

MODELING OF THE HB²TF INJECTOR IN COMSOL WITH BENCHMARKING USING ASTRA AND RF-TRACK

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Abstract

A comprehensive electromagnetic and beam-dynamics model of the High Brightness Beam Test Facility (HB²TF) electron injector under development at INFN-LASA has been implemented using COMSOL Multiphysics. The model incorporates the DC photocathode gun and the low-energy transport line. Three-dimensional electric and magnetic field distributions were computed and employed for particle tracking within COMSOL, enabling analysis of field effects, mesh resolution impacts, and space-charge contributions. The resulting field maps were exported and imported into ASTRA and RF-Track simulation codes to perform cross-validation of beam dynamics. Comparative studies focus on transverse emittance, bunch length, energy spread, and sensitivity to field map resolution. This work establishes a validated modeling workflow for the HB²TF injector and provides crucial input for its optimization and future commissioning.

INTRODUCTION

The High Brightness Beam Test Facility (HB²TF) [1], currently under development at the INFN-LASA laboratory in Segrate, Italy, is designed to support research and development activities in advanced electron injectors and continuous-wave (CW) high-brightness beam generation. The facility consists of a laser-driven DC photocathode gun followed by a normal-conducting RF bunching and acceleration section, delivering electron beams with energies up to approximately 0.8 MeV and average currents up to 2.5 mA.

HB²TF represents the first stage of the broader BriXSiO injector concept [2], which foresees the integration of an additional bunching section and a superconducting booster linac capable of increasing the beam energy to the 4–10 MeV range while preserving high beam brightness and CW operation [3]. In a later stage, a superconducting energy-recovery linac (ERL) is planned to accelerate the beam up to about 45 MeV.

One of the main objectives of HB²TF is the experimental demonstration of stable high-brightness beam production at repetition rates on the order of 100 MHz. Achieving these operating conditions requires accurate modeling of both the electromagnetic fields and the low-energy beam dynamics, where space-charge effects play a dominant role. For this reason, reliable simulation workflows and cross-validation between different numerical tools are essential for the optimization and future commissioning of the injector.

In this work, a detailed COMSOL Multiphysics [4] model of the DC photocathode gun and the focusing solenoid has been developed, including three-dimensional electromagnetic field calculations and particle tracking through the low-energy beamline. COMSOL Multiphysics was selected due to its capability to provide both direct three-dimensional geometry modeling and self-consistent calculations of electric and magnetic fields, together with integrated particle-tracking simulations within the same computational framework. The generated field maps were exported to ASTRA [5] and RF-Track [6], where dedicated particle-tracking simulations were performed for benchmarking and cross-validation studies.

The DC gun adopts the “inverted insulator” scheme originally developed at Jefferson Lab [7], providing a robust and reliable solution for high-repetition-rate operation while ensuring improved electric-field symmetry, enhanced vacuum performance through the combination of NEG and NexTorr technologies, and compatibility with the INFN photocathode handling system.

MODEL

The initial attempt to import the original CAD model of the DC gun into COMSOL significantly increased the complexity of the simulation due to the presence of numerous small mechanical details that do not affect either the electromagnetic field calculations or the particle dynamics. Therefore, a simplified geometry model was developed based on the original CAD Fig. 1 design in order to improve computational efficiency while preserving the relevant physical features of the system. In the Fig. 2 presented simplified model we can see Spherical cathode with installed photocathode molybdenum plug, anode with hole and solenoid.

By applying a potential of -300 kV to the cathode while grounding the anode and the vacuum chamber, the electric field distribution inside the DC gun can be calculated. Both the electric and magnetic field simulations were performed in full-3D in order to enable future studies of effects related to laser misalignment on the photocathode and their impact on beam quality. In the present work, however, only the axially symmetric configuration is considered. Figure 3 shows the normalized electric field distribution inside the gun structure.

The solenoid was modeled as a coil consisting of 1000 turns of copper wire enclosed within a steel yoke used for magnetic-field concentration and improved thermal management. For the simulations presented in this work, the coil current was set to 3.5 A in order to obtain a visible focusing

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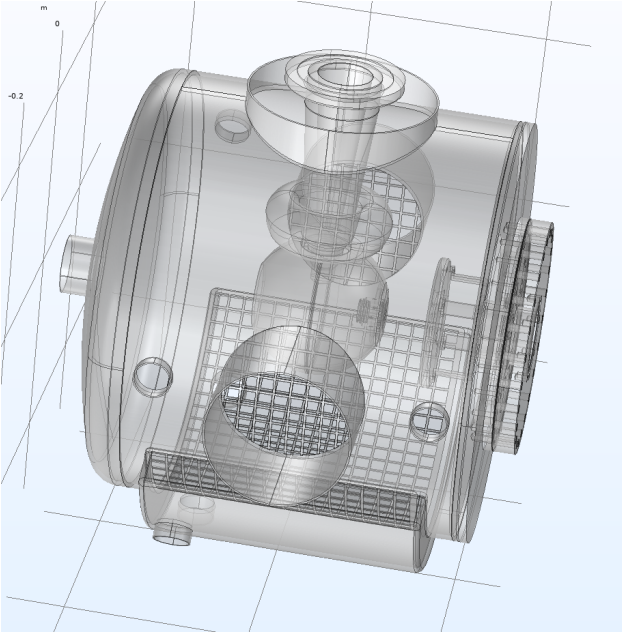


Figure 1: DC gun CAD.

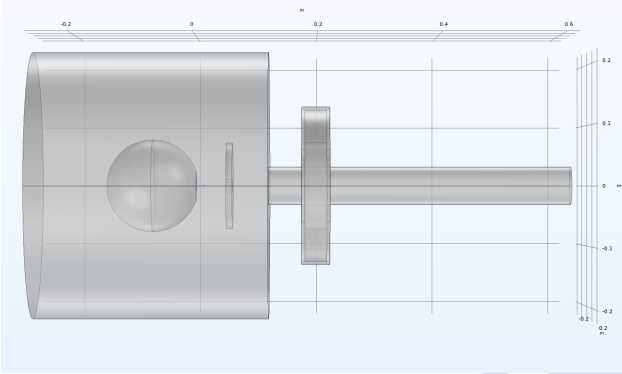


Figure 2: Layout of the DC gun model with the focusing solenoid.

effect on the electron beam. The magnetic field presented in the Fig. 4. Since the solenoid model was based on the already manufactured prototype, Fig. 4 also presents preliminary magnetic-field measurements performed using a handheld magnetometer. A good agreement between the simulated magnetic field distribution and the preliminary measurements can be observed. The difference in the peak magnetic-field value is explained by the higher coil current used during the measurements, which was set to 4 A.

PARTICLE TRACKING

As already mentioned, COMSOL Multiphysics includes an internal particle-tracking module, which we also exploit in this work and benchmark against well-established and widely used beam dynamics codes such as ASTRA and RF-Track. While COMSOL is based on the finite element method (FEM) for the numerical solution of electromagnetic field equations, ASTRA and RF-Track are dedicated beam-dynamics tracking codes using a macroparticle representation of the beam and allowing the inclusion of space-charge

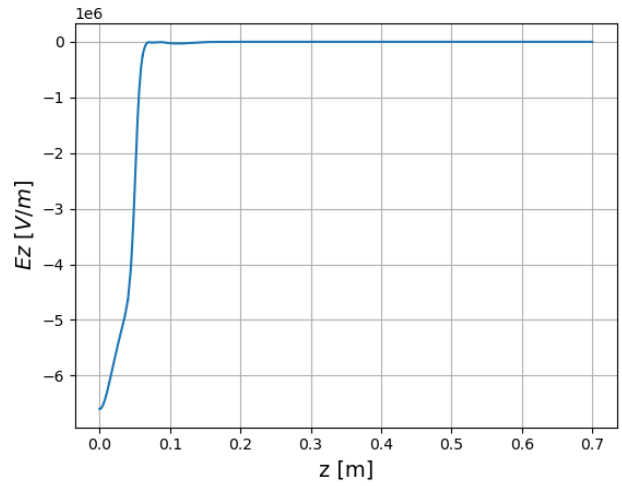


Figure 3: Normalized electric field.

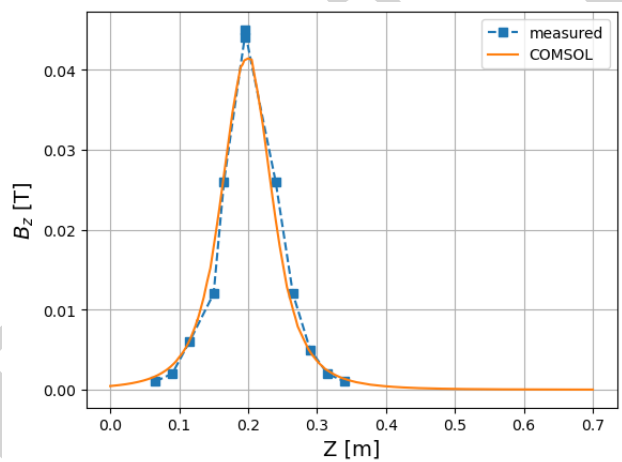


Figure 4: Magnetic field.

and collective effects. The electromagnetic field maps calculated in COMSOL were exported and imported into ASTRA and RF-Track for independent tracking simulations.

In this benchmark study, we focus exclusively on particle tracking, neglecting space-charge effects and mirror-charge contributions at the photocathode. Although all three codes are capable of including these effects, they are omitted here in order to ensure a clean comparison between the tracking algorithms and to reduce computational time. The beam in ASTRA and RF-Track was generated using laser pulse shape data at the gun photocathode (Table 1). In COMSOL, the beam was instead generated using the Particle Beam module, where the release time is used to produce an initial cylindrical particle distribution.

The results of the tracking simulations are presented in Fig. 5. As can be seen, all three codes provide converging results and show overall good agreement in the evolution of the beam parameters along the beamline. The small difference observed in the maximum emittance value obtained with COMSOL can be explained by the lower number of macro-particles used in the simulation: 1000 particles in COMSOL compared with 5000 particles in ASTRA and

Table 1: Laser Pulse Shape Data at the Gun Photocathode

Parameter	Value
Parameter	45.6
Flattop laser pulse	0.7
Rise time	1.0 ps
Transverse uniform σ_{xy}	0.71 mm
Extracted bunch charge	100 pC

RF-Track. The reduced number of particles in COMSOL was chosen in order to limit computational time and resource consumption.

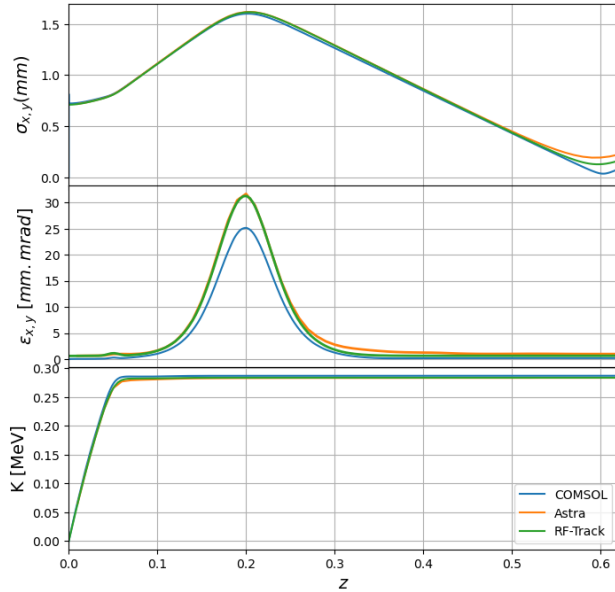


Figure 5: Result of tracking simulations. Transverse beam size, emittance, and kinetic energy.

It is also worth emphasizing the excellent visualization capabilities provided by COMSOL Multiphysics. As an example, Fig. 6 presents the trajectories of particles emitted from the photocathode, accelerated inside the DC gun, and subsequently focused by the solenoid field.

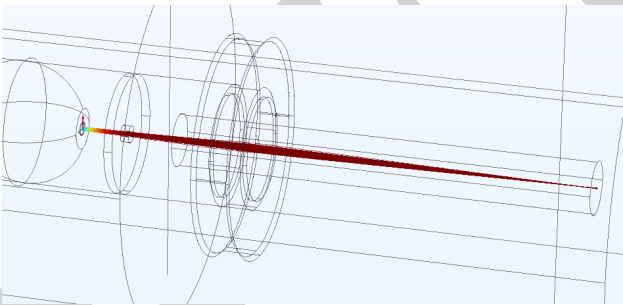


Figure 6: Particle trajectories.

CONCLUSION

A detailed three-dimensional model of the HB²TF DC injector, including the photocathode gun and focusing solenoid,

has been successfully developed in COMSOL Multiphysics. Electromagnetic field calculations and particle-tracking simulations were performed and benchmarked against the well-established beam dynamics codes ASTRA and RF-Track.

Since COMSOL is based on the finite-element method and provides a full multiphysics framework, its simulations are generally more computationally demanding compared with specialized beam-dynamics tools such as ASTRA and RF-Track. It should also be noted that COMSOL is a commercial proprietary software package, whereas ASTRA and RF-Track are freely available for academic users, with RF-Track additionally distributed under an open-source license.

The comparison of tracking results demonstrated good agreement between all three simulation tools in terms of beam size evolution, emittance behavior, and beam energy along the low-energy beamline. The obtained results confirm the reliability of the developed workflow for exporting electromagnetic field maps from COMSOL and using them in external beam-dynamics simulations.

The developed model also demonstrated the capability of COMSOL to provide high-quality visualization of particle dynamics together with detailed three-dimensional electromagnetic field calculations. Such an approach is particularly useful for future studies of alignment tolerances and asymmetric beam configurations.

Future work will include the incorporation of space-charge and mirror-charge effects, studies of asymmetric beam distributions, and optimization of the injector configuration for the future commissioning of the HB²TF facility.

ACKNOWLEDGMENTS

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