

Combined simulation and experimental characterization of space-charge compensation in a high-intensity proton Low Energy Beam Transport (LEBT)

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(Received 2 January 2026; accepted 14 April 2026; published 12 June 2026)

Beam losses in high-intensity proton accelerators are largely caused by space-charge effects, particularly in the low energy beam transport (LEBT) region, where the beam remains nonrelativistic. While space-charge compensation (SCC) through residual gas ionization is a widely used mitigation technique, detailed time-resolved studies combining both simulations and direct experimental measurements are scarce. This work presents a comprehensive investigation of passive SCC in the Low Energy High Intensity Proton Accelerator LEBT using both Particle-in-cell/Monte Carlo Collision simulations and dedicated diagnostics. Detailed simulations using CST Particle Studio are carried out to investigate how compensating gas type, gas pressure, external magnetic field, and beam parameters affect the space-charge compensation time and degree, as well as the resulting variations in beam potential, emittance, and transverse size. Experimentally, the SCC dynamics are characterized using a diagnostic suite that features a retarding field analyzer (RFA) and our novel, indigenously developed particle monitor probe (PMP). The PMP is applied here to estimate SCC time from the transient ionization electron current at the beam periphery, while the RFA determines the local SCC degree. These measurements provide detailed information on the variation of SCC parameters with gas type, pressure, and solenoidal magnetic field. The combined simulation and experimental results provide new physical insights into the dynamics of SCC, particularly regarding the nonmonotonic effect of magnetic fields, and validate a diagnostic methodology applicable to other high-intensity proton injectors.

DOI: [10.1103/g3pg-mxr1](https://doi.org/10.1103/g3pg-mxr1)

I. INTRODUCTION

High-intensity linear accelerators are increasingly central to a wide range of applications, including spallation neutron sources, medical isotope production, and accelerator-driven systems (ADS) for nuclear waste transmutation. In India, significant initiatives are underway to develop high-power proton linacs to support such long-term strategic goals, particularly within the framework of ADS programs [1,2]. A critical challenge in high-intensity high-energy proton accelerators is minimizing beam loss; even minimal losses at high energies can lead to radioactivation of accelerator components, thereby complicating maintenance and increasing operational downtime [3]. Consequently, beam quality control must be strictly enforced at the front end of the accelerator, where low-energy beams are most susceptible to deterioration in quality due to intense, nonlinear space-charge forces [4].

To address these front-end challenges and serve as a technology demonstrator for high-intensity proton linacs, the Low Energy High Intensity Proton Accelerator (LEHIPA) facility has been developed and commissioned at the Bhabha Atomic Research Centre (BARC) [5]. This facility comprises a high-current 50 keV Electron Cyclotron Resonance Ion Source (ECR-IS), a low energy beam transport (LEBT) section, a Radio Frequency Quadrupole (RFQ) for initial bunching and acceleration up to 3 MeV, and a Drift Tube Linac for further energy gain up to 20 MeV [5,6]. Space-charge effects, arising from Coulomb repulsion between beam particles, are particularly pronounced at these low energies, where the beam velocity is insufficient to mitigate mutual repulsion. Without intervention, this leads to rapid emittance growth, beam halo formation, and transmission loss. Consequently, effective mitigation of these effects in the low-energy section, particularly within the LEBT, is thus vital for achieving reliable, high-quality beam delivery downstream.

Space-charge compensation (SCC) is the primary method used to mitigate these repulsive forces. While active techniques such as electron columns and plasma lenses have been investigated [7,8], passive SCC via the ionization of background gas remains the preferred choice for many facilities due to its operational simplicity and the

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precision offered by neutral gas pressure control [9,10]. In passive SCC, the primary proton beam ionizes neutral gas molecules, generating electron-ion pairs. The resulting low-energy electrons are trapped within the positive potential well of the beam, while the heavier secondary ions are repelled toward the vacuum chamber walls. Over time, this accumulation of electrons leads to a quasi-steady state of partial or near-complete charge neutralization, significantly reducing beam divergence.

To fully characterize this complex neutralization process, the investigation relies on a synergy of numerical simulation and experimental measurement. Simulations reveal microscopic dynamics and internal potentials that physical diagnostics cannot access, while experiments provide the essential ground truth to validate these models against real-world beam conditions.

SCC simulation methods represent a trade-off between computational speed and physical fidelity. The effective current method used in Particle-in-cell (PIC) codes (e.g., TraceWin, Bender, TRACK) is the fastest, ideal for lattice design by using a static current scaling factor, but it ignores ionization physics and transients [11–13]. In contrast, Particle-in-cell/Monte Carlo Collision (PIC-MCC) (e.g., CST Particle Studio, WARP, and IBSimu) provides the highest accuracy by kinetically simulating individual collisions and dynamic instabilities, albeit at a higher computational cost [14–18]. Crucially, for compact LEBTs, full 3D PIC simulations are essential to accurately capture the nonlinearities and aberrations in solenoid magnets that 2D models often oversimplify.

SCC experimental characterization utilizes retarding field analyzers (RFAs) and beam profilers to quantify the steady-state compensation degree [19,20], while fast emittance/profile scanners and optical monitors are employed to resolve the compensation time during transients [16,21–23]. Despite their utility, interceptive diagnostics inherently perturb the beam by introducing metallic surfaces that alter local boundary conditions and generate copious secondary electrons, thereby artificially modifying the very compensation state they aim to measure [24,25]. Conversely, noninvasive optical diagnostics avoid these mechanical disruptions but can provide inaccurate results due to line-of-sight integration effects and the complex dependence of signal intensity on gas excitation cross sections rather than pure beam density [22,26]. These measurement limitations highlight the importance of developing novel, nonperturbative diagnostics capable of accurately resolving space-charge dynamics without distorting the underlying physics.

Furthermore, specific physics gaps remain regarding positive ion beams. Many of the existing SCC studies at low energies focus on negative hydrogen ion (H^-) beams, where compensation relies on positive ion accumulation [9,15–17,23]. For positive ion beams, compensation is achieved by electrons, which are much lighter and therefore exhibit different dynamics under the influence of the LEBT

magnetic field [10,14,16–18]. Moreover, secondary electron emission (SEE) from beam-pipe interactions can supplement the electron population, a mechanism absent in negative ion compensation. The scenario is further complicated for proton beams extracted from plasma ion sources like ECR-IS, which generate mixed species—typically comprising $\sim 50\text{--}80\%$ H^+ , $\sim 15\text{--}30\%$ H_2^+ , and $\sim 5\text{--}20\%$ H_3^+ —each possessing different mass-to-charge ratios and ionization cross-sections [11,27].

To address these complexities, this paper presents a combined simulation and experimental characterization of SCC of a high-intensity proton beam in the LEHIPA LEBT. We employ a hybrid 3D PIC-MCC simulation framework using CST Particle Studio [28] to model the complete ionization and transport process. To ensure high fidelity, the simulation model incorporates experimentally measured beam distributions and 3D solenoid field maps. This framework enables a detailed study of the effects of ion-induced SEE and multispecies dynamics. Experimentally, we deploy a dedicated diagnostic suite featuring the novel particle monitor probe (PMP) for time-resolved electron signal detection and an RFA for beam potential measurements. This comprehensive approach allows us to (i) directly measure SCC parameters noninvasively, (ii) quantify the impact of gas type, pressure, and magnetic fields on compensation, and (iii) understand the contribution of secondary electron emission. These results offer new physical insights and a validated diagnostic methodology applicable to other high-intensity proton injectors.

This article presents both simulation and experimental investigations of the LEHIPA LEBT aimed at understanding the complexities of SCC, in addition to the design simulations and development of the SCC diagnostics. The paper is structured as follows: Sec. II establishes the theoretical framework, defining the SCC degree (η) and the SCC time constant (τ_{SCC}) as used throughout this study. Section III provides a technical overview of the LEHIPA LEBT facility. Section IV describes the simulation methodology using the CST Es-PIC solver and presents a detailed parametric analysis of how gas species, pressure, solenoidal magnetic fields, and beam rise time influence the neutralization process. Section V is dedicated to the experimental characterization of SCC dynamics, covering the indigenous design and development of the PMP, RFA, and beam profiler diagnostics, the direct measurement of SCC parameters, and a comparative study of experimental trends against simulation data. Finally, Sec. VI offers concluding remarks and summarizes the key physical insights gained from this work.

II. THEORETICAL FRAMEWORK

The SCC process is fundamentally transient, evolving toward a dynamic equilibrium where the rate of compensating charge accumulation is balanced by various loss mechanisms, such as thermal escape and longitudinal drift.

For a singly charged positive ion beam, a steady state is theoretically approached when the density of trapped ionization electrons becomes sufficient to neutralize the primary beam's space charge. This complex interaction is quantitatively characterized by two primary parameters: the degree of space-charge compensation (η) and the SCC time constant (τ_{SCC}).

(1) Space-charge compensation degree (η): The effectiveness of the neutralization process is quantified by the SCC degree, η , defined as the fractional reduction in the beam's self-potential due to the presence of the compensating electron cloud. This parameter directly dictates the transverse dynamics and the net defocusing force experienced by the beam particles. The relationship between η and the potential reduction is derived in the Appendix, assuming uniform charge distribution and cylindrical symmetry:

$$\eta = 1 - \frac{\phi_c}{\phi_0} \quad (1)$$

where, ϕ_c and ϕ_0 represent the on-axis electrostatic potential [at ($r = 0$) for a given z] relative to the grounded beam pipe (at $r = R_p$) in the presence and absence of compensation, respectively. A value approaching unity indicates near-complete neutralization and maximum mitigation of space-charge-induced emittance growth.

(2) SCC time constant (τ_{SCC}): To characterize the temporal evolution, we define a characteristic time constant, τ_{SCC} [29]. This provides a convenient means to normalize the time evolution of compensation and enables meaningful comparisons across different experimental or simulation conditions, such as variations in compensating gas pressure or beam parameters. Physically, τ_{SCC} represents the average time

required for each primary beam ion to generate one compensating electron through ionization of the background gas. The expression, derived from the ionization rate equation in Appendix A, is

$$\tau_{\text{SCC}} = \frac{1}{\sigma_i(E) \cdot n_g \cdot \beta c}, \quad (2)$$

where $\sigma_i(E)$ is the ionization cross section of the gas for the beam energy E , n_g is the neutral gas density, and βc is the beam velocity. A smaller τ_{SCC} indicates a faster buildup of compensating charge and thus a more rapid establishment of neutralization equilibrium.

III. LEHIPA LEBT OVERVIEW

The LEHIPA LEBT, shown in Fig. 1, is a compact ~ 2.7 m beamline designed to transport and match the high-intensity proton beam from the ECR ion source to the RFQ. The lattice consists of two identical solenoids separated by drift sections. Although the solenoids are geometrically similar, they are energized at distinct magnetic field strengths to provide the required phase-space matching. To correct for transverse misalignments, two sets of steering magnets (SM1 and SM2) are integrated into the line.

The LEBT geometry includes two physical collimators, as shown in Fig. 1: Collimator-1 ($\varnothing 40$ mm) at the beginning and Collimator-2 ($\varnothing 5$ mm) at the LEBT exit. Both are longitudinally distant from diagnostic chamber 1, ensuring no perturbation of the local space-charge environment during measurement. Similarly, the ECR ion source suppression electrode is located ~ 630 mm upstream; this substantial separation prevents its fields from influencing the

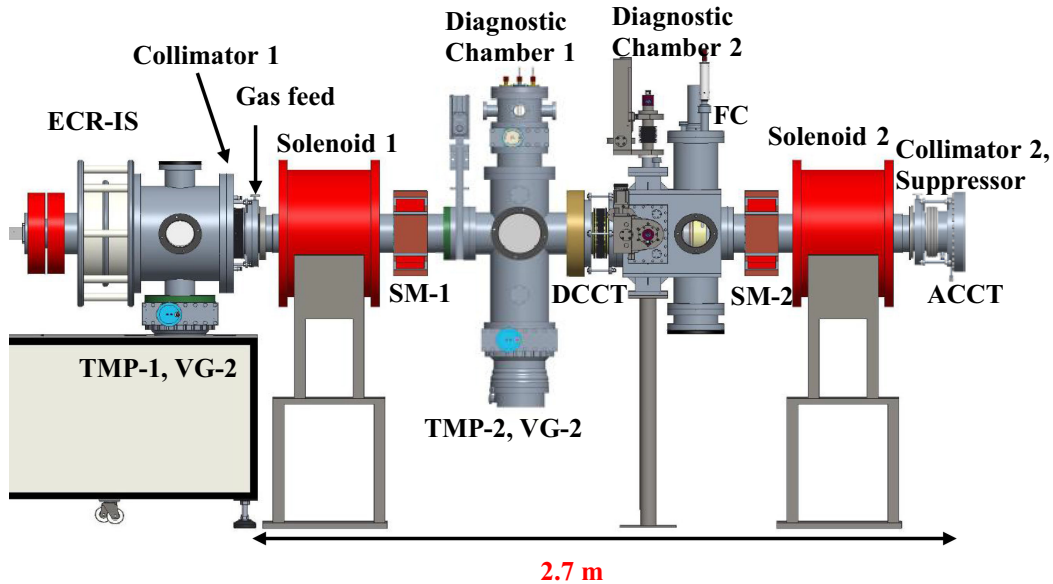


FIG. 1. Schematic of LEHIPA LEBT. ECR-IS, ECR ion source; TMP, turbo molecular pump; VG, vacuum gauge; SM, steerer magnet; DCCT, dc current transformer; FC, Faraday cup, ACCT: ac current transformer.

beam potential or electron accumulation within the diagnostic suite. To ensure a nonperturbative environment, all nearby intrusive diagnostics are retracted during SCC characterization.

Hydrogen (H_2), naturally present from the ion source, is commonly used as a compensating gas due to its low mass, compatibility with beamline components, and minimal beam scattering. However, its relatively low ionization cross section limits the rate of SCC, and in longer magnetic LEBT lines, compensation from H_2 alone may be insufficient, particularly in the downstream region. To enhance SCC for H^+ beams, additional gases such as helium (He), argon (Ar), and krypton (Kr) are often introduced. Heavier noble gases like Ar and Kr offer more ionization due to higher cross sections but also introduce greater beam scattering with increased pressure, which can degrade beam quality. He, being lighter, causes less scattering but provides weaker ionization, and like H_2 , often fails to maintain sufficient SCC in the downstream LEBT. Nitrogen (N_2) is another widely used gas that offers a favorable balance. It has a higher ionization cross section than H_2 and He, enabling faster SCC buildup, while causing less scattering than heavier noble gases. The gas is typically introduced in controlled amounts, using a leak valve or mass flow controller, during experiments or pulsed beam operation to improve compensation without significantly affecting beam quality. In LEHIPA, it is injected at a designated location as shown in Fig. 1, while vacuum conditions are maintained using two turbomolecular pumps: TMP-1 near the ion source and TMP-2 located between the solenoids. Corresponding vacuum levels are monitored using vacuum gauges VG-1 and VG-2.

The LEBT vacuum is maintained at a base pressure of $\sim 1 \times 10^{-7}$ Torr. During source operation, the background pressure from the ECR-IS hydrogen gas stabilizes at $\sim 1 \times 10^{-5}$ Torr (measured at VG-1). For SCC studies, additional compensating gases (N_2 , Ar, and He) are introduced using a mass flow controller, with typical flow rates ranging from 1 to 10 sccm. This allowed for a controlled variation of the beamline pressure between 1×10^{-5} Torr and 1×10^{-4} Torr, providing a broad range for the parametric analysis of the SCC time constant (τ_{SCC}) and compensation degree (η).

In addition, the LEBT is equipped with a comprehensive suite of standard diagnostics, shown in Fig. 1, including a Faraday cup (FC) for current measurements, a dc current transformer (DCCT), an ac current transformer (ACCT), and a multiwire beam profiler. To directly measure SCC parameters, a probe assembly consisting of a novel particle monitor probe (PMP) and a retarding field analyzer (RFA) is installed after the first LEBT solenoid, as shown in Fig. 1. The primary beam and LEBT operating parameters are listed in Table I.

TABLE I. Beam and LEBT operational parameters.

Parameter	Value
H^+ beam current	10 mA
Beam topology	Pulsed (1 ms, 2 Hz)
Beam energy	50 keV
rms normalized emittance at LEBT input	0.3π mm mrad
LEBT length	2.66 m
Aperture radius	75 mm
Injected gas	Ar, N_2 , H_2
Typical gas flow rate (N_2)	6 sccm
Typical field ($Sol1$, $Sol2$)	(0.145 T, 0.22 T)

IV. SCC: SIMULATION STUDIES

To accurately understand the SCC process in LEBT systems, it is crucial to model not only the collective Coulomb interactions within the beam but also the individual interactions between beam particles and compensating gas molecules present in the beamline. A widely adopted approach combines PIC methods with MCC routines. The PIC framework resolves the beam dynamics under self-generated space-charge fields and external focusing elements, while the MCC module simulates beam-gas interactions, such as ionization, charge exchange, and elastic scattering, based on energy-dependent cross sections. This hybrid PIC-MCC simulation enables realistic modeling of the beam dynamics during the SCC process.

While various computational tools such as SOLMAXP, WARP, and IBSimu are available for such studies, this work utilizes the Electrostatic Particle-In-Cell (Es-PIC) solver of the CST Studio Suite. Given the nonrelativistic nature of the 50 keV proton beam, the self-induced magnetic fields are negligible. Consequently, the Es-PIC approach provides the necessary accuracy for modeling space-charge effects while significantly optimizing computational efficiency compared to full-wave 3D electromagnetic solvers. A detailed simulation setup is explained in the following section.

A. Simulation setup

PIC-MCC simulations with a proton beam are performed for the LEHIPA LEBT, which comprises two solenoids and intermediate drift sections, as shown in the CST model in Fig. 2. The solenoid fields are calculated using CST's magnetic solver and validated against experimental axial field measurements to ensure high fidelity in the beam transport modeling.

The beam's Twiss parameters and transverse phase-space distribution at the entrance of the LEHIPA LEBT are experimentally obtained using tomographic reconstruction [6]. Based on this reconstructed distribution, a particle source file is generated that includes the transverse coordinates ($x, y, z = 0$), corresponding momenta (p_x, p_y, p_z), beam

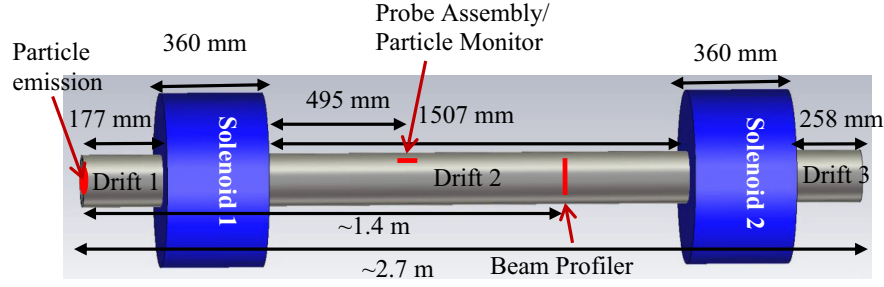


FIG. 2. CST model of the LEBT with dimensions and particle monitors.

current, and energy. This source file, representing a 50 keV, 10 mA H^+ beam with the same phase-space characteristics as the experimentally measured beam, is used as the input for the PIC-MCC simulations, as indicated in Fig. 2. The beam envelope obtained from CST Es-PIC simulations is compared with TraceWin results to validate the accuracy and reliability of the CST Es-PIC setup.

In the present simulation model, a uniform background gas density is assumed throughout the LEBT volume. While the experimental facility exhibits a longitudinal pressure gradient due to the localized gas injection near the diagnostic chamber and discrete pumping at the solenoids, the uniform model provides a baseline for understanding the fundamental scaling of SCC parameters. To account for the experimental gradient, a parametric study is conducted over the full range of pressures measured by gauges VG-1 and VG-2, ensuring that the simulated SCC dynamics bracket the real-world conditions experienced by the beam.

While ionization is the primary focus for studying charge neutralization, the influence of elastic scattering has also been investigated and found to be negligible at the operating pressures considered. The ionization processes for H_2 , N_2 , and Ar are governed by the electron production cross sections (σ_i) at 50 keV. The values adopted in this study, summarized in Table II, are taken from the literature [30,31]. Other key parameters used in the PIC-MCC studies are similar to those in Table I. Numerical stability and physical accuracy are ensured by performing a mesh sensitivity analysis, maintaining a mesh size adequate to resolve the Debye length of the induced plasma.

To track the SCC dynamics, virtual particle monitors, shown in Fig. 2, are strategically integrated into the CST model. A planar monitor ($\sim 20 \text{ cm}^2$) is positioned

transversely near the beam pipe wall, $\sim 60 \text{ mm}$ from the beam axis and 1 m downstream in the LEBT, to measure the SCC buildup time. Another planar monitor intersecting the beam pipe is located at $\sim 1.4 \text{ m}$ downstream to emulate conventional beam diagnostics used for studying emittance growth and beam size evolution. Both monitors operate as passive collectors, with no applied bias, and record the flux of charged particles reaching their surfaces. Secondary electron emission from the monitors themselves is neglected, as they are positioned in the beam periphery where the incident energy of secondary ions is sufficiently low.

B. Simulation results and discussion

As the primary 50 keV, 10 mA proton beam propagates through the compensating gas in the LEBT, continuous ionization produces secondary electrons and positive ions. Figure 3 presents the simulated spatial distributions of these species. The lighter ionization electrons (red dots) are rapidly confined within the deep potential well of the primary beam, initiating the SCC process by reducing the net positive potential. Conversely, the heavier secondary positive ions (N_2^+ in this case, shown as black dots) are repelled radially toward the grounded beam pipe walls. Given the low operating pressures ($\sim 10^{-5} \text{ Torr}$), the resulting beam-induced plasma is effectively collisionless over the transport timescale, meaning the compensation

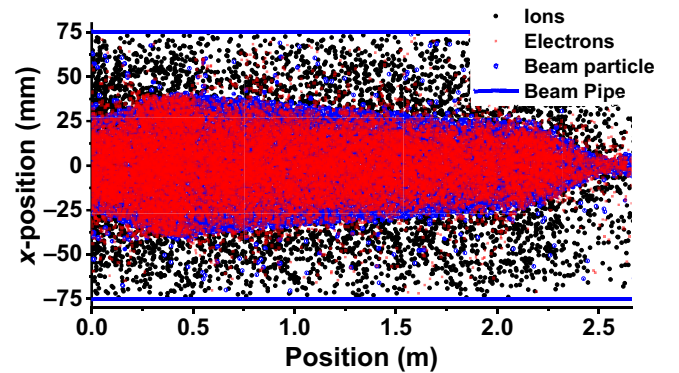


FIG. 3. Beam particles, compensating gas ions, and ionization electrons in the beam pipe during SCC.

TABLE II. Ionization cross section for 50 keV H^+ impact used in PIC-MCC simulations.

Gas species	Cross section (10^{-20} m^2)
H_2	2.02
N_2	5.96
Ar	6.40

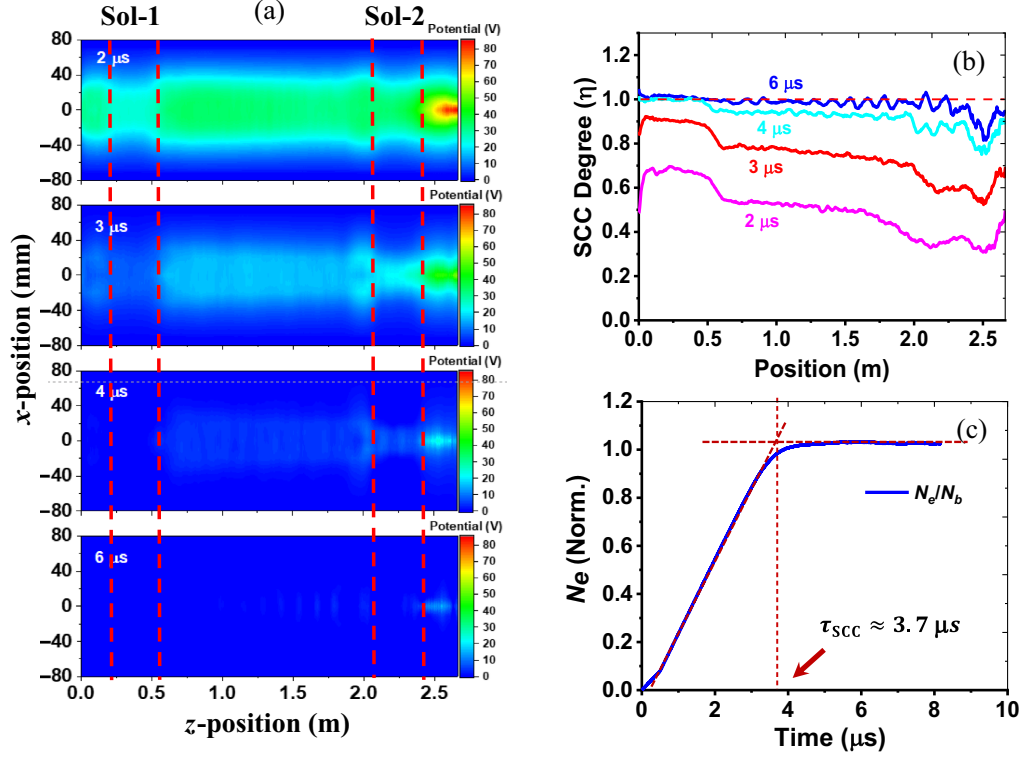


FIG. 4. For 5×10^{-5} Torr nitrogen gas (a) Potential map along the LEBT at various time steps (2, 3, 4, and 6 μs), (b) SCC degree along the LEBT line at different time steps, and (c) Temporal evolution of total number of electrons normalized to the total beam ions.

dynamics are primarily governed by the rates of ionization and electron trapping.

The transient development of SCC for a representative case with Nitrogen at 5×10^{-5} Torr is shown in Fig. 4. The potential maps [Fig. 4(a)] indicate a progressive reduction in the beam potential as electrons accumulate. This neutralization occurs more rapidly within the solenoid regions, where stronger magnetic confinement enhances electron trapping efficiency.

The on-axis beam potential is extracted to compute the SCC degree (η) as a function of time and longitudinal position [Fig. 4(b)]. The results demonstrate that compensation builds up nonuniformly along the LEBT. Specifically, the strong magnetic focusing downstream of the second solenoid locally increases the charge density, thereby raising the potential and requiring a longer duration to reach full neutralization compared to upstream sections.

The total electron population, normalized to the primary beam ions, reaches a steady-state value after $\sim 3.7 \mu s$ [Fig. 4(c)], marking the stabilization of the system. The physical significance of τ_{SCC} is clearly visible across Figs. 4(a)–4(c). While there is a significant reduction in beam potential and a rapid rise in η between 2, 3, and 4 μs , these parameters show negligible change after the 3.7 μs saturation point. The profiles at $t = 6 \mu s$ are nearly identical to those at 4 μs , confirming that the system has entered a stable steady-state plateau. This identifies τ_{SCC} as

the precise boundary between the transient buildup and the stable compensation regime.

However, in experimental conditions, directly measuring the total ionization electron density is challenging. Therefore, SCC time is often inferred indirectly from the temporal evolution of the primary beam size. Figure 5(a) shows that at $t = 0$ (uncompensated), the beam size and emittance are 41.5 mm and 0.62π mm mrad, respectively. As SCC develops, the beam size decreases and eventually saturates at 30.3 mm, coinciding with the τ_{SCC} value identified in Fig. 4(c). The “fall time” of the beam size is frequently adopted in the literature as an estimate for τ_{SCC} [21–23]. The small initial rise in beam size corresponds to the time taken for the beam to fully establish and reach the end of the LEBT before the onset of significant compensation.

In this work, a new, direct approach is used to estimate the SCC time from the electron signal measured using a transverse particle monitor [32]. Figure 5(b) displays the simulated electron current (I_e) and total current ($I_e + I_i$) collected by the probe. The monitor signal reaches its minimum exactly when the SCC process stabilizes [in Figs. 4(c) and 5(a)], providing a reliable, minimally invasive metric for determining the true buildup time without relying on indirect beam-profile-based methods.

The identification of the PMP signal minimum as the characteristic τ_{SCC} is justified by its synchronization with the beam’s physical stabilization. As shown in Fig. 5(b),

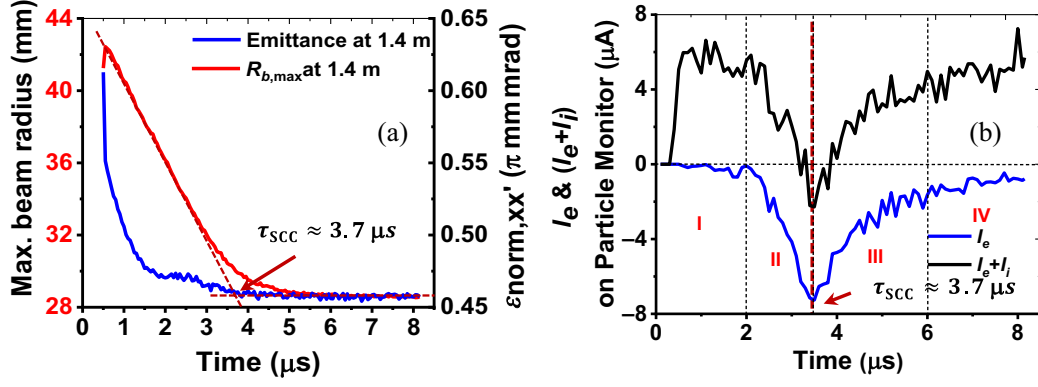


FIG. 5. (a) Change in beam size (left y axis) and emittance (right y axis) with time at a fixed position, and (b) Typical electron current (I_e) and total current ($I_e + I_i$) on particle monitor with time.

this minimum coincides with the point where the normalized electron population reaches saturation [Fig. 4(c)], and the beam-size contraction saturates [Fig. 5(a)]. This confirms that the saturation of the noninterceptive probe signal is a reliable proxy for the transition to a steady-state compensated regime. To ensure a reproducible extraction, τ_{SCC} is defined as the vertex of a local parabolic fit applied to the signal minimum.

The electron signal peak at the transverse probe location is somewhat counterintuitive, as ions are typically expected near the beam pipe. However, at the onset of SCC, ionization electrons possess higher energies, allowing them to reach the probe. This behavior can be used to determine SCC time. To analyze the temporal structure of the probe signal, the evolution of the normalized electron current is divided into four regions [Fig. 5(b)]: (I) Region I ($0 < t < 2 \mu\text{s}$):

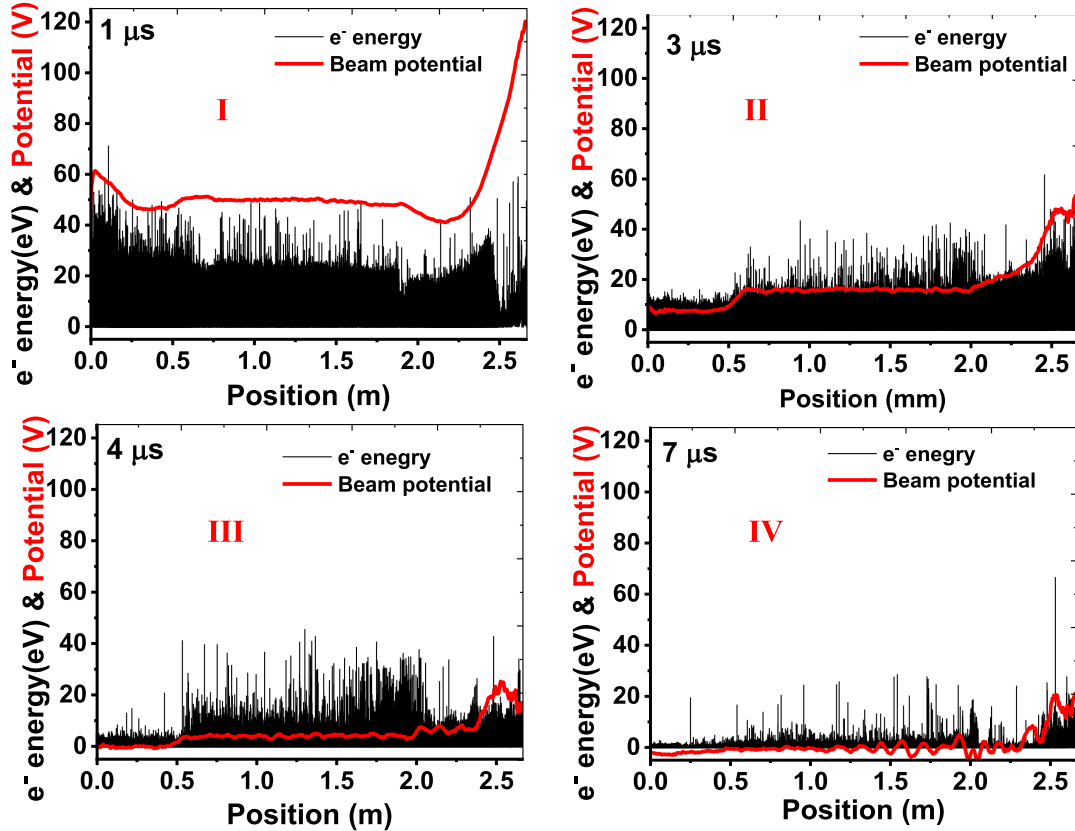


FIG. 6. Electron energy and the beam potential along the beamline is plotted at (I) 1 μs , (II) 3 μs , (III) 5 μs , and (IV) 7 μs , corresponding to the four different regions.

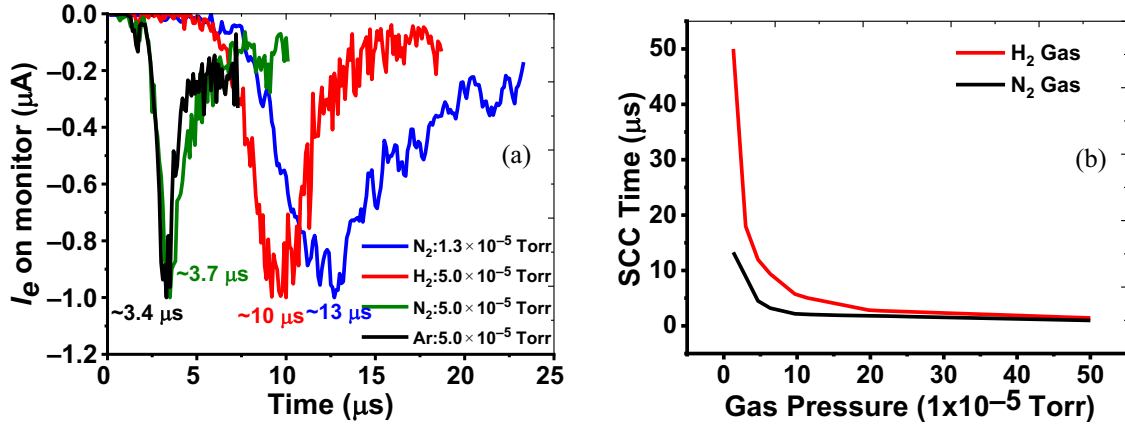


FIG. 7. (a) Temporal variation of normalized electron current on transverse probe for different gases (Ar, N_2 , and H_2) at a fixed pressure (5×10^{-5} Torr) and N_2 at different pressures (5×10^{-5} Torr and 1.3×10^{-5} Torr), and (b) SCC time variation with gas pressure for N_2 and H_2 gases.

Precompensation phase with negligible electron signal. (2) Region II ($2 \mu s < t < 3.7 \mu s$): Rapid rise in electron signal, indicating the onset of SCC as ionization electrons accumulate. (3) Region III ($3.7 \mu s < t < 6 \mu s$): Declining electron signal, indicating the final transient of the SCC process. (4) Region IV ($t > 6 \mu s$): Saturated electron signal, corresponding to a steady-state compensation level.

Figure 6 presents the evolution of the ionization electron energy and the beam potential along the beamline for each of these regions. In region I ($1 \mu s$), although the average electron energy is relatively high, it remains insufficient to overcome the confining beam potential, preventing electrons from reaching the probe. In regions II and III (at 3 and 5 μs , respectively), both the beam potential and electron energy decrease; however, the electron energy remains higher than the beam potential, allowing a significant number of electrons to escape and be detected by the probe, resulting in the peak signal. The subsequent decline in the signal reflects the reduction in electron energy, which lowers the number of electrons capable of reaching the probe. By the end of region III, the beam potential nearly vanishes, marking the quasi-completion of the transient compensation phase. In region IV (at 7 μs), although the electron energy further decreases, the beam potential remains close to zero. Consequently, at this stage, only a small fraction of low-energy electrons possesses sufficient energy to reach the probe, and this fraction remains nearly constant over time, leading to a stable, saturated probe signal.

Thus, the signal measured on the transverse particle monitor provides a reliable means of determining the SCC time, with the added advantage that this diagnostic approach can be implemented in practice without perturbing the primary beam. Its nonintrusive nature also ensures that no extra secondary electrons are produced in the beamline, avoiding any effect on the SCC time. Based on this approach, further simulation studies are performed

to examine how various physical and operational parameters affect the SCC process. In particular, the influence of compensating gas type and pressure on both the SCC time and the degree of compensation is analyzed. The effect of the solenoid magnetic field on the SCC time is also investigated. Additionally, the dependence of SCC dynamics on primary beam parameters such as beam current, rise time, and the presence of multiple ion species is systematically studied.

C. Compensating gas species and pressure

The rate of compensation buildup is highly sensitive to the properties of the background gas. Figure 7(a) presents the electron signal for different gas species at a fixed pressure of 5×10^{-5} Torr. For this fixed pressure, the analytical times are 9.62 μs (H_2), 3.26 μs (N_2), and 3.03 μs (Ar), which are in close agreement with our simulation results of 10.2, 3.7, and 3.4 μs , respectively. The marginal increase in simulation values is due to the inclusion of electron kinetic effects and escape probabilities, which are not accounted for in the simplified analytical scaling.

Furthermore, Fig. 7(a) demonstrates that for N_2 , reducing the pressure to 1.35×10^{-5} Torr increases the SCC time, as the lower gas density results in a reduced frequency of ionization events.

To study this further, Fig. 7(b) shows the variation of SCC time with gas pressure for H_2 and N_2 . It is observed that the SCC time is longer for H_2 compared to N_2 , and that it decreases with increasing gas pressure for both cases. The increase in SCC time at lower pressures is mainly due to reduced ionization rates, which slow down the compensation process since fewer gas molecules are available to produce secondary electrons. Beyond a certain pressure, the SCC time tends to level off, indicating an optimal pressure range where further increases have little effect. This behavior mainly results from two competing effects:

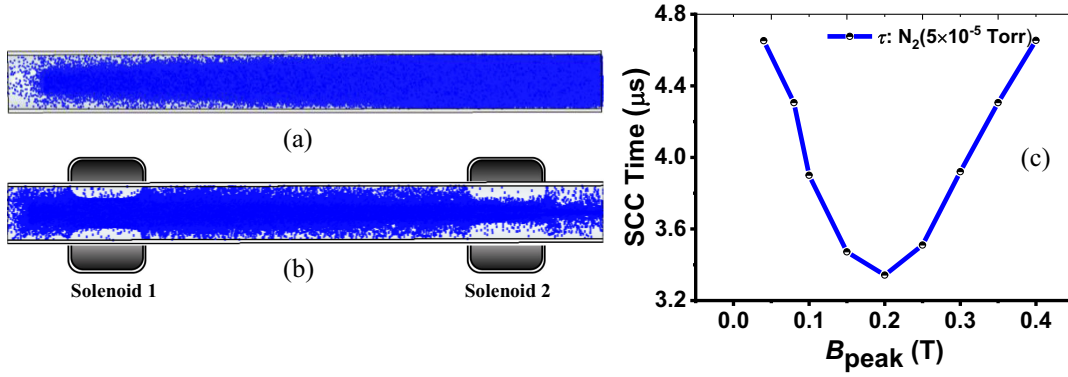


FIG. 8. Electron density profile (a) without magnetic field, (b) with magnetic field, and (c) the variation of SCC time with solenoid-1 fields.

the finite beam rise time and the time required for the beam to fully develop along the line, and the increased scattering of the primary beam by compensating gas ions at higher pressures. For gas pressures above $\sim 1 \times 10^{-3}$ Torr, scattering becomes strong enough to cause significant beam losses before the beam reaches the end of the LEBT.

D. Solenoidal magnetic field

In the LEBT, solenoidal magnetic fields are essential for the efficient transport of the beam from the ion source. This section analyzes the impact of these magnetic fields on the SCC process. The presence of a magnetic field affects SCC dynamics by altering both the spatial distribution of the trapped electrons and the depth of the beam's space-charge potential [33]. As shown by the electron density in Figs. 8(a) and 8(b), confinement is clearly tighter near the solenoids compared to the unmagnetized drift regions.

The resultant interplay of these magnetic effects is revealed by plotting the SCC time against the magnetic field strength, as shown in Fig. 8(c). This simulation study focuses on the first ~ 1.5 m of the LEBT, isolating the effect of Solenoid 1. The initial decrease in SCC time with increasing field strength can be attributed to the transition from a diffuse electron cloud to a tightly confined on-axis accumulation. At very low fields, the wide, underfocused beam results in a diffuse electron distribution, requiring more time to build up sufficient local charge density to achieve on-axis neutralization. As the field increases to an optimum level, the magnetic force efficiently compresses the lighter ionization electrons into the beam core, rapidly neutralizing the space charge and minimizing τ_{SCC} .

However, beyond this optimum field strength, the stronger focusing effect becomes detrimental. The beam becomes overfocused, creating a tight transverse waist that significantly deepens the localized space-charge potential. Furthermore, the severe convergence and subsequent rapid divergence of the beam envelope physically disrupt stable electron trapping, leading to increased radial electron loss. Consequently, the SCC time increases again, resulting in a

nonmonotonic trend that is fundamentally driven by the transition from diffuse electron accumulation to optimal confinement and ultimately limited by the disruptive dynamics of beam overcompression.

E. Beam parameters: Rise time and current

Rise time (T_{rise}) is the time that primary beam is taking to reach the full current; the relationship between T_{rise} and τ_{SCC} is a critical factor in pulsed beam dynamics. When $T_{\text{rise}} \ll \tau_{\text{SCC}}$, the SCC process remains relatively simple; however, when T_{rise} is comparable or more than the τ_{SCC} , the process becomes more complex. For cases with higher T_{rise} , the neutralization process begins during the transient phase of the beam, when the current is still ramping up. As a result, neutralization and beam formation occur simultaneously, leading to a delayed onset of full compensation. This overlap complicates the understanding of the compensation process.

Figure 9 shows that for a sharp rise time of 1 ns, τ_{SCC} is ~ 3.7 μs , whereas a slower rise time of 4 μs extends this to ~ 5.8 μs . The reduced electron current at the probe during slower rise times is attributed to the lower instantaneous beam current, which generates fewer ionization events during the transient phase. Nevertheless, the final steady-state SCC degree converges to a similar value regardless of the rise time, suggesting that the ultimate compensation level is largely independent of the initial ramp.

The effect of primary beam current is also evaluated for values of 2.5, 5, and 10 mA. As shown in Figs. 10(a) and 10(b), both the SCC time and the SCC degree remain remarkably stable across different current levels. While higher currents generate more ionization electrons, they also create a deeper potential well requiring more charge for neutralization. These effects scale proportionally, which is consistent with the analytical definition of τ_{SCC} in Eq. (2), where the beam current is not an explicit parameter.

F. Multispecies beam composition

In practical operation, ECR ion sources produce a mixture of ionic species, primarily H^+ and H_2^+ . To

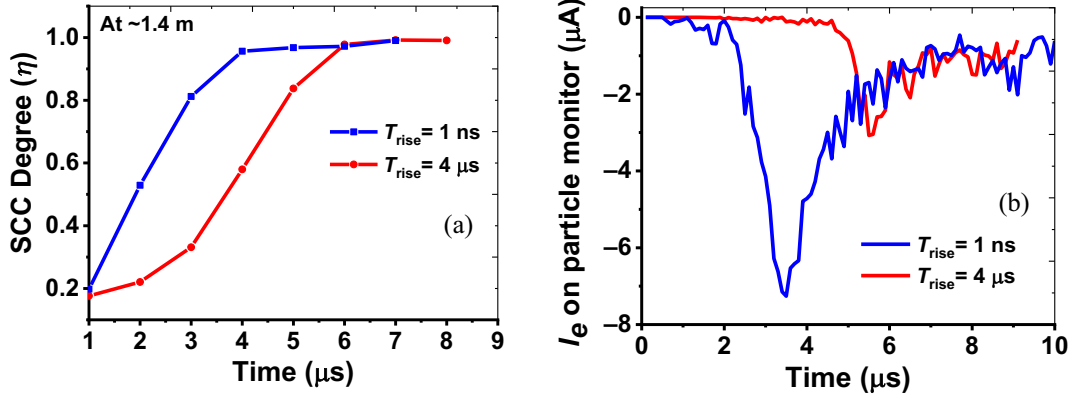


FIG. 9. For beam rise times of 1 ns and 4 μs , the temporal evolution of (a) the SCC degree at the longitudinal particle monitor, and (b) the electron current (I_e) measured on the transverse particle monitor.

evaluate their impact on SCC dynamics, PIC-MCC simulations are performed using a composite 10 mA beam (5 mA H^+ and 5 mA H_2^+) at 50 keV. Both species are assigned identical transverse phase-space distributions based on tomographic reconstruction data. Due to the availability of ionization and elastic collision cross-sections data for H_2^+ projectiles, hydrogen (H_2) is utilized as the compensating gas for this study [31]. To ensure significant transmission, the Solenoid-1 field is increased to 0.2 T, providing sufficient focusing for both species.

Figure 11 compares the SCC evolution for a pure H^+ beam against the multispecies beam in the presence of 5×10^{-5} Torr H_2 gas. The results indicate that the presence of H_2^+ slightly extends the effective SCC buildup time from 10.2 to 10.9 μs as compared to a pure H^+ beam. While the inclusion of H_2^+ introduces additional inter-species space-charge interactions, the resulting change in the SCC buildup time and final neutralization degree is not significant.

G. Contribution of ion-induced secondary electron emission (SEE)

In addition to gas ionization, the SCC process can be influenced by secondary electrons produced when the primary beam strikes the metallic vacuum chamber walls or the beam diagnostics [25]. To quantify this, simulations are performed assuming a secondary electron yield (SEY) of 1.0 for the stainless steel (SS-304) pipe under 50 keV proton impact. While specific experimental data for 50 keV H^+ on SS-304 is not available to our knowledge, an SEY of 1.0 represents a conservative exhaustive limit based on its primary constituents (Fe, Cr, and Ni) [34,35].

Figure 12 shows the temporal evolution of the normalized electron number (N_e/N_b), which serves as a global figure of merit for the compensation state; as N_e/N_b reaches saturation, it signifies the system has reached a steady state.

At low gas pressure ($< 1 \times 10^{-3}$ Torr), the probability of primary proton scattering is negligible. Consequently,

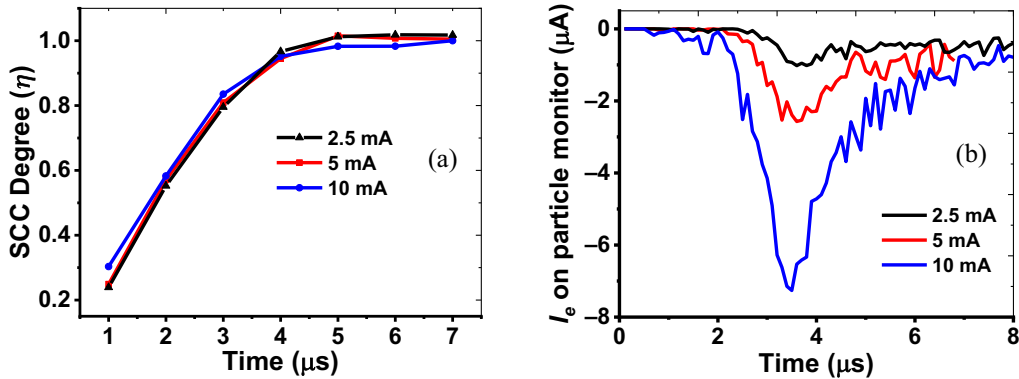


FIG. 10. For beam currents of 2.5, 5, and 10 mA: temporal evolution of (a) the SCC degree at the longitudinal particle monitor, and (b) the electron current (I_e) measured on the transverse particle monitor.

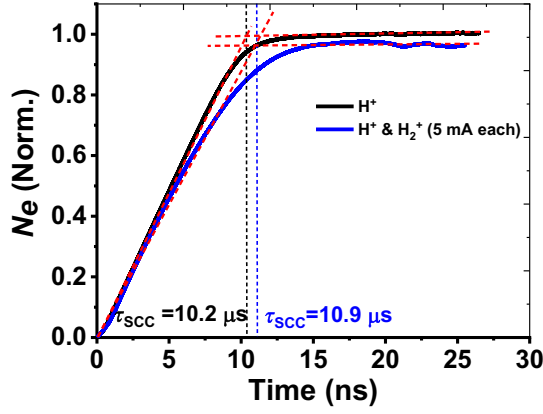


FIG. 11. Temporal evolution of the normalized electron population (N_e/N_b) for a pure H^+ beam (black) and a multispecies $H^+ + H_2^+$ beam (blue) in 5×10^{-5} Torr H_2 . The extracted τ_{SCC} values are 10.2 and 10.9 μs , respectively.

the primary beam core does not contribute significantly to SEE. In our simulation, the surfaces configured to produce SEE are the beam pipe walls and peripheral diagnostic housings (PMP and RFA). The particles striking these surfaces are limited to a highly diffuse fractional beam halo and the slow, secondary residual gas ions that are radially expelled by the space-charge potential. Because the incident flux of these halo/secondary particles is exceptionally small, the overall contribution of SEE to the core plasma remains negligible, even with the aggressive $SEY = 1.0$ assumption. Simulation results confirm that under these specific vacuum conditions, the contribution of wall-generated secondary electrons to both the SCC time constant and the final neutralization degree is negligible compared to the dominant role of direct gas ionization. The SEE can be significant with the introduction of intrusive beam diagnostics, which is not covered in this work.

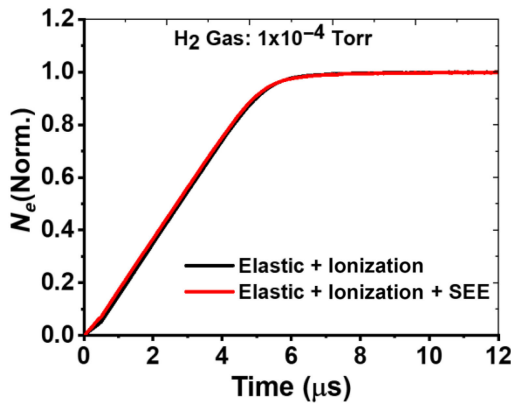


FIG. 12. Temporal evolution of normalized N_e in the beamline with (black) and without (red) inclusion of secondary electron emission from the beam pipe in the simulation calculations, for 1×10^{-4} Torr H_2 gas.

H. Considerations for experimental comparison

While the PIC-MCC model accurately captures the fundamental physics and scaling of SCC, the simulation represents an idealized baseline. In a practical LEBT environment, factors such as the finite beam rise time, continuous electron loss mechanisms (e.g., thermal escape over the potential barrier), and the presence of residual background gas mixtures are expected to extend the absolute SCC buildup time beyond the idealized theoretical limit. Furthermore, the longitudinal pressure gradients inherent in the experimental setup may cause local vacuum gauge readings to differ from the average gas density actually experienced by the beam. These real-world effects, which account for the quantitative shifts observed in the experimental data, are discussed in further detail in Sec. V C.

V. EXPERIMENTAL CHARACTERISATION OF SCC DYNAMICS

A. SCC diagnostics development

To experimentally characterize the transient behavior and steady-state parameters of the beam-induced plasma in the LEHIPA LEBT, three specialized diagnostic systems have been developed and deployed: the particle monitor probe (PMP), the retarding field analyzer (RFA), and the multigrid beam profiler. These instruments are designed to provide high temporal and spatial resolution and sensitive detection of the low-density beam-induced plasma with minimal perturbation to the primary proton beam.

1. Particle monitor probe (PMP)

Based on the analysis of the transverse monitor in the PIC-MCC simulations (Sec. IV B), the particle monitor probe (PMP) is utilized to experimentally characterize the SCC time. While the fundamental design and operational principles of the PMP are detailed elsewhere [32], this work employs an upgraded version with a significantly faster response time.

Briefly, the device consists of an isolated copper disc [50 mm diameter, 2 mm thick, *cf.* Fig. 13(a)] mounted at the periphery of the beam pipe. Its transverse orientation allows it to monitor the flux of ionization products without intercepting the 10 mA proton beam, thereby preserving beam quality and preventing thermal damage to the probe. The probe signal is transmitted to the Digital Storage Oscilloscope (DSO) using a high-bandwidth (26 GHz) semirigid SMA cable. The key features utilized for this study include (i) *Temporal resolution*: The probe allows for precise detection of rapid SCC onset, with a response time of ~ 1.3 ns. Time domain reflectometry characterization confirms this performance, showing a 10%–90% signal rise time of ~ 1.3 ns in Fig. 13(a). (ii) *Nonintrusive operation*: Positioning the probe at the periphery of the beam pipe ensures that negligible secondary electrons are generated, which could otherwise perturb the SCC process. (iii) *Signal*

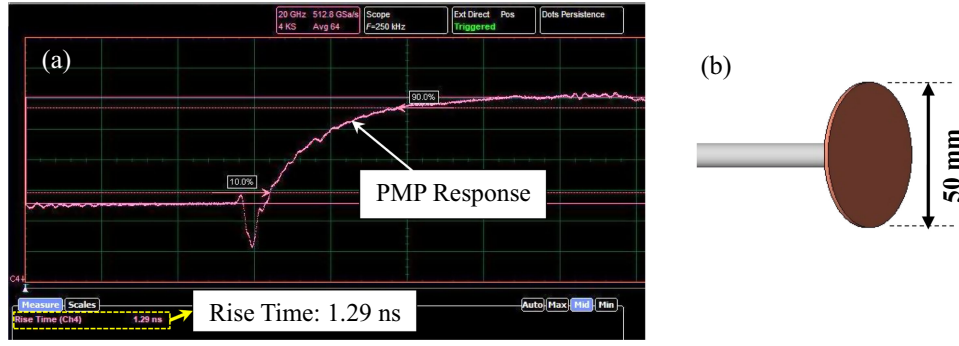


FIG. 13. (a) Time domain reflectometry (TDR) plot of PMP. Rise time of the PMP probe signal is indicated within the dashed yellow box. Time base: 780 ps/div and vertical scale: 16 mV/div. (b) 3D model of the PMP probe head.

processing: The PMP provides a direct electrical readout processed through a high-bandwidth current-to-voltage converter [Femto DHCPA-100], ensuring a high signal-to-noise ratio even in low-density plasma environments.

The mechanical design of the PMP head is shown in Fig. 13(b).

To ensure high temporal resolution and signal integrity, waveforms are acquired using a 3 GHz Digital Storage Oscilloscope (DSO, R&S RTO2034). Typical PMP signal, recorded on the DSO, is shown in Fig. 14 for two cases: with and without the introduction of compensating gas. A pronounced dip is observed in the presence of gas, indicating the onset of SCC. This dip corresponds to the rapid accumulation of low-energy electrons generated through ionization of the compensating gas, which neutralize the beam's space charge.

For the measurement, data acquisition is performed with a time window of 5 μ s/div. To mitigate the primary sources of experimental uncertainty, specifically, high-frequency electromagnetic interference (EMI) and pulse-to-pulse statistical beam fluctuations from the ion source, the diagnostic signals are routed through high-shielding, semi-rigid rf cables (Huber Suhner EZ_141) and acquired using a ten-pulse waveform averaging mode on the DSO.

This combination of hardware shielding and signal averaging yields stable, low-noise waveforms.

The SCC time is extracted from the PMP signal using the same methodology described in Sec. IV B for the analysis of the electron current signal from the transverse particle monitor. In this signal, the time when the PMP signal reaches its minimum is taken as τ_{SCC} .

2. Multigrid retarding field analyzer (RFA)

The RFA is employed to determine the SCC degree (η) by measuring the energy distribution of ions repelled from the beam core. Since ionization ions are created within the beam's potential well under a collisionless regime (10^{-4} – 10^{-5} Torr), they gain kinetic energy equivalent to the local potential at the point of creation as they move toward the grounded wall. Given that the initial thermal energy of these ions is negligible compared to the beam potential, and the probe is located in a field-free drift region to minimize sheath distortions, the measured ion energy serves as a direct measurement of the on-axis compensated beam potential (ϕ_c). The potential obtained from the RFA can be used to estimate the compensation efficiency using Eq. (1).

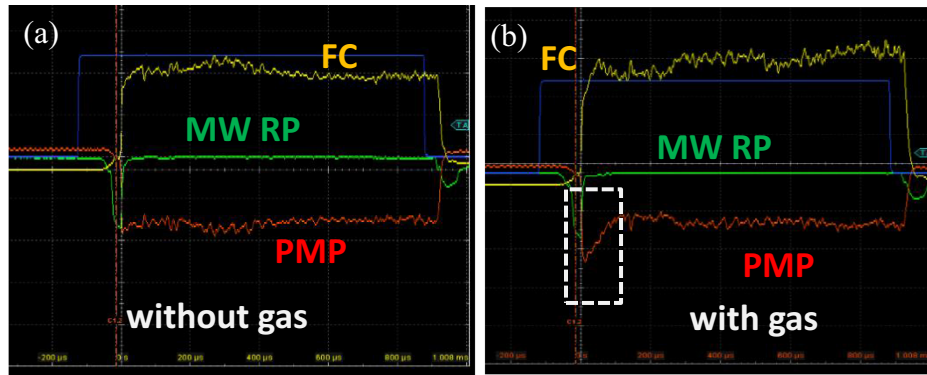


FIG. 14. DSO signal (a) without and (b) with compensating gas consisting of FC (Faraday cup), MW RP (microwave reflected power), and PMP (particle monitor probe).

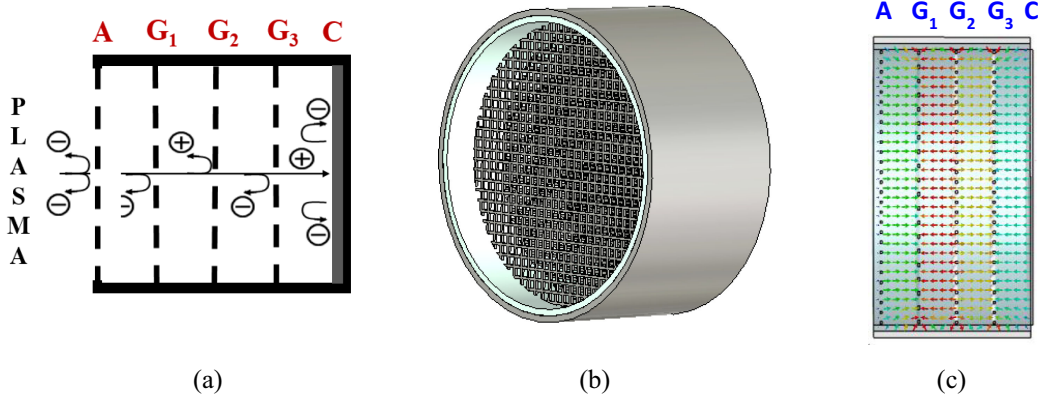


FIG. 15. (a) 2D schematic, (b) CST model, and (c) electric field lines between the grid plates of the designed multigrid retarding field analyzer.

The RFA is mounted perpendicularly to the beamline with a well-defined entrance aperture to selectively sample ions with purely radial trajectories. As shown in Fig. 15, the assembly consists of an entrance mesh aperture (A), three retarding grids (G_1 – G_3), and a collector plate (C). Designed and validated with the CST Particle Tracking Solver, the geometry ensures a high geometric transparency of $> 90\%$ (defined as the ratio of open mesh area to total grid area). This high transparency allows for sufficient particle flux from the low-density plasma while maintaining effective species discrimination. To achieve this, the grids are biased as follows: Grid G_1 : (i) Biased negatively to repel plasma electrons while focusing ions toward the collector. (ii) Grid G_2 : Serves as the variable retarding potential barrier for energy analysis. (iii) Grid G_3 : Biased negatively to suppress secondary electron emission from the collector, preventing measurement errors.

Under SCC conditions, the beam produces a low-density plasma composed of compensating gas ions and electrons, primarily H^+ , H_2^+ , and e^- for H_2 compensating gas. In the simulations, three representative sources: protons, H_2^+

ions, and electrons, are modeled with energies in the range of 5–15 eV and a total current of $\sim 1 \mu A$, consistent with PIC-MCC simulation results of the steady-state SCC plasma.

Ideally, the RFA should have a small entrance aperture to limit the angular spread of incoming ions and electrons. However, because the SCC plasma in the LEBT is of low density, the entrance is designed as a mesh plate to allow sufficient particle flux for measurable signals. The influence of particle energy spread ($\Delta E = 0$ –5 eV) and angular spread ($\Delta\theta = 0$ – 25°) on RFA performance is analyzed from the collector current response.

The final design parameters of the RFA are listed in Table III. Figures 16(a) and 16(b) present the variation of the collector current with the retarding grid (G_2) potential when the aperture, G_1 , G_3 , and collector are biased at 0, -15 , -10 , and 0 V, respectively. The negatively biased G_1 prevents plasma electrons from entering the RFA probe; its potential magnitude is chosen to exceed the typical electron energy, while also assisting the transmission of compensating gas ions into the probe. The variable potential on G_2

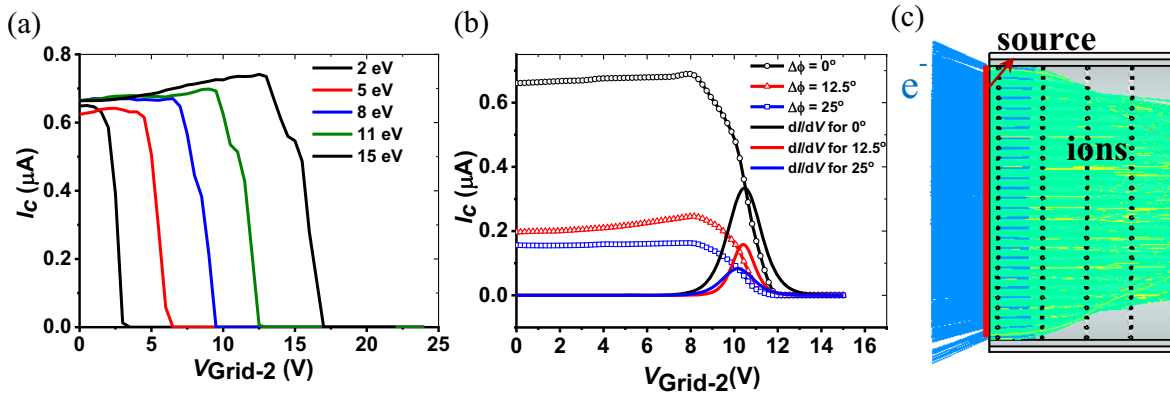


FIG. 16. Collector current with change in variable potential for (a) varying source energy, (b) varying angular spread, and (c) particle trajectory inside the probe; electron (blue) is getting reflected due to G_1 potential, ions (green/yellow) above 5 eV are reaching the collector plate.

TABLE III. RFA design specifications.

RFA parameters	Value
Grid plate spacing	2.5 mm
Grid transparency	>90%
Probe head diameter	25 mm
Probe head length	28 mm

establishes the retarding field, allowing only ions with kinetic energy greater than the applied potential to reach the collector. A negative bias on G_3 suppresses secondary electron emission, thereby minimizing errors in the measured collector current.

The simulated ion and electron trajectories inside the RFA for a G_2 potential of 5 V are shown in Fig. 16(c). For a 10 eV source energy, the -15 V bias on G_1 effectively blocks electron entry, while ions with energy above 5 eV reach the collector. In the absence of applied biases, the overall grid transparency exceeds 95%, and the electric field lines between successive grids remain uniform, showing only minor distortion near the aperture boundaries in Fig. 15(c).

From the collector current characteristics, the ion energy distribution is obtained, with the derivative (dI/dV) representing the energy distribution function, as shown in Fig. 16(a). As the ion energy increases, the dI/dV peak shifts toward higher potentials, consistent with energy scaling. For a 10 eV source, the influence of angular spread between 0° and 25° is shown in Fig. 16(b). With increasing angular spread, the transmission efficiency decreases, and the dI/dV curve broadens, but the mean energy remains close to 10 eV. This confirms that the RFA accurately determines ion energies even with a relatively large angular acceptance due to its mesh entrance. Furthermore, an energy spread without angular divergence does not significantly affect the dI/dV spectrum, indicating that the mean ion energy remains unchanged.

Probe transparency is further examined by rotating one of the grids relative to the others around the probe axis to

study the effect of internal grid-wire misalignment. As shown in Fig. 17(a), the transparency decreases from about 97% to 56% with a 5° rotation of the first grid and remains above 54% for all subsequent rotation angles. These results confirm that the RFA maintains adequate transparency for reliable characterization of low-density plasmas in the LEBT. Finally, based on this design, a multigrid RFA is developed and installed in the LEHIPA LEBT; a 3D model of the same is shown in Fig. 17(b).

Experimentally, a typical collector plate signal from the RFA, recorded for a given set of grid potentials, is shown in Fig. 18(a). As the retarding grid potential is progressively varied, the ion current (represented as the RFA voltage) decreases, enabling the construction of the I - V characteristic. The initial dip in the RFA signal is due to the onset of SCC, a similar behavior is also observed in the PMP. Neglecting this negative transient signal for steady-state measurement, the average of the RFA signal is taken as the collector current for each configuration. Since the RFA is positioned in a field-free drift region to minimize sheath distortions, the measured ion flux accurately reflects the beam-induced potential. For a potential of 0, -50 , -50 , and 0 V on A, G_1 , G_3 and C, respectively, a representative I - V curve obtained for varying G_2 potential is shown in Fig. 18(b). The increased bias of -50 V on G_1 and G_3 is optimized to effectively suppress secondary electron emission and eliminate baseline offsets from stray electrons. Differentiating the I - V data yields the dI/dV curve, which corresponds to the energy distribution of the detected ions. Because the ionization rate peaks at the beam axis, where the primary density is highest, the peak of this distribution provides the peak ion energy representing the full axis-to-wall potential. While the absolute cutoff represents the theoretical maximum potential, extracting the peak provides a significantly more statistically robust measurement that is less susceptible to instrumental noise. This peak energy for this particular example provides the compensated beam potential ϕ_c (~ 15 V), which is then used to determine the SCC degree using Eq. (1) for know ϕ_0 (from simulation).

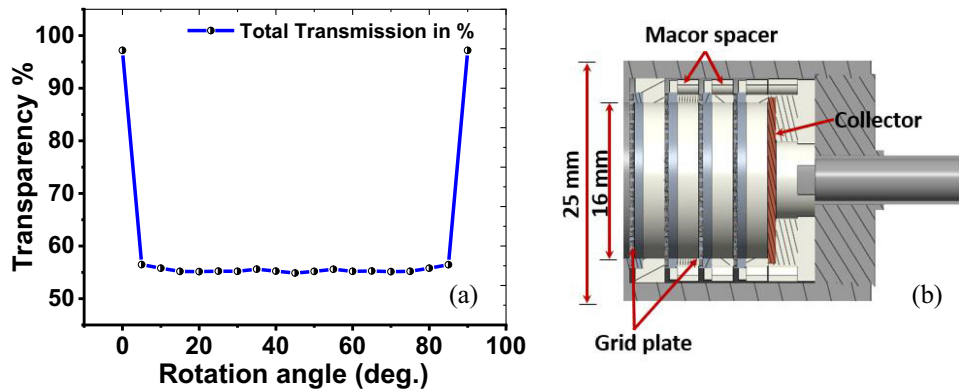


FIG. 17. (a) Probe total transparency with rotation angle of grid-1, and (b) CST model of the RFA probe head.

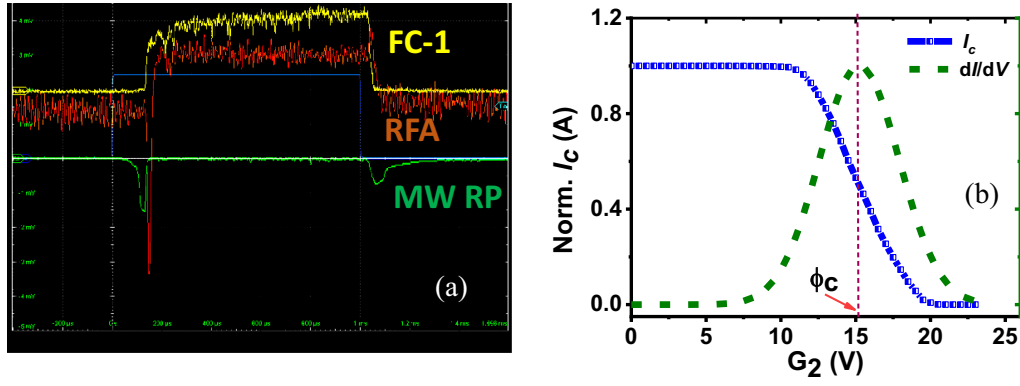


FIG. 18. (a) Typical DSO trace showing the RFA collector signal along with the Faraday cup (FC) and microwave (MW) reflected signals, and (b) Typical I - V characteristic extracted from the DSO plot along with the dI/dV curve to evaluate ϕ_c .

3. Beam profiler

To study the impact of SCC on transverse beam properties, a multiwire beam profiler (MWP) has been installed downstream in the LEBT. It consists of 33 parallel wires, each approximately $80\ \mu\text{m}$ thick, arranged with 3 mm spacing across a $100 \times 100\ \text{mm}^2$ active area, as shown in its 3D drawing in Fig. 19(a). These wires are connected to four 8-channel relay boards, enabling sequential readout of beam-induced currents. Typical beam profile measured using the multiwire is shown in Fig. 19(b). The interface consists of an upper plot depicting the real-time beam pulse (time-indexed by sample number) and a lower plot showing the integrated beam profile. The latter visualizes intensity as a function of wire position for all 33 channels. To improve spatial resolution, the entire assembly is mounted on a motorized linear actuator, allowing the profiler to be

translated across the beam path in mechanical increments smaller than the wire pitch.

All the SCC diagnostics, including the PMP, RFA, and beam profilers, along with the existing beam diagnostics, are installed in the LEHIPA LEBT, as described in the following section.

B. SCC diagnostic assembly

Figure 20 presents the 3D model of the LEHIPA LEBT, highlighting the placement of the beam and SCC diagnostics. Figure 21 shows the installation photograph of the SCC diagnostic assembly, which includes the RFA and PMP, in the LEBT Diagnostics Chamber-1 shown in Fig. 20. These diagnostics are used sequentially to study the SCC process, ensuring that their measurements do not interfere with each other.

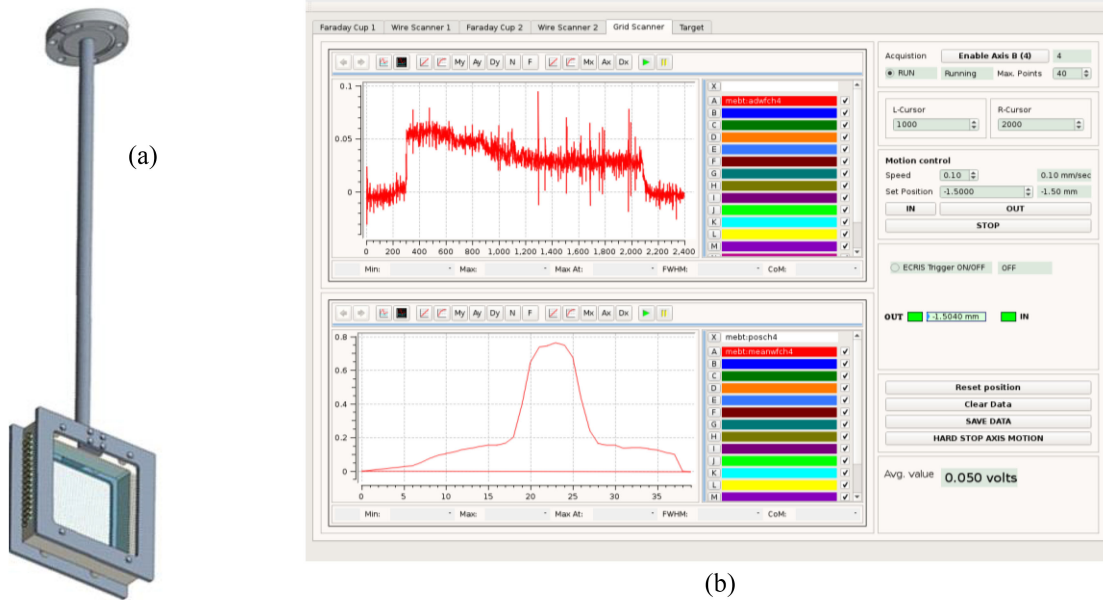


FIG. 19. (a) 3D drawing of the MWP and (b) typical beam profile on the GUI.

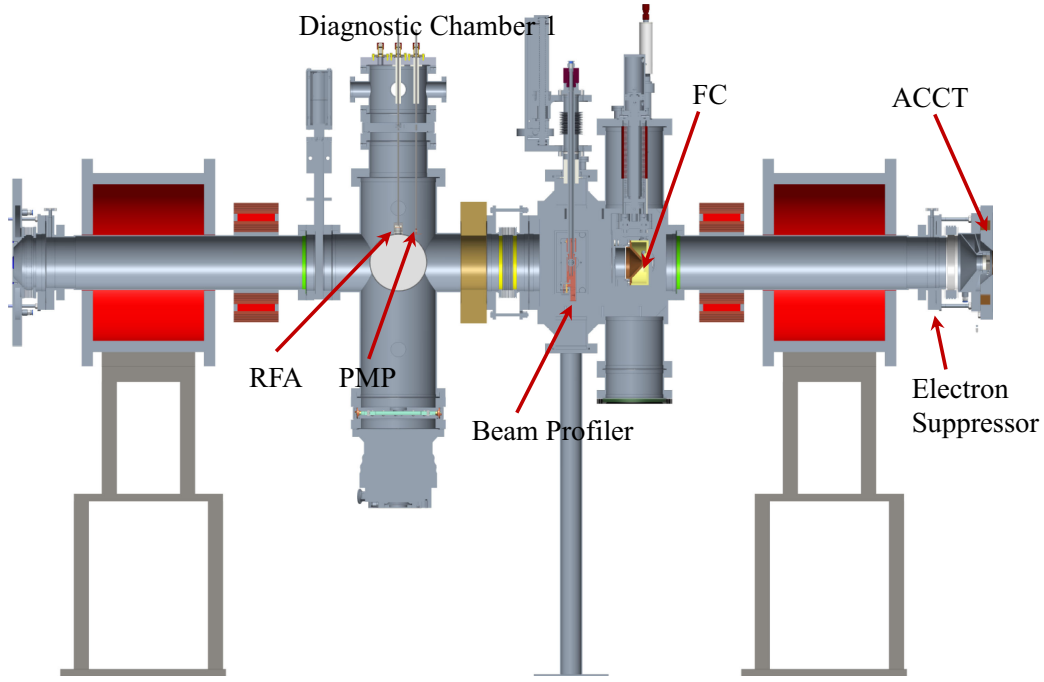


FIG. 20. Cut view of the LEHIPA LEBT, showing the diagnostics assembly.

Detailed experimental results for varying gas types and varying gas pressures are explained in the following section.

C. Experimental results and discussion

The SCC time in the LEHIPA LEBT is measured for different gases over a range of gas pressures and solenoid field strengths. As shown in Fig. 22, the SCC time

decreases with increasing gas pressure for all gases studied, and the gas pressure to reach the minimum SCC time is lower for Ar and highest for H_2 gas. This behavior results from enhanced ionization rates at higher pressures, which increase the density of compensating electrons and thus reduce the time required for space-charge neutralization. Hydrogen, having a relatively low ionization cross section at 50 keV, exhibits a longer SCC time compared to argon and nitrogen at lower pressures. In contrast, argon and nitrogen, with their higher ionization cross sections, achieve faster compensation even at lower gas pressures. A similar trend is observed in the simulation results shown

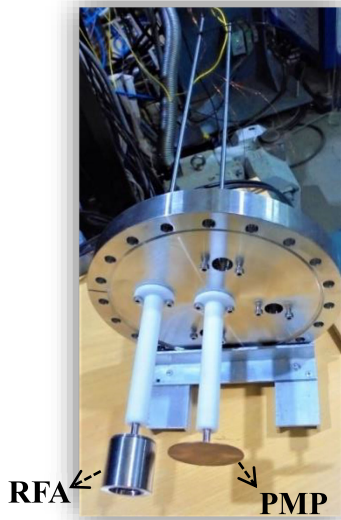
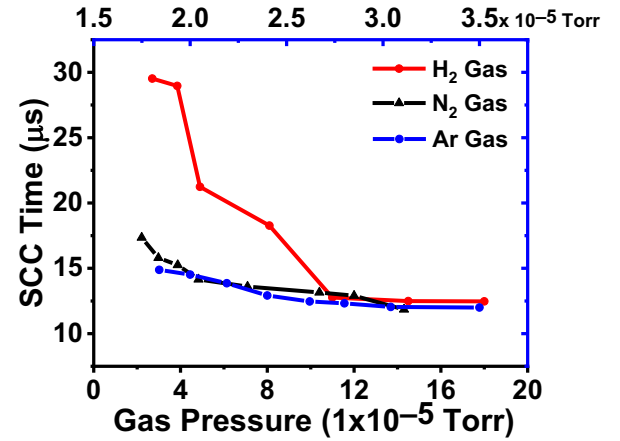


FIG. 21. Photograph of the SCC probes installed in diagnostic chamber-1 in the LEHT.

FIG. 22. SCC time variation with variation in compensating gas pressure for H_2 (red), N_2 (black), and Ar (blue) gases; the abscissa for Ar is shown at the top.

in Fig. 7(b), where the SCC time for H_2 is also longer than that for gases with higher ionization cross sections. Beyond a certain pressure, the SCC time approaches saturation for all gases, while further pressure increase during the experiment leads to noticeable beam quality degradation due to enhanced scattering and charge-exchange processes.

A minimum SCC time of $\sim 12.5 \mu s$ is observed in the experimental results, which is significantly higher than the values shown in Fig. 7(b). This difference can be primarily attributed to the following factors: (i) Finite beam rise time: The SCC time cannot be shorter than the beam's current rise time, as it inherently includes this contribution. This explanation is consistent with the simulation results presented in Sec. IV E, which shows a clear increase in the measured SCC time for beams with longer rise times. (ii) Electron loss mechanisms: These processes, which are unavoidable in experiments, are not accounted for in the simulations. The loss of electrons due to recombination or escape to the beamline walls leads to a longer effective SCC time for all gases and pressure conditions. (iii) Presence of background gas: In simulations, only a single gas species is considered for studying the SCC process. However, in the actual beamline, residual hydrogen from the ECR ion source is always present, even when another gas is introduced. This background gas alters the effective ionization dynamics and contributes to the longer SCC times observed experimentally. (iv) Longitudinal pressure gradient: While most contemporary SCC simulations utilize a uniform gas distribution for computational efficiency and to establish clear physics scaling [9,10,14–18], the experimental LEBT features localized gas injection and discrete pumping. The resulting pressure profile, governed by the system's conductance, implies that the effective average density experienced by the beam may differ from the local gauge readings. This nonuniformity contributes to the discrepancy in absolute τ_{SCC} values while the simulation maintains the correct functional dependence on pressure.

The variation of SCC time with LEBT solenoid field for different gases at selected pressures is shown in Fig. 23. The observed trend aligns with the behavior discussed in Sec. IV D: the SCC time decreases at lower solenoid currents as the beam is more effectively confined and ionization electrons are better trapped within the beam potential. Beyond an optimal solenoid current, further beam compression increases the local space-charge potential, thereby requiring more ionization to achieve neutralization and leading to a rise in SCC time. This nonmonotonic behavior is consistent with simulation predictions and confirms the balance between improved confinement and overcompression in determining SCC dynamics.

Furthermore, the SCC degree, characterized at the Diagnostic Chamber-1 location, is shown in Fig. 1. The η values are calculated using Eq. (1), where ϕ_c is the RFA-measured potential and ϕ_0 is the uncompensated on-axis beam potential at the RFA location (~ 71 V) determined

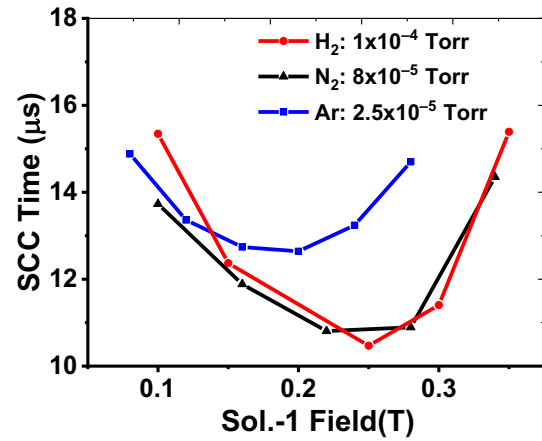


FIG. 23. SCC time variation with variation in LEBT Solenoid-1 field, for different types of compensating gases.

from the numerical simulations in Sec. IV using the experimental beam parameters. For experiments with argon as the background gas, G_1 is biased at -50 V to repel electrons, G_2 is swept over a range of voltages to filter ions by kinetic energy, and G_3 is biased at -50 V to suppress secondary electrons. The resulting I - V curve for Argon [Fig. 24(a)] is numerically differentiated to obtain the ion energy distribution, from which the compensated beam potential ϕ_c is extracted. At the RFA location, ~ 1 m from the beamline entrance, the SCC degree for argon is about 0.96. This $\sim 4\%$ deviation from the simulated steady state ($\eta = 1$) is attributed to electron heating and escape mechanisms, where high-energy ionization electrons overcome the potential well, preventing total neutralization.

The SCC degree is also measured for hydrogen at two different gas pressures. It is observed that, with increasing hydrogen pressure, the SCC degree remained comparable to that obtained for argon. The normalized collector current as a function of G_2 voltage, along with its derivative, is presented in Fig. 24(b). This behavior indicates that the lower ionization cross section of hydrogen results in a longer SCC buildup time; however, once a sufficient gas density is reached, the final SCC degree at the probe location remains nearly unchanged. In addition, it can be noted that with an increase in compensating gas flow rate, the potential is further reduced.

Furthermore, to investigate the influence of SCC on the primary beam, transverse beam profiles are measured using beam profilers. With solenoid 1 set to 80 A (~ 0.16 T), beam profiles are recorded at various gas flow rates (expressed in sccm), as shown in Fig. 25. The results show that increasing the gas pressure leads to a reduction in beam size and a transition toward a more Gaussian-like profile. This occurs as space-charge neutralization reduces the internal repulsive forces, which otherwise distort the beam into a flatter or hollow-centered profile. Beyond a flow rate of ~ 6 sccm, the beam profile reaches an optimum condition.

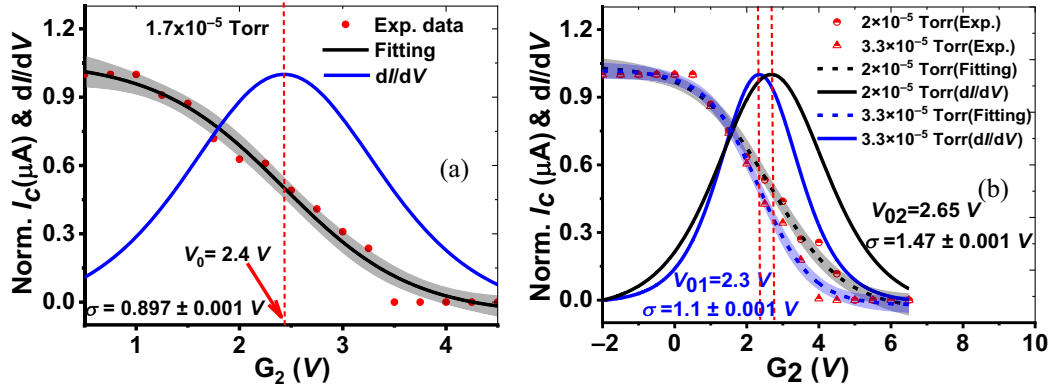


FIG. 24. I - V characteristics and corresponding dI/dV energy distributions for (a) Ar gas, and (b) two different gas pressures of H_2 gas.

Ideally, under uniform gas distribution and negligible electron losses, once SCC equilibrium is established, the beam size at the probe assembly location should remain independent of gas pressure. However, since the beam profiler is positioned ~ 370 mm downstream of the probe assembly, toward the RFQ side, where electron losses are more significant, complete compensation is not achieved at lower pressures. These profiles are recorded during the beam pulse flattop, after the SCC has reached steady state. The observed discrepancy between experiment and simulation arises largely from the latter's assumption of a uniform background gas. In practice, the vacuum conductance and localized pumping speeds create a pressure profile that modifies the ionization density along the beamline. While the uniform model correctly predicts the functional scaling of SCC with pressure, the localized gas density at the diagnostic location determines the specific buildup dynamics. Therefore, an optimum gas pressure is necessary to maintain a uniform neutral gas density and achieve effective SCC. Increasing the gas pressure beyond this

optimum does not further enhance beam quality; instead, excessive pressure leads to additional beam losses due to increased scattering. This measurement also gives an idea of the optimum gas flow rate during accelerator operation.

VI. CONCLUSION

This study provides a comprehensive characterization of SCC dynamics in the LEHIPA LEBT through a rigorous combination of PIC-MCC simulations and experimental measurements. By utilizing a diagnostic suite consisting of an indigenous particle monitor probe (PMP), a retarding field analyzer (RFA), and a multiwire profiler, we have successfully correlated internal plasma evolution with macroscopic beam behavior. The PMP, validated as a fast, noninvasive diagnostic, accurately identified the SCC buildup time (τ_{SCC}) by detecting ionization electrons at the beam periphery, while the RFA provided direct measurements of the compensated beam potential. Experimental results indicated that near-complete neutralization ($\eta \approx 96\%$) is achieved for both argon and hydrogen gases, with measured values of approximately 12 μs for argon and 30 μs for H_2 at 3×10^{-5} Torr.

Both simulations and experimental data confirmed that the compensation timescale is primarily governed by the ionization cross section of the background gas and the ambient pressure. Significantly, the investigation revealed a nonmonotonic dependence of on the solenoidal magnetic field, highlighting a critical competitive balance between improved electron confinement and increased space-charge density due to beam focusing. While the experimental SCC time is found to be fundamentally limited by the finite beam rise time and residual background gas effects, the final degree of compensation remained largely independent of the beam current once steady-state equilibrium is reached. Furthermore, simulations incorporating elastic scattering and secondary electron emission (SEE) confirmed that wall-generated electrons have a negligible impact on the

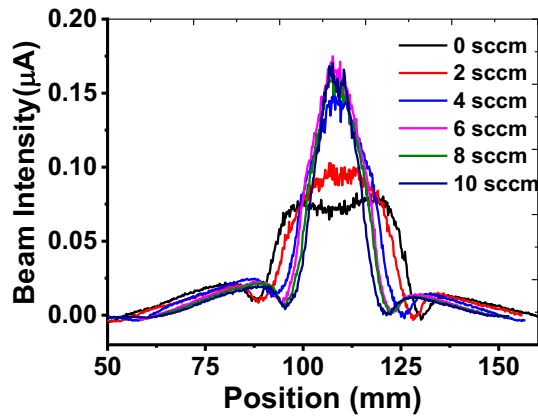


FIG. 25. Beam profile at profiler location with variation in gas pressure for nitrogen gas.

compensation process at typical LEBT operating pressures ($< 10^{-3}$ Torr). These findings establish a robust, validated methodology for optimizing high-intensity proton beam transport and designing future injectors for ADS and spallation neutron sources.

ACKNOWLEDGMENTS

The authors thank Dr. Srinivas Krishnagopal, Dr. Olli Tarvainen, and Dr. Dan Faircloth for their invaluable technical discussions. The authors also thank Mr. U. D. Malshe for his support and Dr. Romesh Chandra for his assistance with the CST simulations.

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: DERIVATION OF THE SCC PARAMETERS

1. Space-charge compensation degree (η)

To derive the relationship between electrostatic potential (ϕ) and the degree of compensation (η), we solve Poisson's equation in cylindrical coordinates for a beam of radius R_b inside a grounded conducting pipe of radius R_p :

$$\nabla^2 \phi(r) = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi}{\partial r} \right) = -\frac{\rho_{\text{net}}}{\epsilon_0}. \quad (\text{A1})$$

Assumptions: (1) The beam is infinitely long with cylindrical symmetry ($\partial/\partial z = 0, \partial/\partial \theta = 0$). (2) The potential is relative to the grounded beam pipe: $\phi(R_p) = 0$. (3) Secondary ions are repelled to the grounded wall, and their transient density is negligible in the steady-state potential. (4) For a uniform beam of density n_b and trapped electron density n_e , the net charge density is $\rho_{\text{net}} = e(n_b - n_e)$ for $r \leq R_b$ and $\rho = 0$ for $R_b < r < R_p$. (5) The spatial distribution of trapped electrons follows that of the primary beam. We assume n_e follows the same transverse distribution as n_b , such that $\rho_{\text{net}} = e.n_b(1 - \eta)$ where $\eta = n_e/n_b$.

Integrating Eq. (A1) twice with these conditions, the on-axis potential ($r = 0$) is:

$$\phi(0) = \frac{e.n_b(1 - \eta)R_b^2}{4\epsilon_0} \left[1 + 2 \ln \left(\frac{R_p}{R_b} \right) \right] \quad (\text{A2})$$

For an uncompensated beam ($\eta = 0$), the potential is ϕ_0 . For a compensated beam, it is ϕ_c . Taking the ratio ϕ_c/ϕ_0 from Eq. (A3) results in:

$$\frac{\phi_c}{\phi_0} = 1 - \eta \Rightarrow \eta = 1 - \frac{\phi_c}{\phi_0}. \quad (\text{A3})$$

2. SCC time constant (τ_{SCC})

The accumulation of compensating electrons is governed by the ionization rate equation. The rate of change of the electron density n_e is given by

$$\frac{dn_e}{dt} = n_b.n_g.\sigma_i(E).\beta c. \quad (\text{A4})$$

Assumptions: (1) The neutral gas density (n_g) and primary beam density (n_b) remain constant throughout the ionization process. (2) Electron loss mechanisms (such as longitudinal drift or recombination) are negligible during the initial buildup phase. (3) Only primary ionization is considered; secondary ionization by trapped electrons is ignored. The SCC time constant, τ_{SCC} , is defined as the theoretical time required for the accumulated electron density to equal the primary beam density ($n_e = n_b$) under the zero electron loss condition. Integrating Eq. (A4) with these conditions gives:

$$n_e(t) = \int_0^t n_b.n_g.\sigma_i(E).\beta c dt' = n_b.n_g.\sigma_i(E).\beta c.t. \quad (\text{A5})$$

Setting $n_e(\tau_{\text{SCC}}) = n_b$ and solving for τ_{SCC} :

$$\tau_{\text{SCC}} = \frac{1}{n_g.\sigma_i(E).\beta c}. \quad (\text{A6})$$

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