Preliminary results concerning the simulation of beam profiles from extracted ion current distributions for mini-STRIKE[a)]

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I. ABSTRACT

The Radio Frequency (RF) negative hydrogen ion source prototype has been chosen for the ITER neutral beam injectors due to its optimal performances and easier maintenance demonstrated at IPP Garching in hydrogen and deuterium. One of the key information to better understand the operating behavior of the RF ion sources is the extracted negative ion current density distribution. This distribution - influenced by several factors like source geometry, particle drifts inside the source, cesium distribution, and layout of cesium ovens - is not straightforward to be evaluated. The main outcome of the present contribution is the development of a minimization method to estimate the extracted current distribution using the footprint of the beam recorded with the mini-STRIKE calorimeter. To accomplish this, a series of four computational models have been set up, where the output of a model is the input of the following one. These models compute the optics of the ion beam, evaluate the distribution of the heat deposited on the mini-STRIKE diagnostic calorimeter and finally give an estimate of the temperature distribution on the back of mini-STRIKE. Several iterations with different extracted current profiles are necessary to give an estimate of the profile most compatible with the experimental data. A first test of the application of the method to the BATMAN beam is given.

II. INTRODUCTION

To further develop the ITER heating and current drive neutral beam systems, two experiments are planned to operate in the next future in the PRIMA testbed facility at Consorzio RFX (Padova, Italy)[1]. The experiments are a full-size negative ion source, SPIDER, with a maximum of 100 keV high voltage, and a prototype of the full ITER injector beam line at 1 MeV high voltage, MITICA. The STRIKE diagnostic calorimeter[2] will be used in SPIDER to investigate the beam properties. A small-scale version of STRIKE, called mini-STRIKE, has been developed and built to check the performance of this type of diagnostic system in existing experiments[3]. It is made of two CFC tiles directly exposed to the beam, whose temperature profile is measured by a thermal camera providing a fine spatial resolution. The tiles are produced with a special material[4] that permits to obtain a much higher value of thermal conductivity along the beam direction, with respect to the directions perpendicular to the beam. This results in a well-defined footprint of the beam also on the downstream side of the tiles, where it can be acquired by the thermo-camera without significant blurring.

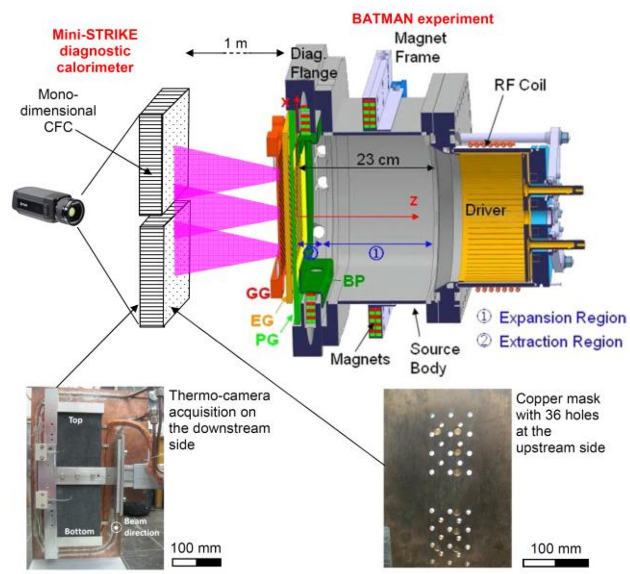

FIG. 1. Installation of mini-STRIKE in the BATMAN testbed.

Since 2007, IPP RF negative ion source prototype has been chosen as baseline design for the ITER[4] neutral beam

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injectors systems. The testbed BATMAN is equipped with one prototype source and has a 1/8 size of the ITER source. Its main aim is to investigate the physics underlying the generation and extraction of negative ions. The prototype ion source attached on this testbed features three grids biased at different voltages, the Plasma Grid (PG) where most of the extracted negative ions are produced, the Extraction Grid (EG) and the Grounded Grid (GG). The grids have 126 apertures through which negative ion beamlets (one per aperture) are extracted and accelerated. To investigate the beam properties, the mini-STRIKE diagnostic calorimeter has been mounted about 1 m downstream of the Grounded Grid, as shown in Fig. 1. In contrast to SPIDER and MITICA, for which the beam optics will be optimized, in BATMAN a significant overlapping of the beamlets reaching the mini-STRIKE front is foreseen. Therefore, in order to better exploit the diagnostics capabilities of mini-STRIKE, a copper mask with 36 passing holes (having a diameter of 7 mm) was used, to sample portions of the whole beam into a certain number of “pseudo-beamlets”.

III. SIMULATION OF THE BEAM FOOTPRINT AND COMPARISON WITH EXPERIMENTAL DATA

A method to estimate the extracted current density from the beam footprint measured in mini-STRIKE was set up, by adapting the codes which are currently used to model the SPIDER and MITICA experiments to the negative ion beam of BATMAN. In particular, the SLACCAD[6] and EAMCC[7] codes have been used to simulate the beam optics, the NBImag[8] code for the magnetic fields and a dedicated model developed in COMSOL for the temperature distribution on the tile. An overall scheme of the method is shown in Fig. 2a. First of all, a simulation of the single beamlet optics was carried out with the SLACCAD code (see Fig. 2b), by applying the grid voltages of pulse 97364 (considered as the reference pulse and having PG, EG and GG voltages of 0, 4.7 and 19.9 kV, respectively). Sixteen levels of extracted current density, ranging from 5.5 to 20.5 mA cm^{-2} with 1 mA cm^{-2} steps, were considered for these simulations. According to previous estimations[9], a space charge region[10] of 20 mm was considered downstream of the GG. For each current density assumption, a potential map taking into account the space charge of the beam was evaluated. The potential maps calculated with SLACCAD were used as an input for the EAMCC model (see Fig. 2c). This model considers a single beamlet and includes the stripping and charge-exchange reactions inside the accelerator (depending on the density profile evaluated with AVOCADO[11]) and the deflection caused by the magnetic fields generated by the magnets embedded in the EG and the ones located in the movable magnet frame mounted at the sides of the source. The BEAMTRACKER program was developed to extend the beam particle trajectories calculated by EAMCC from the accelerator exit to mini-STRIKE, taking into account the magnetic field. This operation was carried out for all 126 beamlets, assuming for each beamlet a certain amount of extracted current density and the corresponding optics calculated with SLACCAD. As a first test of the method, only uniform distributions of extracted current densities were simulated. Namely, five cases were considered with a extracted current density of 10.5, 12.5, 14.5, 16.5 and 18.5 mA cm^{-2}, uniform over the whole extraction area. As a result of BEAMTRACKER, an evaluation of the heat deposited by the whole beam on the upstream surface of the mini-STRIKE calorimeter was obtained in all the cases.

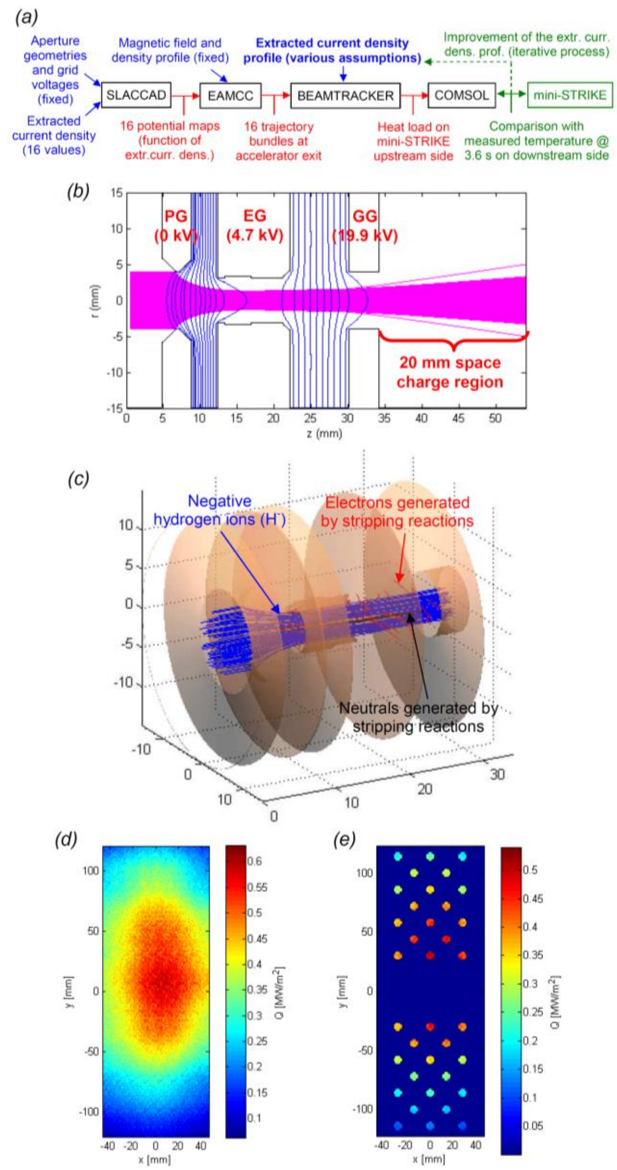

FIG. 2. Overview of the models: (a) Overall scheme of the adopted approach (the iterative process to estimate the extracted current density profiles is yet to be done); (b) SLACCAD model to simulate the electrostatic field and particle trajectories; (c) EAMCC model to simulate the beam transport and reactions in the accelerator; (d) heat load on the mini-STRIKE upstream side, as calculated with the superimposition of 126 beamlets and assuming 16.5 mA cm^{-2} uniform extracted current density; (e) same as previous, adding the copper mask.

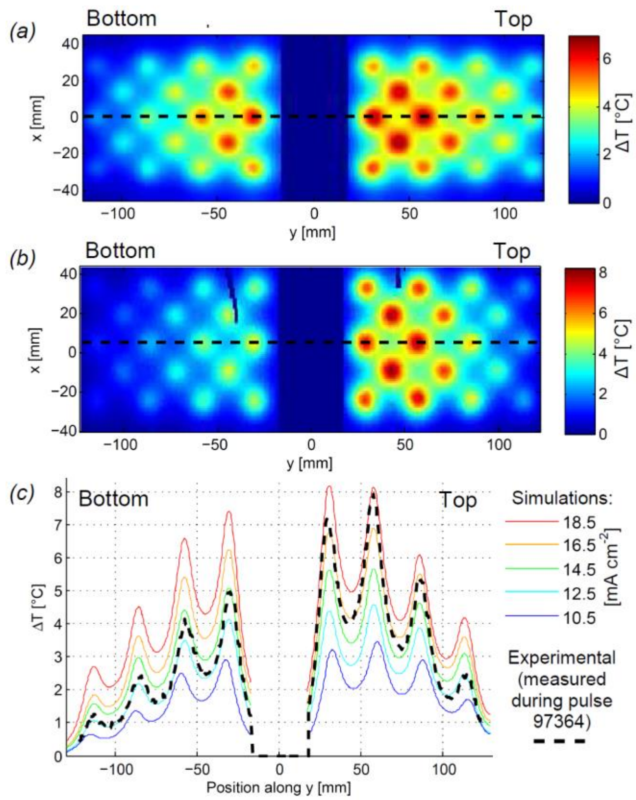

FIG. 3. Comparison between simulation and experimental ΔT distributions after 3.6 s of heat application: (a) estimated ΔT on the downstream side of mini-STRIKE, considering 16.5 mA cm^{-2} uniform extracted current density (b) measured ΔT on the downstream side of mini-STRIKE; (c) comparison of estimated and measured ΔT along the most heated lines. It can be observed that the best fitting conditions are obtained with about 14.5 mA cm^{-2} uniform extracted current density on the bottom tile and 16.5 mA cm^{-2} on the top tile.

As an example, Fig. 2d shows the estimated power load in the case of 16.5 mA cm^{-2}. It can be observed that the footprint is shifted upwards due to the magnetic filter field. To consider the presence of the copper mask, this distribution was modified as in Fig. 2e, where all the parts outside the circles not covered by the mask were put to zero heat load. The mini-STRIKE carbon tiles were then simulated with a non-linear, transient, finite element model developed in COMSOL. This model can calculate the temperature across the downstream surface of the tile during and after the beam pulse, by applying as boundary condition on the upstream side the heat load calculated by the BEAMTRACKER code with the mask and considering also the heat loss by thermal radiation. The anisotropy of the thermal behavior of the CFC tiles was implemented: the thermal conductivity is about 20 times larger (depending also on temperature) along the beam direction (a reference value is 766 W m^{-1} K^{-1} at 50 °C) than in the other two directions (38 W m^{-1} K^{-1} at 50 °C). A comparison can be made on the simulated and measured ΔT, ΔT being the temperature increase observed during the beam-on time. An example is shown in Figs. 3a and 3b, with the ΔT distribution calculated with the simulations (considering the case of 16.5 mA cm^{-2}) and measured on the experiment, respectively. The temperature profiles along the most heated line (intersecting eight peaks, as shown in Fig. 3a and 3b) are reported in Fig. 3c. It can be observed that the estimated ΔT are in the same range of the measured one, with the best estimates obtained with about 14.5 mA cm^{-2} uniform extracted current density on the bottom tile and 16.5 mA cm^{-2} on the top tile. The effect of the magnetic field, deflecting the overall beam upwards, seems underestimated by the codes, as the difference between the peaks on the top and bottom tile is smaller in the simulations than in the experimental results

IV. CONCLUSIONS

The negative ion beam in the BATMAN experiment has been simulated with a comprehensive set of codes, permitting to link the assumed vertical profile of the extracted current density to the temperature distribution on the downstream side of the mini-STRIKE diagnostic. In this way, it is made possible to estimate the extracted current density with a minimization method, assuming a parabolic shape of the profile.

A first test of this method has been carried out considering only uniform current density distributions, ranging between 10.5 and 20.5 mA cm^{-2}. The assumptions that better fit the measured ΔT profile are the ones with 14.5 mA cm^{-2} uniform extracted current density for the bottom tile and 16.5 mA cm^{-2} for the top tile. These results are in good agreement with the value estimated from the current measurement at the power supply for the considered pulse (16.2 mA cm^{-2}). Better estimates could be obtained upon assuming a more detailed distribution of the extracted current density instead of a uniform one. Other possible improvements include a comprehensive sensitivity analysis on the main parameters of all models, to estimate the error bars, and a comparison with other available measurements on the BATMAN experiment, to benchmark the method.

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