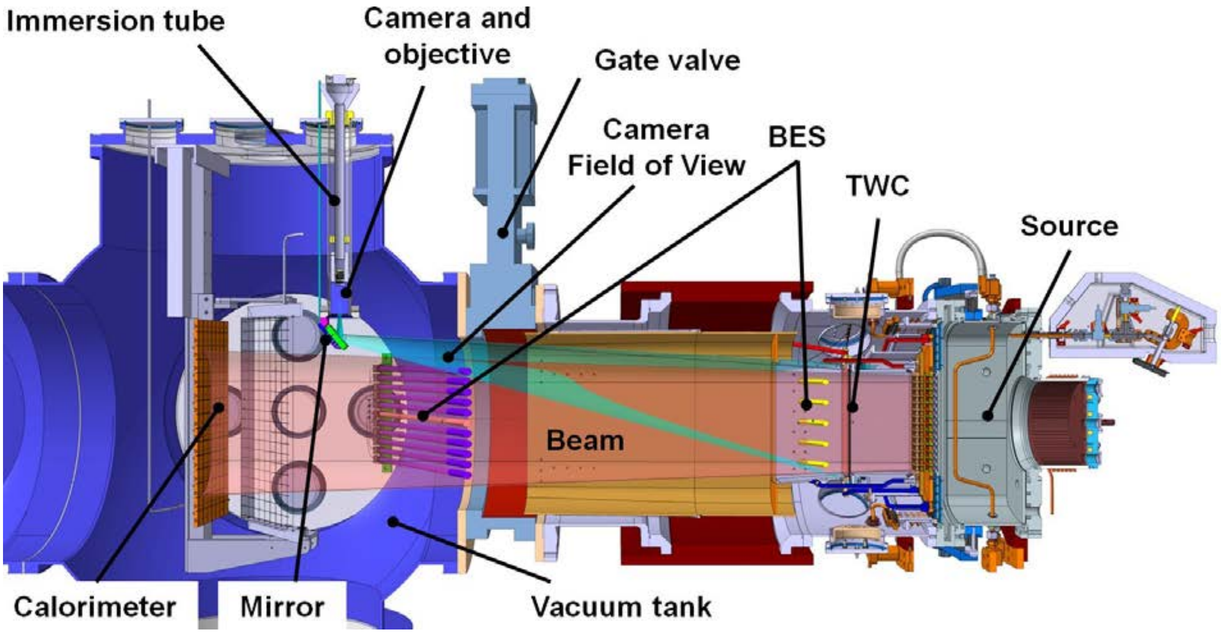

Figure 3 Cut out through a CAD drawing of the BATMAN Upgrade test facility showing the layout of the camera acquisition system for the new TWC. For a 2° divergence the beam (pictured in transparent red) does not intercept the immersion tube hosting camera and objective nor the first surface copper mirror

One vertical wire is placed in correspondence of each aperture column of the extraction system, i.e. with a spacing of 20 mm. For the central column of apertures, 11 wires have been positioned with 2 mm spacing to produce a more detailed mapping of the power density distribution of these beamlets. For this central aperture column 15% of the beam is intercepted by the TWC wires.

The "calibration wire" is place on the right side of the TWC (in beam direction) due to space constraints. Two Kapton®-insulated flat ribbon copper cables are used to carry the current to the tungsten wire. The flat ribbon is connected to the wire via a TZM clamp. This has been designed with a dovetail-shaped side, allowing it to slide over a MACOR® insulator and ensuring that the wire is electrically insulated from the TWC frame.

A CCD camera looks at the calorimeter and records the emitted light. The pixel intensity obtained via the camera corresponds to the radiation emitted by the wires, which in turn depends on the beam power impinging on them. The system calibration is done by ohmically heating one wire with an external power supply. From the ohmic heating power it is possible to calculate the corresponding thermally radiated power density per emitting length unit of the wire. This value can be associated to the pixel intensity of the heated wire at the CCD camera. By repeating the measurement for several input powers it is possible to obtain a calibration curve which allows evaluating the beam power density directly from the pixel intensity. This calibration procedure has the advantage to bypass the evaluation of the wire temperature, e.g. by an IR camera, and therefore being independent from the estimation of the tungsten surface emission coefficient, which is highly non-linearly depending on the wire temperature, surface finish, material aging, tungsten recrystallization at high temperature.

2.1 Image acquisition system

A monochromatic camera, Genie Nano-M4060 by Teledyne Dalsa with 7.5 mm x 14.2 mm sensor area and a resolution of 2176 x 4112 pixels, has been installed in the testbed to take high resolution pictures of the TWC during calibration and beam extraction. The camera has been equipped with a "12 megapixel" TAMRON M111FM50 objective with 50 mm of focal length. The resulting field of view is enough to observe the projection of all the beamlets on the new TWC.

The TWC is observed via a first surface copper mirror attached to an immersion tube, as shown in Figure 3. The camera is inserted into the immersion tube and air-cooled by a fan. The mirror is placed as close as possible to the camera to minimize its dimensions and reduce the risk of being damaged by the energetic ions of the beam halo. A simplified analysis performed by CAD shows that the mirror is not going to interfere with the beam for a typical beam divergence of 2° or smaller. As a precaution the mirror is also equipped with an "inertial" water cooling to remove heat that could be generated by impacting ions. The distance between camera and TWC is about 1.5 m. This, combined with the other characteristics of camera and objective, allows for a resolution of about 0.12 mm width per pixel at the TWC plane, which ensures that at least one pixel is completely "inside" the projection of a tungsten wire. In this way the influence of the background light (e.g. from the source plasma) on the measured wire thermal emission is minimized. Before the start of the experimental campaign, the calibration curve was determined up to a power density of ~1.5 MW/m^2 due to the available power supply.

3 First results

The new TWC has allowed detailed observation of the beamlets generated in BATMAN Upgrade during the experimental campaign in June-July 2018. At the beginning of operation, without caesium, the beam power was insufficient to heat up the wires to a temperature high enough to record light emission. With the introduction of caesium, the beam intensity increased and the glowing wires became detectable. The single beamlets are clearly visible in the TWC, as shown in Figure 4, when the ratio of acceleration (U_{acc}) to extraction (U_{ex}) voltage is close to the value of 5, which produces the best beam optics. Some expected phenomena could be seen for the first time, e.g. the left-right deflection of the beamlets caused by the ESM in the EG. It has been observed that this deflection is influenced also by the ratio of U_{ex} and U_{acc}. Non-uniformities in the extracted beamlet current could be seen, depending on characteristics of the source operation as caesium distribution and magnetic filter field intensity and topology.

As caesium conditioning of the ion source improved, the beam power increased to such a level that the minimum camera exposure time of 1 µs was no longer sufficient to avoid saturation of the pixel intensity. To avoid this problem an optical neutral density filter (optical density 2.0) was placed in front of the camera objective.

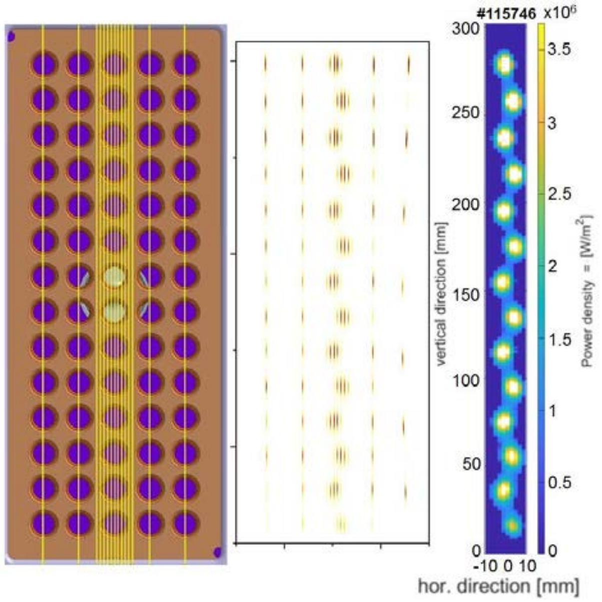

Figure 4 *Left*: CAD drawing of extraction apertures in the GG and position of tungsten wires (in yellow). *Center*: image of light emitted by the new TWC when heated by the beam (U_{ex}: 4 kV, U_{acc}: 27 kV; RF power: 50 kW). The rightmost cable is the one used for calibration and it is curved due to stuck sliding clamps. *Right*: preliminary evaluation of beam power density at the new TWC. Beamlet deflection by electron suppression magnets in EG can clearly be seen at this low U_{ex}.

Unfortunately, at the end of the last experimental campaign in July, during a beam pulse with high power and good beam optics (U_{ex}: 5.6 kV, U_{acc}: 32.2 kV; RF power: 60 kW), very high beam intensity was reached on the beam top side and three wires were damaged. Microscopic optical analysis of the wires (one is shown in Figure 5), suggests that the wires have melted (fusion temperature of W: 3422°C) in correspondence to the points of highest beam intensity. An approximate calculation indicates that a beam power density of about 12 MW/m^2 was impinging locally on the wires.

The remaining wires will be used in the next experimental campaign starting in September 2018. The calibration wire is still available. In addition, a new power supply will be used to extend the system calibration to the higher power density range.

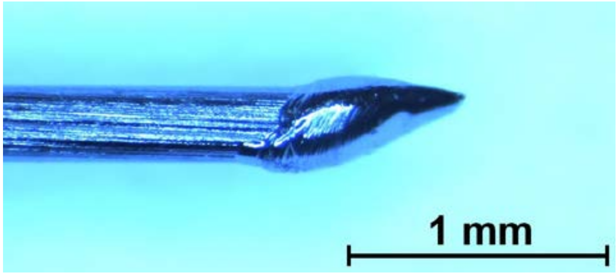

Figure 5 Microscope photo of melted tungsten wire.

4 Conclusions and outlook.

A new calibrated tungsten wire calorimeter has been designed, manufactured, assembled and installed in the negative ion source test facility BATMAN Upgrade at IPP Garching, at only 19 cm downstream from the GG. Valuable information has been gained on the beam uniformity at the individual beamlet level for the first time in an ITER relevant RF source. The new TWC has provided insight on previously unobserved phenomena as beamlet deflection due to ESM and beam non-uniformity due to caesium conditioning and magnetic filter field intensity and topology. The collected data is still being analyzed and the interpretation of the results will be subject of a future publication. Unfortunately, due to the high power density (≈ 12 MW/m^2) of a few beamlets, three tungsten wires melted at the end of the first experimental campaign of BATMAN Upgrade. The TWC will continue to be used in the next experimental phases with the remaining wires as long as possible. In the long term it is envisaged to use a TWC at a position of a few tens of cm downstream from the current one. This would reduce the power load density on the tungsten wires and still allow observing the beamlets when good optics is achieved.

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