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Modeling of beam acceleration for the negative ion source NIO1

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Abstract. The RF negative ion source NIO1 (Negative Ion Optimization 1) [1], built at Consorzio RFX in Padova (Italy), aims at investigating basic issues of ion source physics while providing a tool to benchmark and validate beam simulation codes. On the other hand, because of its small size and its modular design, NIO1 represents a valuable testbed for DEMO relevant solutions, such as energy recovery and alternative systems for ion beam neutralization [1]. To such purposes it is important to improve NIO1 performance to make it comparable to those expected for other negative ion sources e.g. the full-size ITER ion source prototype SPIDER [2]. In particular the latest NIO1 upgrades focused on reducing the co-extracted electrons by enlarging the magnetic field strength close to the plasma grid and on improving the beam optics. As anticipated in [3], a new extraction grid was designed [4] to guarantee a better optics and a significant reduction of the beamlet deflection which proved to be quite large with the previous set of magnets [5]. The present paper presents the computation of the NIO1 beam optics as a function of the operating parameters. Throughout this work, the finite element code OPERA3D [6] and the Monte Carlo particle tracing code EAMCC3D [7] were used to model the NIO1 accelerator in both its previous and new configurations. Results from simulations are also compared with the data from NIO1 beamline diagnostics [8].

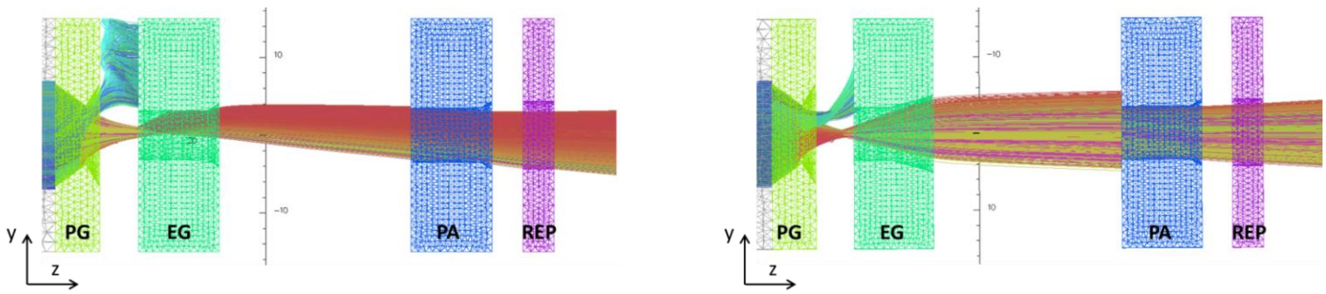
INTRODUCTION

The electrostatic accelerator of the test facility NIO1 is formed by four grids (see Figure 1), each featuring 9 apertures arranged in a 3×3 lattice. The plasma grid (PG) is kept at the potential of the plasma ion source. A first potential difference is applied to extract the H^- ions (V_{EG}-V_{PG}). Magnets are embedded in the extraction grid (EG) to deflect the co-extracted electrons and to dump them onto the EG itself (CESM magnets). Such magnets are also responsible for an alternate deflection of the 3 columns of beamlets in the vertical direction to reduce which another set of magnets (ADCM magnets [9]) is installed in the post-acceleration grid (PA), that is grounded ($U_{tot}= V_{PA}-V_{PG}$). A fourth electrode, called repeller (REP) is positively biased to avoid the backstream of positive ions from the drift region downstream the accelerator.

The modeling activity of NIO1 was carried out by means of the commercial code OPERA [6]. In particular the magnetic module (TOSCA) was used to determine the magnetic field generated by the CESM and ADCM magnets. Subsequently by the SCALA package beam particles are tracked in such magnetic field and in the electric field due to the grids of the accelerator. SCALA takes into account the beam space charge and it iterates up to an equilibrium solution. In addition, it may determine the location of the plasma meniscus in a self-consistent way. At present, since in NIO1 a large electron current I_e is extracted (j_e ~20-60 times the negative ion current j_H), as suggested by the large current collected on the NIO1 EG, a proper modeling requires to consider also the electron extraction. An example of combined ion-electron tracking is given in Figure 1, in which the old configuration (EG_1) and the new one (EG_2) are compared. As it may be seen the latter lowers the fraction of H^- hitting the EG, reduces the beamlet divergence δ and minimizes its deflection angle α [10].

A crucial role in the present NIO1 configuration is then played by the large pressure p_v in the vacuum vessel (about 0.1-0.4 Pa when the source pressure p_s is between 0.5 Pa and 1.5 Pa) which results into large stripping of the negative ions. When the source pressure is p_s = 1.5 Pa for example, the stripping fraction along the accelerator is about the 50 % [11]. OPERA permits to take into account the stripping losses as a reduction of the beam current along the accelerator. A final aspect to be considered is that at present, the NIO1 performance are quite limited and a non-negligible fraction of the beam hits the PA, as shown in Figure 1. When aiming at comparing the OPERA outputs with the experimental findings of NIO1, it is necessary to have an estimation of the beam current. To this purpose the calorimetric measurements have been used [5].

In the operations with EG_2, NIO1 performances have been unfortunately more limited in terms of extracted current than with EG_1 [12]. For such reason, the configuration EG_2 is here presented only for comparison, while the benchmark with experimental data is limited to EG_1, for which more reliable data are available.

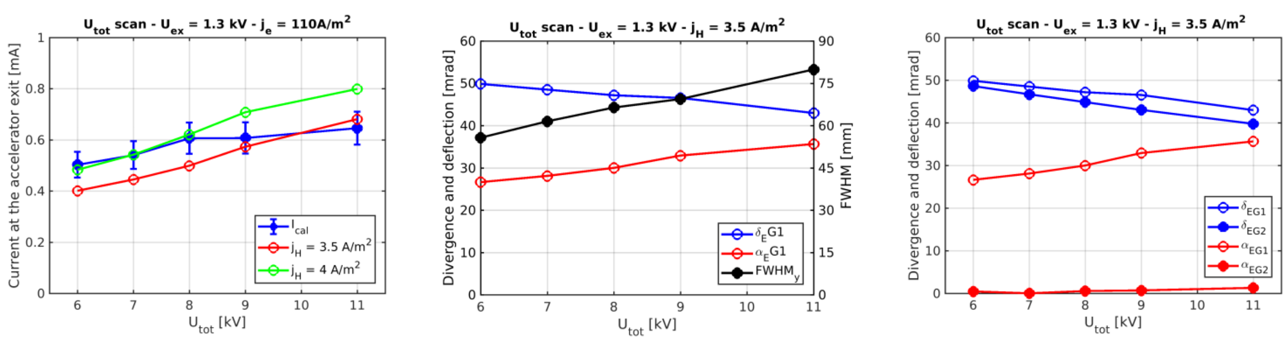


(a) (b)

Figure 1. Trajectories by OPERA, electrons are in light blue. j_H = 3.5 A/m^2, j_e = 110 A/m^2, V_{PG} = - 11 kV, V_{EG} = - 9.7 kV, V_{PA}= 0V, V_{REP}= 60 V. (a) Old EG, α = 35.6 mrad, δ = 43.0 mrad (b) New EG, α = 1.3 mrad, δ = 39.8 mrad . Domain size: 15×15×80 mm^3.

BENCHMARK WITH THE NIO1 DIAGNOSTIC CALORIMETER

The comparison reported here below is performed in a total voltage (U_{tot} = V_{PA}-V_{PG}) scan, i.e. a series of pulses in which only U_{tot} is changed. Since the current I_{cal} measured on the calorimeter is about 0.5 mA, the most appropriate extracted H^- current density is around j_H = 4 A/m^2, as shown in Figure 2a, where the current exiting the accelerator according to OPERA is compared to the calorimetric estimate, showing a satisfactory agreement. In this set of simulation the emitted current was kept fixed since U_{tot} should not influence it. The increase in the current exiting the accelerator is due to beam focusing by the voltage in the second gap. It is worth noticing that slight variations of j_H in the range [3.5,4] A/m^2 are enough to reproduce the measurements. Please note that the values of I_{cal} here reported have been obtained upon assuming that the ions carry only 70% of the total beam power measured on the calorimeter: this assumption will be justified in the following.

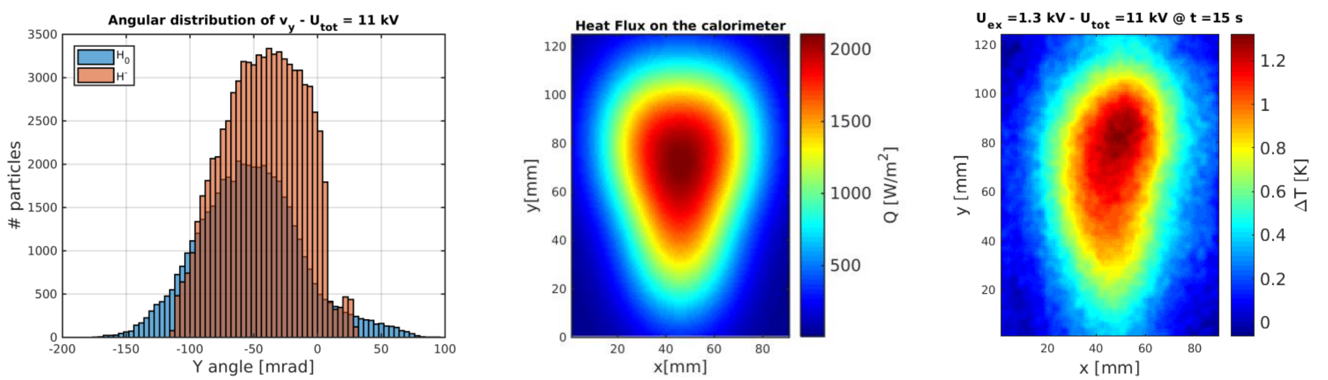


(a) (b) (c)

Figure 2. (a)-(b): Comparison between OPERA and calorimetric measurements. (a) Beam parameter dependence on the total voltage. (a) Current exiting the accelerator. (b) Beam optics. (c) Comparison between EG_1 and EG_2 for the same operational parameters as in (b).

In Figure 2b the full width at half maximum (FWHM) of the thermal footprint is plotted together with the OPERA calculated deflection and divergence. It may be seen in particular that by increasing U_{tot} the beamlet deflection is enlarged and this is consistent with the elongation of the beam profile measured experimentally. In order to match the data anyhow, the deflection should be much larger: this discrepancy lowers when the large contribution of H_0 to the beam power profile is considered. This aspect will be treated in the following. The FWHM of the beam profile in the horizontal direction (not shown in Figure 2) instead, is found to be almost constant, and this is consistent with the trend of the beamlet divergence, that changes only slightly within this scan. If the same operational parameters were achieved in the new NIO1 accelerator, the beam profile would be much more compact along the vertical direction, but almost unchanged in the horizontal one.

The OPERA solution for the electric potential in such condition has then been used as an input for EAMCC3D. The latter code allows for predicting the heat load on the calorimeter thus verifying its consistency with the experimental measurements. A first aspect to be considered is how the H_0 population exiting the accelerator enlarges the beam footprint, as shown in Figure 3a. In particular, according to EAMCC3D, 40% of the particles impinging on the calorimeter are H_0 and their average energy E_{H0} is about 65% of the beam particle energy U_{tot}. This means that the H_0 particles carry about 30% of the total power, while only 70% is left to H^-, as assumed earlier. The expected heat load on the NIO1 calorimeter (placed about 400 mm downstream the PA) was then calculated (Figure 3b) and compared with the experimental measurements (Figure 3c). As a first attempt the optics of a single-beamlet simulation was replicated for each beamlet thus neglecting the beamlet-beamlet interaction. The calculated heat load appears broader, in particular in the horizontal direction, suggesting that beamlet divergence is overestimated or that the homogeneity hypothesis underlying such approach does not hold.



(a) (b) (c)

Figure 3. (a) Angular distribution of H^- and H_0 along the vertical direction by EAMCC3D; 200000 macro-particles have been tracked, bin width is 4 mrad. (b) Beam footprint on the calorimeter predicted by EAMCC3D. (c) Temperature map measured by the IR camera.

CONCLUSIONS

The numerical codes OPERA and EAMCC3D were used to model the beam features of the negative ion source NIO1 and the comparison with the measurements by the NIO1 diagnostic calorimeter gave a first order agreement. From this benchmark the necessity to properly model the role of the secondaries in the large pressure operations appears clearly. The addition of other effects like the beamlet- beamlet interaction is ongoing.

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