

Broadband electron gun design for a 5 T solenoid Electron Beam Ion Source for hadron therapy

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The design and optimization of a broadband electron gun with a semi-immersed cathode for an Electron Beam Ion Source (EBIS) operating with a 5 T solenoidal magnetic field is presented. The work contributes to the development of high-performance, tunable EBIS for next-generation all-linac medical accelerators for cancer therapy, as well as other applications in accelerator physics. The system is primarily designed to meet the requirements for the production of fully stripped carbon ions. An acceptance criterion for the injection of the electron beam into a full magnetic field is derived and used to validate the design. The gun position is optimized for the transmission of an electron beam with a current of 2.0 A and a current density of 1000 A/cm² inside the solenoidal field. The operating range of the electron beam can be broadened from 0.2 to 3 A by using a nonadiabatic magnetic field on the beam path close to the gun, which transfers the transverse component of the electron energy into the longitudinal direction and therefore reduces the amplitude of the beam scalloping. The current density can be adjusted by the use of another coil surrounding the cathode.

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I. INTRODUCTION

The development of compact, high-performance accelerators is one of the main goals in the advancement of ion beam therapy for cancer treatment. Traditionally, carbon ion acceleration in hadron therapy relies on the production of C⁴⁺ ions at low energies, which are then transformed into fully ionized C⁶⁺ ions through a stripping stage in the injector. After the injector, acceleration is performed by a synchrotron operating at low repetition rates, on the order of Hz, requiring very large pulse charges in order to fulfill the treatment requirements. For example, at the Heidelberg Heavy Ion Cancer Therapy Centre (HIT), the linac delivers C⁴⁺ pulses that are subsequently stripped to C⁶⁺ before injection into the synchrotron, with 3×10^{10} C⁶⁺ particles per injection at a repetition rate of 5 Hz [1]. In an all-linac approach, the synchrotron is replaced by a high-repetition linear accelerator, enabling rapid scanning of the entire

tumor volume with a high-quality beam while reducing beam losses throughout the accelerator chain. In addition, the concept ideally accelerates C⁶⁺ ions directly from the source, which results in improved acceleration efficiency, elimination of the stripping stage in the injector, and better beam emittance.

CIEMAT is designing Acelerador Lineal de Multi-hAdrones (ALMA), a dedicated linear accelerator for fully stripped carbon ions (C⁶⁺), under a precommercial procurement [2] led by the company Added Value Solutions (AVS) [3]. The accelerator chain consists of a commercial electron cyclotron resonance ion source (ECRIS), a 750 MHz radio-frequency quadrupole (RFQ), and a set of Interdigital H-mode drift tube linac (IH-DTL) drift tube cavities. The RFQ brings the ions from 15 keV/u up to 5 MeV/u, and the accelerator reaches 10 MeV/u, delivering tens of particle-μA in pulse lengths of 5–10 μs with a repetition rate of 200–400 Hz with a minimum yield of 10⁸ C⁶⁺ ions per pulse [4]. ALMA is meant to operate as a stand-alone research infrastructure, although it could be integrated into a full-fledged therapy facility in the future.

The challenge lies in producing high-quality C⁶⁺ beams, i.e., with sufficient current, low impurity levels, small transverse emittance, and short pulses at high repetition

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rates. For this reason, in parallel to the ALMA project, CIEMAT and CERN, within a collaboration framework, are exploring the use of an Electron Beam Ion Source (EBIS) as an alternative ion source [5]. EBIS devices confine and ionize ions through their interaction with an electron beam, allowing rapid production of highly charged ions that can be extracted with pulse lengths of $<10 \mu\text{s}$. Due to the ultrahigh vacuum of these devices, ion beam contamination is limited. Furthermore, the transverse emittance is expected to be small, although the axial energy spread is significant for short extracted ion pulses. Designs of EBIS devices geared toward this task have been tested in the past, such as EBIS-SC (DREBIT) [6] and Krion-6 T (JINR) [7]. To achieve the required repetition rates, the EBIS must feature a high-current density electron beam. This is obtained by compressing the beam in a strong solenoidal magnetic field, which enhances the ionization process and thereby enables higher repetition rates. The main constraint for the concept is the limited space-charge capacity of the electron beam itself, which restricts the number of ions that can be produced per pulse. To meet these requirements, a new broadband electron gun is being developed to operate with a 5 T superconducting solenoid.

The broadband gun with a semi-immersed cathode adds flexibility compared to conventional Brillouin guns. Covering a wide current and current density range helps to maintain control over beam stability while maximizing the current density and thereby the ion production. In addition, since the electron current and current density can be controlled independently, the parameters can be tuned so that the gun becomes suitable for use in other facilities, for example, at HIE-ISOLDE [8]. Furthermore, electron guns of this type can also be used beyond EBIS sources, including high-power rf and electron cooling systems [9–11]. The gun is designed to operate between 0.2 and 3 A, with tunable current densities ranging from 200 to 1900 A/cm^2 , adjusted via the cathode coil. The limits of the operating range were determined by the potential application for closed atomic-shell charge breeding at lower energies and by the need to boost the electron current up to the cathode emission limit while still maintaining a reasonable lifetime. The nominal operating point is 2 A with 1000 A/cm^2 .

Optimal transmission of the electron beam from the gun into the high solenoidal field is a critical factor for the performance of an EBIS. Several strategies are employed to evaluate whether a beam will successfully enter the trap region without reflection. On the one hand, analytical criteria, based on the magnetic mirror acceptance and the Bursian limit, are applied to predict transmission efficiency based on the initial parameters of the beam at the cathode [12,13]. Others focus on physical adjustments, such as tuning of the cathode magnetic field between immersed and Brillouin flow to reduce the relative

amplitude of oscillations [14,15]. Finally, full-path, domain-divided simulations are capable of explicitly tracking electrons through the full solenoidal field [16], but such simulations are computationally demanding and can be difficult to converge for high-current, high-density beams.

In this study, a hybrid approach is adopted: the beam is simulated up to an intermediate plane where convergence is still good, and there the beam parameters are extracted. These parameters are then evaluated using an analytical criterion based on the magnetic mirror and Bursian limits to determine the transmission efficiency imposed by the beam scalloping. Due to the extended length of the electron beam transport into the full solenoidal field, numerical simulations of the entire system are ruled out as convergence problems arise. The hybrid approach allows beam effects to be taken into account while avoiding the high computational cost of full-domain simulations. The next section details the physics framework used to determine the thresholds.

II. MAXIMUM TRANSMITTABLE CURRENT

Electrons traveling from the gun into the high solenoidal field are subject to two potential obstacles: a mismatch between the electron beam and magnetic field can lead to beam scalloping and subsequent reflection from the magnetic mirror, and space-charge effects combined with too low beam velocity can result in the formation of a virtual cathode. These effects can result in electrons going back toward the gun and in particular to the anode, which may in turn cause vacuum degradation and beam instabilities. The performance of an EBIS depends critically on how well the scalloping effects are mitigated and thus how efficiently the electron beam can be transmitted into the full solenoidal field. In the presented case, beam simulations have been performed from the electron gun to an intermediate magnetic field, for which numerical convergence could be achieved within reasonable computational time. This location is hereafter referred to as Plane 1. The point located inside the full-field trap is denoted as Plane 2; see Fig. 1.

The magnetic mirror created by the solenoidal field influences the transmission of the electron beam into the trap region [17]. As mentioned before, electrons with large pitch angles may be reflected. The pitch angle is defined as the ratio between the transverse and longitudinal velocities at Plane 1:

$$\theta = \arctan(v_{1\perp}/v_{1\parallel}). \quad (1)$$

The magnetic momentum, $\mu = \frac{mv_{1\perp}^2}{2B}$, is an adiabatic invariant under the assumption of a slowly varying axial magnetic field strength. Thereby

$$\frac{mv_{1\perp}^2}{2B_1} = \frac{mv_{2\perp}^2}{2B_2}, \quad (2)$$

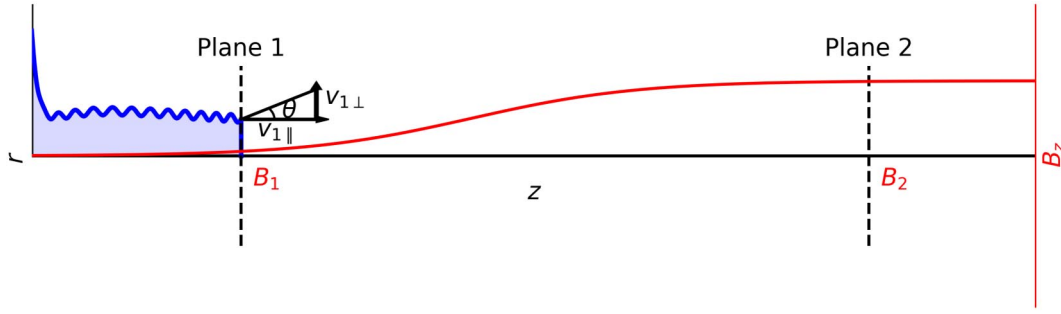


FIG. 1. Schematic plot of the beam analysis approach. The simulated beam envelope (blue) extends up to Plane 1, where the beam trajectories are extracted and evaluated according to the acceptance criteria imposed by Plane 2. The magnetic field is shown in red. Dimensions are not to scale.

which provides the perpendicular velocity at Plane 2 as

$$v_{2\perp}^2 = v_{1\perp}^2 \frac{B_2}{B_1}. \quad (3)$$

The kinetic energy for an electron can be divided into axial and perpendicular parts and can be nonrelativistically written as:

$$E = e(\phi + \phi_{sc}) = \frac{mv_{\parallel}^2}{2} + \frac{mv_{\perp}^2}{2}, \quad (4)$$

where $\phi = \phi_{DT} - \phi_{cathode}$ is the voltage difference between the drift tube and cathode and ϕ_{sc} is the space-charge depression due to the electron beam. The velocity components can be expressed in terms of the pitch angle as:

$$v_{\perp} = v \sin \theta, \quad v_{\parallel} = v \cos \theta, \quad (5)$$

in which the total electron velocity is determined by the beam energy $v = \sqrt{\frac{2e(\phi + \phi_{sc})}{m}}$. Using Eq. (2), the magnetic mirror formed by the solenoid transmits only those electrons whose pitch angles lie within the transmission cone, satisfying the condition

$$\sin^2(\theta) < \frac{B_1}{B_2}. \quad (6)$$

Combining Eqs. (3) and (4) for the two planes, the forward velocity ($v_{2\parallel}$) can be isolated as in the following equation:

$$\begin{aligned} \frac{m}{2e} v_{2\parallel}^2 &= \frac{m}{2e} v_{1\parallel}^2 + \frac{m}{2e} \left(1 - \frac{B_2}{B_1}\right) v_{1\perp}^2 \\ &+ (\phi_2 + \phi_{2sc} - \phi_1 - \phi_{1sc}), \end{aligned} \quad (7)$$

where ϕ_1 and ϕ_2 are the external potentials and ϕ_{1sc} and ϕ_{2sc} are the space-charge potentials at the respective planes. At Plane 2, the current can be related to the local negative space-charge potential [Eq. (10)] and forward velocity as:

$$I_2 = \frac{4\pi\epsilon_0 v_{2\parallel}}{2 \ln \frac{r_e}{r_{DT}} - 1} \phi_{2sc}, \quad (8)$$

in which r_{DT} denotes the drift tube radius and r_e is the beam radius predicted by the Herrmann radius [18]. The space-charge expression is given by the solution to the Poisson equation for on-axis potential:

$$\begin{aligned} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi_{sc}(r)}{\partial r} \right) &= -\frac{\rho(r)}{\epsilon_0}, \\ \rho(r) &= \begin{cases} -\frac{I}{v_{\parallel} \pi r_e^2} & \text{if } r \leq r_e, \\ 0 & \text{if } r > r_e, \end{cases} \end{aligned} \quad (9)$$

under the assumption that the electron beam is an infinitely long cylinder with a uniform charge density ρ across its radius r_e . The solution is expressed as:

$$\phi_{sc}(r) = \begin{cases} \phi_0 \left[2 \ln \left(\frac{r_e}{r_{DT}} \right) + \left(\frac{r}{r_e} \right)^2 - 1 \right] & \text{if } r \leq r_e, \\ \phi_0 2 \ln \left(\frac{r}{r_{DT}} \right) & \text{if } r > r_e \end{cases}. \quad (10)$$

Here, ϕ_0 refers to the potential drop between the edge and the center of the beam,

$$\phi_0 = \phi_{sc}(r_e) - \phi_{sc}(0) = \frac{I}{4\pi\epsilon_0 v_{2\parallel}}. \quad (11)$$

The maximum transmittable current is given by the Bursian limit and can be derived as [19,20]:

$$\frac{\partial I_2}{\partial (\Phi + \phi_{2sc})} = 0, \quad (12)$$

where $\Phi = \frac{m}{2e} v_{1\parallel}^2 + \frac{m}{2e} \left(1 - \frac{B_2}{B_1}\right) v_{1\perp}^2 + (\phi_2 - \phi_1 - \phi_{1sc})$ and $v_{2\parallel} = \sqrt{2e(\Phi + \phi_{2sc})/m}$. This condition defines the limit for the formation of a virtual cathode at Plane 2, where the

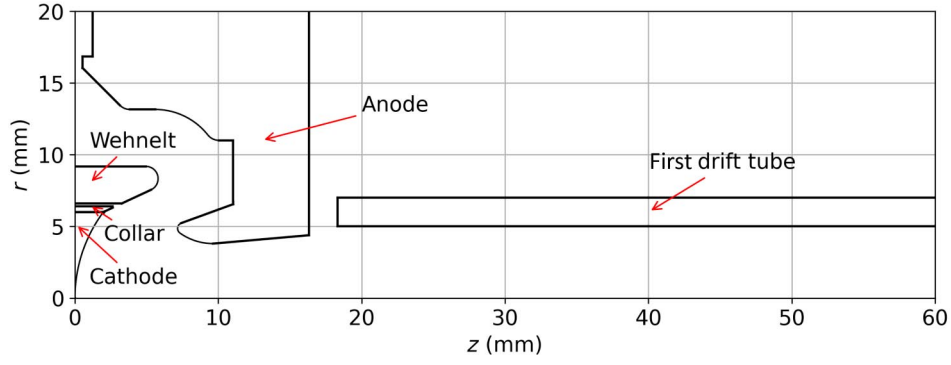


FIG. 2. Axisymmetrical view of the electrostatic model of the electron gun.

beam would then be essentially reflected by its own space-charge field.

As a result of Eq. (12), the maximum transmittable current of the electron beam at Plane 2, derived by taking both space-charge and magnetic mirror effects into account, can be estimated as:

$$I_{\max} = \frac{8\pi\epsilon_0}{3} \sqrt{\frac{2e}{3m}} \left(\frac{m}{2e} v_{\parallel}^2 + \frac{m}{2e} \left(1 - \frac{B_2}{B_1} \right) v_{\perp}^2 + (\phi_2 - \phi_1 - \phi_{1sc}) \right)^{3/2} \frac{1}{1 - 2 \ln \frac{r_e}{r_{DT}}}. \quad (13)$$

This formula synthesizes three key physical effects: the 3/2 power space-charge dependence, the magnetic mirror effect (term involving B_2/B_1), and the geometric factor ($1/(1 - 2 \ln \frac{r_e}{r_{DT}})$). The expression follows the derivation provided in Ref. [12], the addition of the magnetic field in Ref. [13], and the Bursian limit derivation found in Ref. [19].

III. MODEL

Numerical simulations were performed until Plane 1 to provide the necessary input parameters for the analytical limit described in the previous section. Given the large number of simulations required to characterize the full operating range, a 2D axisymmetric geometry was used instead of a full 3D implementation. This allowed to maintain a highly refined mesh near the cathode surface and the beam region while still keeping the computational time reasonable. The geometry was implemented as a 2D model in the Trak Charged Particle Toolkit [21], which calculates electric and magnetic field maps and tracks the electron beam while including space-charge effects self-consistently.

The electrostatic model is composed of the electron gun and a drift tube (Fig. 2). The electron gun itself consists of a spherical cathode (radius 10.1 mm) with an emission radius of 6 mm, a molybdenum collar crimped flush around the cathode, a focusing Wehnelt electrode, an

anode, and the first drift tube. The collar is specifically used to prevent edge-emitted electrons and has been used in earlier gun designs [10]. An external Wehnelt, in addition to the collar, allows for additional beam focusing adjustments, which may be required to reduce beam oscillations of the peripheral electron trajectories. Note that in the presented simulations the Wehnelt has been kept at the same voltage as the cathode. The layout is based on a previous design by A. Pikin [22], with modifications to adapt it to a 5 T solenoidal field. The electrostatic field was calculated on a grid of approximately 600 000 mesh points, and a zoomed view of the critical meshing area at the edge of the cathode can be seen in Fig. 3.

The magnetic field is produced by an unshielded superconducting 5 T solenoid, with a 1 m winding length and a bore diameter of 206 mm. A set of correcting coils on each side of the solenoid ensures sufficient homogeneity in the central part of the solenoid; see Fig. 4. The electron gun is

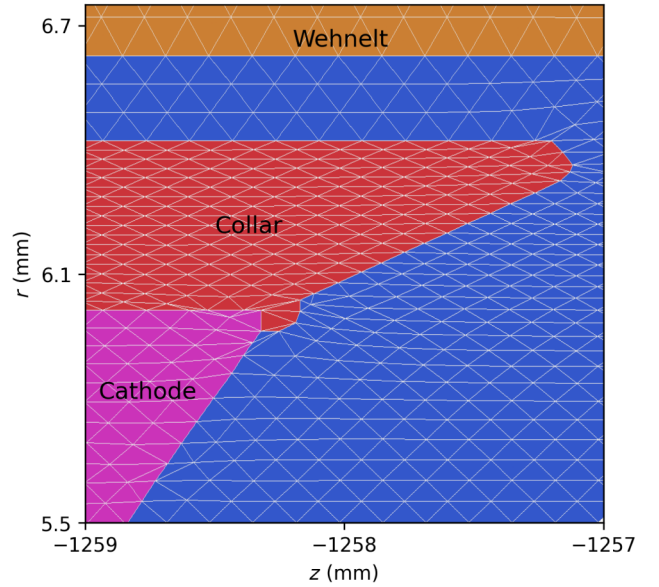


FIG. 3. Electrostatic meshing composed of nodes and regions. This geometrical area requires particular attention because the peripheral electron trajectories carry a relatively large current.

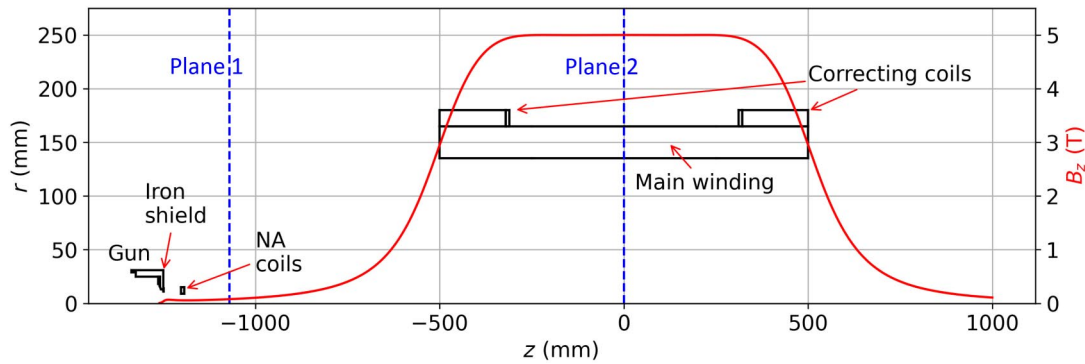


FIG. 4. Magnetic model of the EBIS. The longitudinal magnetic field is shown in red. The magnetic field at the end of the simulations, indicated by Plane 1, has a value of 0.0792 T.

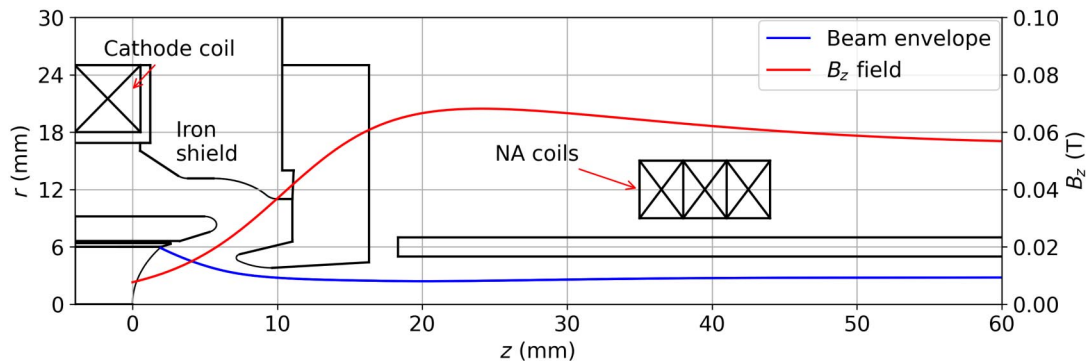


FIG. 5. Electron gun with cathode coil, iron shield, and NA coils. The beam envelope is shown in blue and the longitudinal magnetic field in red. The NA coils are inactive in the presented case.

placed inside a magnetic shield, which is made of soft iron, with its B-H curve defined using the Superfish material table from Los Alamos National Laboratory [23]. The anode is split into magnetic and nonmagnetic sections in order to allow the magnetic fringe field from the main solenoid to penetrate onto the cathode surface. The magnetic model covers a significantly larger spatial domain than the electrostatic model and was computed on a grid of approximately 1 000 000 mesh points.

The gun is located in the fringe field of the solenoid, with the cathode situated 1260 mm from the solenoid center. A coil is placed around the cathode on the inner surface of the magnetic shield and locally controls the magnetic field strength at the cathode surface (Fig. 5). By adjusting the coil current, the compression ratio can be tuned: increasing the coil current adds to the strength from the fringe field of the solenoid, which in turn reduces the final compression of the electron beam and vice versa (Fig. 6). This allows the beam current density to be adjusted, enabling optimization of the electron beam for different operational regimes. Additionally, a movable set of three nonadiabatic (NA) coils is positioned over the first drift tube to suppress the scalloping of the beam. The NA element is placed outside the vacuum tube in the

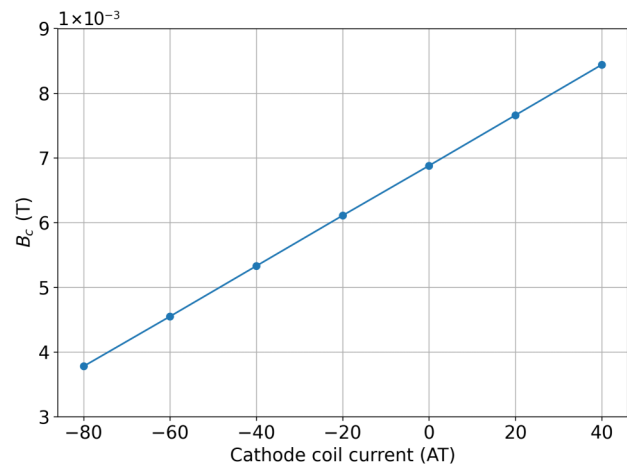


FIG. 6. Magnetic field at the cathode as a function of the current applied to the cathode coil.

atmosphere, simplifying cooling and axial positioning. The vacuum tube between the drift tube and coils is not represented in the drawing.

The beam current is determined by the potential difference between the anode and the cathode, following the

Child-Langmuir relation,

$$I = P(\phi_{\text{anode}} - \phi_{\text{cathode}})^{3/2}, \quad (14)$$

where P is the perveance, with a value of $2.08 \times 10^{-6} \text{ A/V}^{3/2}$. The beam energy is defined by the potential difference between the drift tubes in the trapping region and the cathode, reduced by the potential well created by the space-charge from the electron beam. The Wehnelt and collar shapes and the drift tube position were optimized to minimize the amplitude of radial oscillations, i.e., the pitch angle of the nominal electron beam with $I = 2.0 \text{ A}$ and $\phi_{\text{DT-cathode}} = 10.0 \text{ kV}$. The maximum electric field at the tip of the Wehnelt is 8.4 kV/mm , giving a Kilpatrick's safety factor of 2.2 [24], for an upper current limit of 3.0 A and a voltage difference of 12.7 kV between the Wehnelt and the anode.

Convergence of the simulations was judged by examining the numerical relative residual value of the matrix solution for the electrostatic potential, which was required to reach $< 2 \times 10^{-9}$. In addition, the electron trajectories were visually inspected for unphysical behavior.

IV. RESULTS

A series of studies were conducted to optimize the gun performance and ensure stable transport at high-current densities. This section first presents the axial optimization of the gun position for the nominal operating point. The analysis then evaluates the influence of the space-charge and magnetic mirror and thermal effects on the transmission limit. Finally, the operational range is extended, and the influence of an NA coil is explored for high- and low-current cases.

The first set of simulations was run for the nominal electron current, $I = 2.0 \text{ A}$, aiming for a desired current density range of $j = 1000\text{--}1500 \text{ A/cm}^2$ in the full-field region. No perturbation fields from the NA coils were applied. To minimize the scalloping originating from the modified cyclotron motion, the axial position of the electron gun relative to the solenoid center was optimized. The minimum potential difference between the drift tube and cathode was chosen following Busch's theorem for an ideal beam in the absence of beam optic imperfections for the 2.0 A case. According to the conservation of canonical angular momentum, when the beam is compressed into the solenoidal field, it inevitably starts to rotate with an angular velocity, given by the Busch theorem [25,26],

$$\dot{\theta} = \frac{e}{2m} \left(B_1 - B_c \frac{r_c^2}{r_1^2} \right), \quad (15)$$

where B_c and B_1 are the magnetic fields at the cathode and Plane 1, respectively, and r_c and r_1 are the corresponding electron beam radii. Using $\theta = \arctan(r_1 \dot{\theta} / v_{1\parallel})$, a voltage

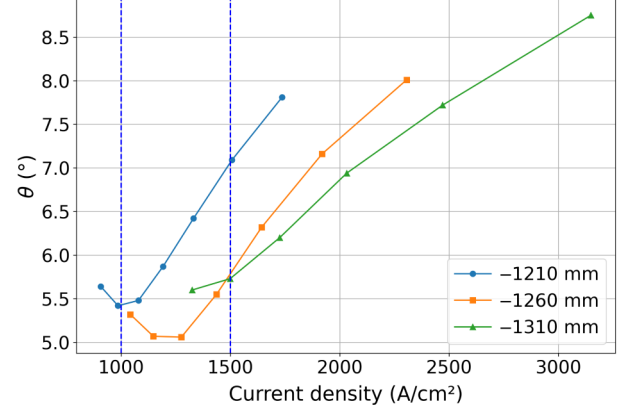


FIG. 7. Maximum trajectory angle at the end of the simulation as a function of the current density for three different positions. The electron current is 2.0 A , and the cathode-drift tube potential difference is 10 kV . The region between the dashed vertical lines indicates the desired current density range.

$\phi_{\text{DT-cathode}}$ of 10 kV is sufficient to ensure that the Busch angle is transmittable according to Eq. (13). The motivation for minimizing the extraction potential is to enhance the electron-impact ionization cross sections and space-charge capacity.

The electron trajectories were traced for three longitudinal positions while scanning the cathode coil current. The goal was to minimize the angles between the electron trajectories and the beam axis in the desired current density range. These angles were identified within the simulated final oscillation of the electron beam before Plane 1. The results are shown in Fig. 7, where one can conclude that a gun position $z_c = -1260 \text{ mm}$ from the solenoid center yields the lowest angles. The current density was calculated as $j = I/(\pi r_e^2)$, where r_e is the Herrmann radius.

Thereafter, using the said $z_c = -1260 \text{ mm}$ position, beams with currents in the range of 0.2 to 3 A at 10 kV were tracked to Plane 1. The maximum transmittable current into the full field was then computed using Eq. (13). This analysis was performed for cathode coil currents in the range -80 AT to 40 AT, in steps of 20 AT in ampere turns. As seen in Fig. 8(a), which showcases the transmittable configurations, none of the cathode coil cases for the nominal 2.0 A beam are accepted when effects such as scalloping and aberrations are taken into account from the simulations. For reference, the angle increases from the ideal Busch value of 4.1° to 5.1° for a 2.0 A beam, with 10 kV and 0 AT cathode coil current. Only when the voltage is increased to 12 kV , Fig. 8(b), the 2.0 A beam demonstrate full transmission for several magnetic field strengths at the cathode. For context, Fig. 9 shows the maximum angles that allow transmission of different beam currents for the 12 kV potential for 0 AT on the cathode coil. The configuration with the lowest angle, which is achieved for $+20$ AT, produces a highly laminar, nonscalloping electron beam as shown in Fig. 10.

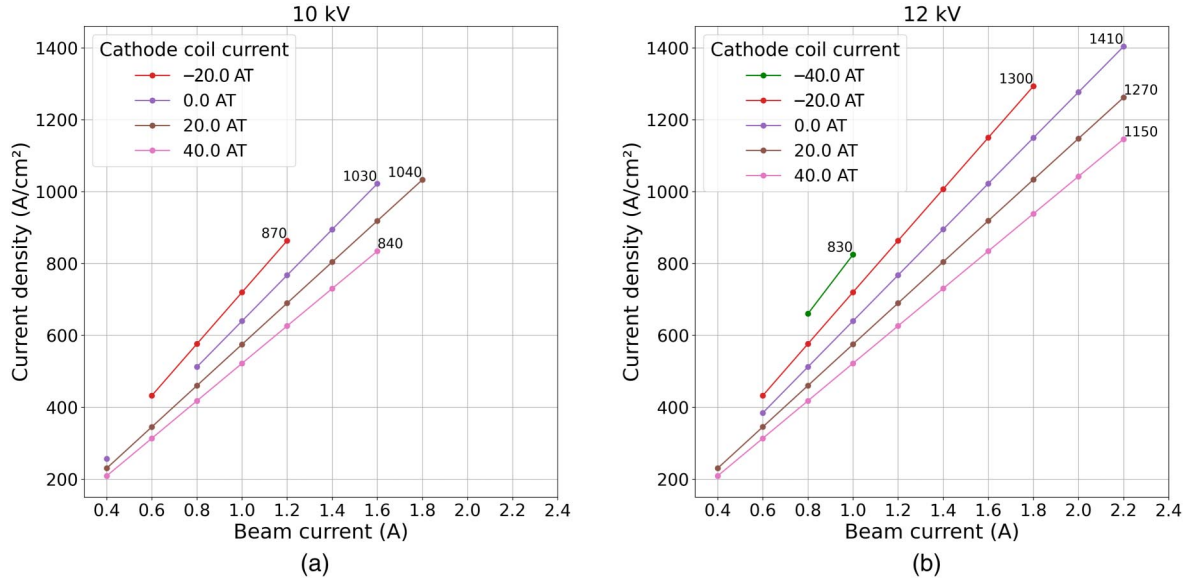


FIG. 8. Current density as a function of beam current and current applied on the cathode coil for (a) 10 and (b) 12 kV cathode-drift tube potential differences. Only transmittable cases according to Eq. (13) are shown for beam currents in the range 0.2 to 3 A.

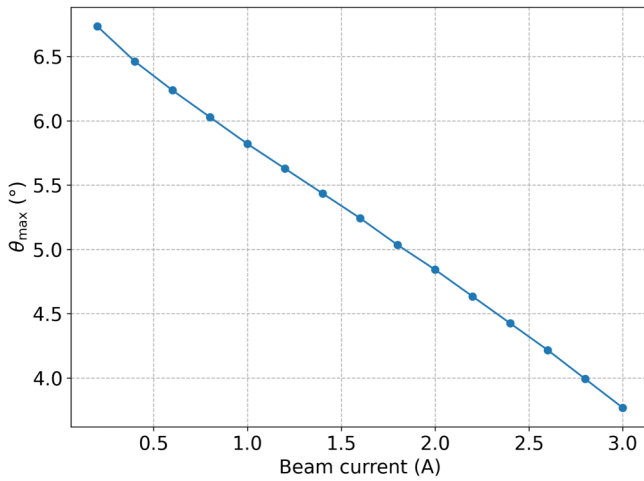


FIG. 9. Maximum transmittable trajectory angle at the end of the simulation as a function of beam current, for 12 kV cathode-drift tube potential difference and no current on the cathode coil.

The evolution of the current density profile up to Plane 1 is presented in Fig. 11. Close to the cathode, the distribution is relatively flat. Further downstream, peaks begin to develop in the outer radial region. As the beam propagates, the profile exhibits a cyclic behavior, alternating between flatter distributions and profiles with pronounced off-axis peaks. This can be related to the outermost trajectories of the beam, which carry a significant fraction of the current, being out of phase from the rest.

Another factor affecting the beam is the cathode temperature, which determines the transverse velocity spread of the emitted electrons. Assuming noninteracting electrons

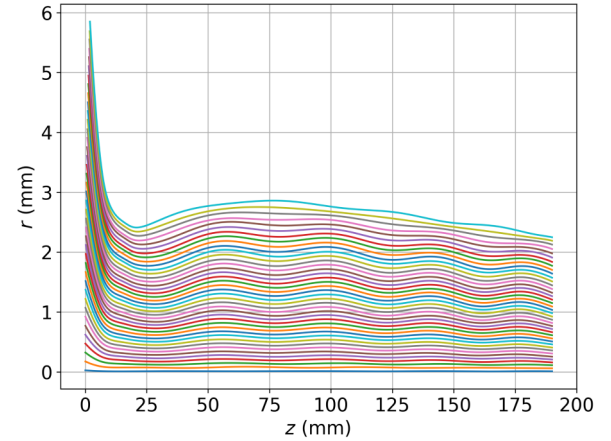


FIG. 10. Trajectories of the nominal 2.0 A, 12 kV configuration with a 20 AT cathode coil current.

from a cathode with temperature T_c , the transverse velocity distribution at Plane 1 is nearly Maxwellian with an effective temperature [27]

$$T_1 = T_c / M^2, \quad (16)$$

where M is the magnification, which is given as $M^2 = B_c / B_1$. For a cathode temperature of 1000 °C, $B_c = 7.7$ mT and $B_1 = 79.2$ mT, the transverse velocity distribution becomes equal to 1.1 eV at Plane 1. This results in a theoretical angle increase of $\sqrt{1.1/12000} \approx 0.5^\circ$. Simulations that include both space-charge and cathode temperature reproduce this behavior, also showing an increase of 0.5° for the 12 kV case.

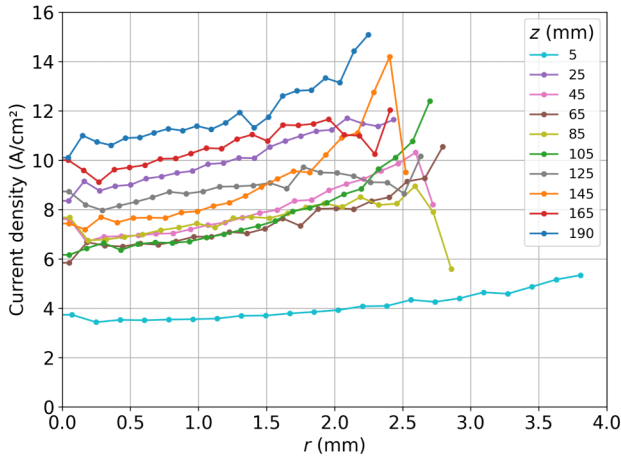


FIG. 11. Electron beam current density profiles evaluated every 20 mm from the cathode up to Plane 1, for the beam shown in Fig. 10, as a function of beam radius.

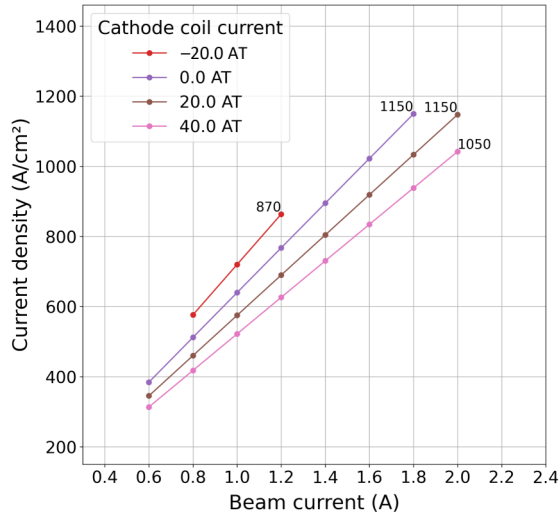


FIG. 12. Current density as a function of beam current and current applied on the cathode coil. Only transmittable cases according to Eq. (13) are shown, taking an increase of 0.5° from the temperature into account for 12 kV cathode-drift tube potential difference.

Multicurrent results including an addition of 0.5° from cathode heating are illustrated in Fig. 12 and confirm that the system maintains sufficient margin to deliver 2.0 A at 12 kV cathode-drift tube potential difference without the use of NA coils. The current density reaches 1150 A/cm^2 for 20 AT cathode coil current. The trajectories have a maximum angle value of 4.3° when taking into account temperature effects, which is below the limitation. Under these conditions, some electron trajectories begin to cross (as seen in Fig. 13). Despite these effects, transport from the cathode into the full 5 T region should be possible, thereby fulfilling the requirements for the nominal operation regime. However, note that the beam envelope in

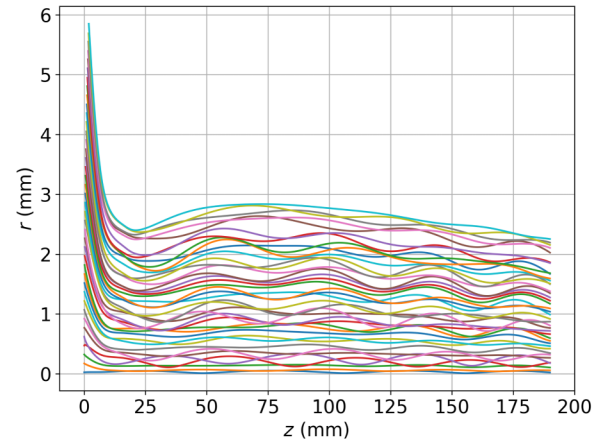


FIG. 13. Trajectories of the nominal 2.0 A, 12 kV configuration with a 20 AT cathode coil current, this time simulated with temperature effects.

Fig. 13 is identical to Fig. 10 due to the beam being magnetized, which makes the effect of temperature on the beam radius insignificant.

A. Nonadiabatic coil

As demonstrated in previous work [28,29], the operating range of an EBIS in terms of electron beam current, current density, and energy can be significantly increased by introducing a local NA magnetic field modification, which extends over approximately a quarter of a period of the modified cyclotron oscillation. One way to create this local field change is to use an iron ring, which deflects some flux and locally reduces the magnetic field. The iron ring should be positioned over the descending phase of the radial oscillation.

The same effect can be achieved using a coil that creates a dip or an increase in the axial magnetic field by placing it over the ascending or descending part of the modified cyclotron motion, respectively. The effect of a local increase or decrease is equivalent, as in both cases, part of the electron energy in the transverse direction is translated into the axial direction, which in turn reduces beam scalloping.

The NA element itself is implemented as a set of $3 \times 3 \text{ mm}$ coils placed sequentially (Fig. 5), and allows the magnetic field profile to be tuned for different beam currents. These coils are located outside the vacuum chamber and can be moved axially over a certain range to optimize the nonadiabatic field along the beam path for different current settings.

As shown in Fig. 14, the use of an NA coil significantly reduces electron oscillations, leading to a less scalloping beam. In this configuration, electron beam currents between 0.2 and 3 A, reaching 1900 A/cm^2 for the high-current case, can be transmitted through the magnetic mirror, while the beam energy is adjusted. Using the NA

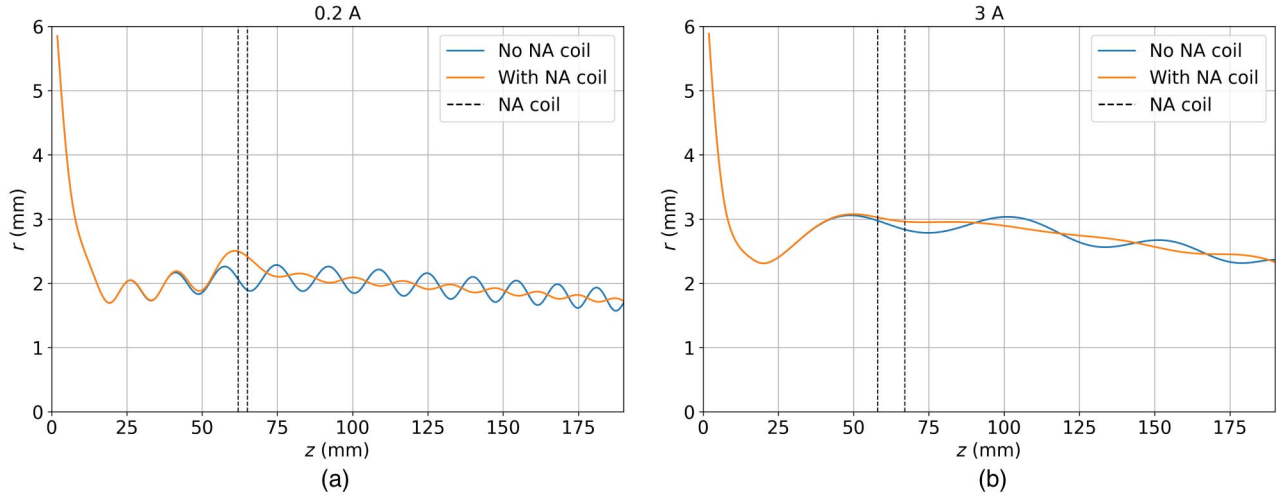


FIG. 14. Beam envelopes for a (a) 0.2 A electron beam, 2 kV cathode-drift tube potential difference, with a 1×3 mm NA coil and a (b) 3 A electron beam, 16 kV cathode-drift tube potential difference, with 3×3 mm NA coils. The coils are positioned at -1198 mm and -1202 mm from the center of the solenoid, with $I_{\text{coil}} = -220$ AT and -60 AT for (a) and (b), respectively.

element, the angle is reduced from 7.7° to 3.8° for the low-current case and from 5.3° to 4.6° for the high-current beam, making both cases transmittable.

In addition to high-current operation for medical accelerators, the broadband electron gun design enables stable operation over a wide range of beam energies and currents. This flexibility is a desirable requirement for charge breeding applications, such as REXEBIS for HIE-ISOLDE. Operating at lower energies [Fig. 14(a)] permits better control of the ionization process, with the goal of maximizing the $1+ \rightarrow n+$ transformation efficiency rather than the total number of extracted ions. By carefully adjusting the electron energy so that it falls within an atomic shell gap of the charge-bred ion, it is possible to control the charge state distribution. In this way, ions are effectively prevented from advancing to charge states higher than the shell gap. This strategy increases the fraction of ions in the target charge state, thereby improving the charge breeding efficiency and enabling the efficient production of weak or rare radioactive beams. For example, the ionization energies of Kr^{25+} and Kr^{26+} are 1205 and 2928 eV, respectively [30]. Although a beam of 2 kV, 0.2 A, only provides a current density of 165 A/cm^2 and thus imposes a breeding time of up to 500 ms to reach Kr^{26+} , nearly 100% abundance in the $26+$ charge state can be achieved according to *ebisim* [31]. This code provides the abundances of the different charge states involved as a function of breeding time, for a specific current density and beam energy.

B. Ion beam estimation

The expected C^{6+} ion yield was also estimated using *ebisim* for the nominal 2 A, 12 kV beam, corresponding to 1150 A/cm^2 current density, while applying pulsed gas

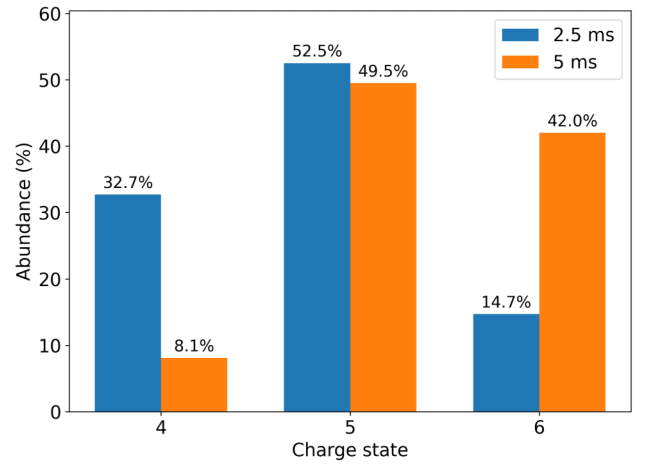


FIG. 15. Carbon charge state abundance for 2.5 and 5 ms breeding times, for a 12 kV voltage and 1150 A/cm^2 beam.

injection of CH_4 . Figure 15 shows the abundances of the carbon charge states, as a function of breeding time, for the given current density and beam energy. The number of electrons, determining the space-charge capacity, is estimated as $N = LI/(ev)$, where $L = 80$ cm is the trap length, I is the electron beam current, and v is the electron beam velocity. Assuming that all H^+ ions are boiled off, the electron and ion beams are fully overlapped, and the space-charge neutralization is 50%, the simulations predict approximately $2.6 \times 10^9 \text{ C}^{6+}$ ions for 2.5 ms breeding time and $6.7 \times 10^9 \text{ C}^{6+}$ ions for 5 ms. These values fulfill the requirements of the ALMA accelerator, which demands a minimum yield of 10^8 ions per pulse and a repetition rate of at least 200 Hz.

Note that there are several factors that will affect the actual number of accelerated ions through the linac.

Of major concern is the axial energy spread of the extracted ions, which may exceed the longitudinal acceptance of the RFQ, in particular if ramped extraction has to be used to extract the ions with a short pulse length. This may result in lower effective ion numbers than quoted above. Furthermore, in practice, the ion-electron beam overlap, and thereby also the ion production rate, decreases to a higher degree of neutralization. Pulsed gas injection makes best use of the space-charge capacity and reduces charge-exchange processes. Continuous gas injection, as hitherto used at TwinEBIS, has been shown to reduce the effective current density and increase transverse emittance [32]. Pulsed injection can be more easily obtained when the drift tubes are at cryogenic temperatures rather than at room temperature [7].

V. CONCLUSIONS

A broadband electro-optical system with a semi-immersed electron gun and nonadiabatic coils has been designed and simulated for a 5 T EBIS, demonstrating that a laminar and nonscalloping beam can be obtained for the nominal 2 A and 12 kV operating point. For a broader range (0.2 to 3 A), beyond the operating point, the NA coils have been proven essential for suppressing radial oscillations. This not only provides operational margin but also allows the gun to be adapted for other applications. To validate the design, an acceptance criterion was derived for a nonrelativistic electron beam, which takes both magnetic mirror and space-charge effects into account.

The proposed system meets the design goal of a 2 A and 1000 A/cm² beam, and with these parameters, the theoretically estimated amount of C⁶⁺ ions could also fulfill the requirement for the targeted cancer therapy accelerator. In order to attain this practically, pulsed gas injection is mandatory and can, for example, be obtained with a cryogenic drift tube structure. One would also need to ensure that the inherent energy spread of the extracted beam remains within the RFQ's energy-spread acceptance. Another application for the gun design is charge breeding to a closed atomic shell, which enhances the breeding efficiency. In most cases, this translates to a significantly lowered electron beam energy. The analysis shows that this can be successfully attained. Future work will focus on the adaptation of the EBIS collector to a high-density electron beam and on the ion extraction and transport to the RFQ.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not

technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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