

Suppressing emittance growth via ion cloud traps in low-energy beam transport

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(Received 20 January 2026; accepted 19 September 2026; published 7 October 2026)

Space-charge compensation is routinely used to mitigate emittance growth in linear accelerator beam transport lines. Severe space-charge effects and incomplete compensation within low-energy beam transport sections universally induce beam divergence and emittance degradation, constituting a key bottleneck for low-energy, high-intensity beams. This work investigates the evolution of residual-gas-generated secondary-ion clouds under applied electric fields and their impact on primary beam emittance growth. By implementing barrier electrodes to confine the secondary-ion cloud, we achieve substantial reductions in both the emittance and beam radius of an H^- beam while preserving full beam intensity. The proposed ion cloud trap scheme also has important implications for neutral beam injection in magnetic confinement fusion and high-current ion implanters, providing insights into low-energy charged particle transport across diverse ion-beam platforms.

DOI: [10.1103/hrgq-mrtk](https://doi.org/10.1103/hrgq-mrtk)

I. INTRODUCTION

Low-energy, high-density ion beams play an important role in frontier physics research and accelerator-based industrial applications. Typical scenarios include the front-end systems of high-energy particle accelerators [1–3], neutral beam injection (NBI) systems for magnetic confinement fusion devices [4,5], and high-current ion implantation equipment for semiconductor manufacturing [6,7]. In such low-energy, high-intensity beam systems, strong mutual repulsion between charged particles significantly leads to a rapid increase in beam divergence and emittance [8]. This decline in beam quality results in undesired beam loss, decreased transmission efficiency, and heightened radiation levels, imposing significant constraints on the performance and dependability of accelerators [9]. Hence, effective mitigation of beam divergence and emittance growth is imperative for optimizing the operation of various low-energy, high-intensity ion-beam systems.

Once a low-energy, high-intensity ion beam is extracted from an ion source, it propagates through the beam pipe and is matched to the subsequent accelerating structure. Taking high-intensity H^- beams as an example, interactions between the beam and residual gas molecules inside the pipe trigger beam-induced gas ionization, generating abundant secondary ions and free electrons [10,11]. During negative hydrogen beam transport, heavy positively charged secondary ions such as H_2^+ cannot escape the beam potential well and remain

stably trapped within the beam envelope. In contrast, light electrons exhibit high mobility and are rapidly expelled from the beam region by the beam self-field. The accumulated positive secondary ions partially cancel the negative self-space-charge field of the primary H^- beam, constituting the core physical mechanism of space-charge compensation (SCC) [12,13]. At a background gas pressure around 1 mPa and with no external electric field, a timescale of tens of microseconds is needed to establish a steady-state secondary-ion cloud for SCC [14,15]. Benefiting from SCC, the net space-charge force inside low-energy beams is substantially reduced. As the space-charge compensation degree (SCCD) rises, the net beam self-field weakens, suppressing nonlinear beam distortion and significantly mitigating beam divergence and emittance growth.

Common approaches for improving SCCD of low-energy, high-current ion beams include additional gas injection [16–18] and direct introduction of compensating particles [19,20]. As the most prevalent auxiliary compensation scheme, additional gas injection artificially raises the residual gas density inside the pipe. The increased collision frequency between the beam and gas molecules generates a greater population of positive secondary ions within the beam volume, enhancing neutralization of the negative beam self-field and elevating the overall SCC degree. Nevertheless, this method inevitably introduces notable adverse effects on beam transmission and quality, including stripping loss and enhanced beam-gas scattering. In contrast, direct injection of compensating particles can enhance SCC without gas-induced beam degradation. This approach, however, is rarely implemented, as it demands sophisticated hardware and encounters considerable engineering design challenges.

Although auxiliary gas injection can yield a reasonably high overall SCCD, the established compensating ion cloud can be rapidly expelled from the beam region within hundreds of nanoseconds under an external electric field exceeding the

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beam space-charge potential by one order of magnitude. This rapid loss of the ion cloud leads to locally vanished space-charge neutralization. Even ion clouds far from the high-field region undergo axial depletion as they replenish the escaping ions, thereby further reducing the overall SCCD [21,22]. Prior work has proposed various electrode geometries to restrict the motion of compensating particles and suppress ion cloud leakage. Representative examples include repeller electrodes for fringe-field shielding in fusion NBI ion sources [23,24], positively biased barrier electrodes for ion confinement in accelerator low-energy beam transport (LEBT) systems [25], and electron-blocking electrodes for ion source protection [26]. Nevertheless, most existing studies remain limited to numerical simulations and qualitative experimental validation. A quantitative characterization of the dynamic evolution of the ion cloud under external electric fields, as well as its actual effectiveness in controlling emittance growth, is still lacking.

In this paper, experiments and numerical simulations are combined to investigate the negative effects of electric fields on space-charge compensation. An electric field-shaping strategy is proposed to confine secondary ions, thereby maintaining high-quality beam transport in the LEBT. The transverse field generated by the chopper is first quantitatively examined for its disruption of localized SCC and the consequent emittance growth. During H^- beam transport, a local axial potential well is further observed to induce more extensive SCC deterioration, accompanied by severe emittance degradation. To address this issue, barrier electrodes are innovatively employed to tailor the axial potential and effectively confine secondary ions. The proposed theoretical analysis and hypotheses are finally validated through numerical simulations. Importantly, the barrier-electrode scheme enables simultaneous optimization of beam emittance and preservation of beam current—a distinct advantage over conventional gas injection methods, which inherently introduce additional beam loss.

II. EXPERIMENTAL SETUP

Experiments were conducted on the newly designed LEBT line for Phase II of the China Spallation Neutron Source (CSNS-II) [27]. Figure 1(a) shows the CSNS-II LEBT experimental platform. The H^- beam is extracted from a cesiated rf-driven ion source [28,29], capable of delivering an H^- beam current exceeding 60 mA with exceptional stability, exhibiting less than 1.1% rms fluctuation over a one-month period. The entire ion source is mounted on a negatively biased high-voltage platform. By adjusting the extraction voltage, H^- beams of varying intensities can be produced and subsequently accelerated to around 50 keV by a grounded electrode. Two solenoids are employed to focus the beam and match its transverse phase space to the acceptance of the downstream radio-frequency quadrupole (RFQ) accelerator.

As shown in Fig. 1(a), a static electric beam chopper, featuring two sloped deflecting plates, was designed and installed at the end of the LEBT to impose a temporal structure on the beam pulse synchronized with the rapid cycling synchrotron. A bending magnet located upstream of Solenoid 2 deflects the primary H^- beam and protons (produced via residual gas stripping) by 1.8° in opposite directions. This

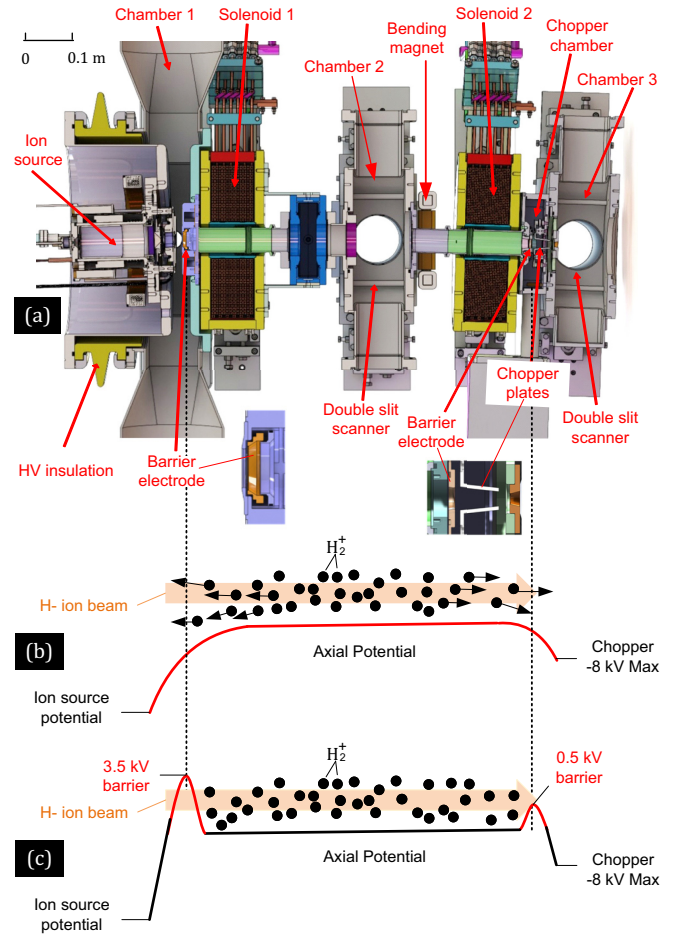


FIG. 1. (a) Experimental setup of the CSNS-II LEBT test stand. Key components and beam diagnostic equipment are indicated by red arrows. (b) Axial potential distribution along the LEBT beam line without the barrier electrode. (c) Axial potential distribution along the LEBT beam line with positively biased barrier electrodes.

configuration successfully removes over 99% of the stripped protons, significantly reducing beam loss and protecting the subsequent superconducting linac sections [27]. In the present measurements, the RFQ was replaced by Chamber 3, in which a metal circular plate with a 9 mm entrance aperture was installed to shield the fringe field from the chopper. Both Chamber 2 and Chamber 3 were equipped with beam diagnostics, including current transformers (CTs) and double-slit emittance scanners. Each double-slit scanner featured two precisely machined slits of 0.1 mm width. Systematic measurements showed that the beam transmission from Chamber 2 to Chamber 3 was approximately 90%, depending on the ion source gas flow rate and the optimization of beam optics parameters.

Two ring-shaped barrier electrodes are positioned immediately downstream of the ground electrode and upstream of the chopper electrodes, with their locations indicated by red arrows in Fig. 1(a). Their primary function is to axially confine the secondary H_2^+ ion cloud by modifying the axial electric potential along the H^- beam line in the LEBT, as illustrated in Figs. 1(b) and 1(c). When the barrier electrodes are grounded, the H_2^+ ions are allowed to drain axially out of the confinement

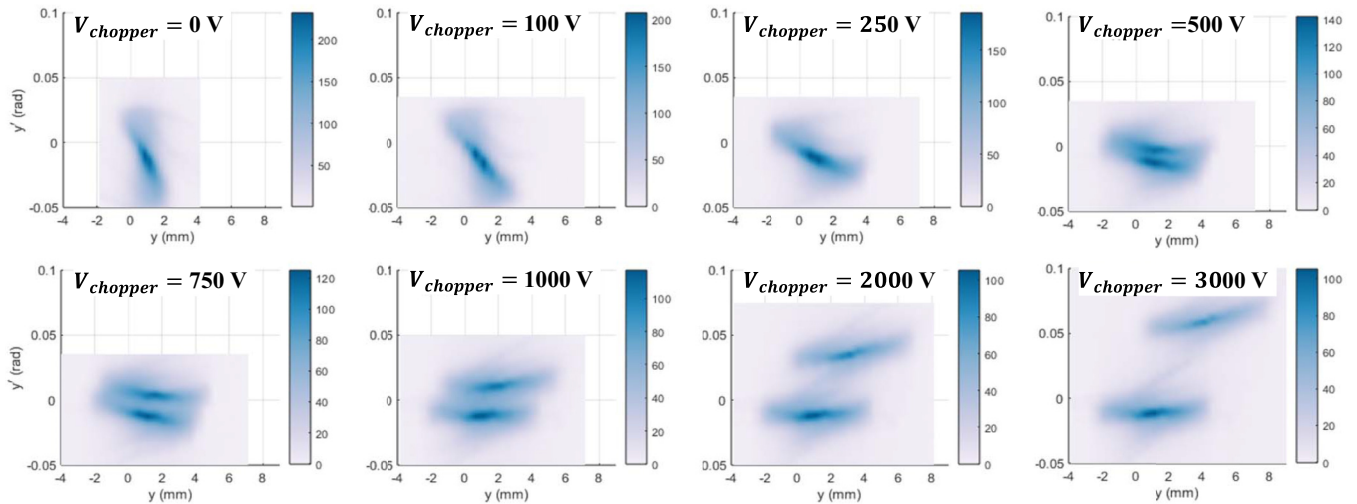


FIG. 2. Measured y - y' phase space of the H^- ion beam after chopping, with a 1.02 MHz square-wave voltage applied at a 50% duty cycle. The double-slit measurements were performed in Chamber 3 without the metal shield behind the chopper plates.

region. Conversely, when a positive bias is applied to the barrier electrodes, the H_2^+ ions become radially confined by the space-charge potential of the H^- beam and simultaneously confined axially by the potential barrier created by the biased electrodes. Under this condition, the secondary ions become effectively trapped within the beam line.

III. SCC DESTRUCTION BY ELECTRIC FIELD

An electrostatic beam chopper in the LEBT is employed to generate a pulsed H^- beam by deflecting a portion of the beam outside the acceptance of the RFQ. To study the SCC destruction caused by the transverse electric field of the chopper, the beam phase space is immediately measured by the double slit (y direction) in Chamber 3. In the experiment, the chopper operates with one plate grounded and the other biased to a pulsed positive high voltage at an off/on frequency of 1.02 MHz. Figure 2 shows the phase-space evolution of a 32 mA H^- beam as the chopper voltage is increased from 0 to 3000 V. Following the removal of the metal shielding plate, the double-slit measurement distinctly differentiates between the deflected and undeflected beams. As the voltage increases, the deflected beam separates from the primary beam, accompanied by the evolution in the Twiss parameters of the primary beam as a result of the gradually disrupted SCC. Particularly for voltages exceeding approximately 1000 V, the phase-space distortion of the undeflected beam stabilizes, indicating that the SCC near the plates is nearly fully destroyed.

As the chopper voltage is increased even more (e.g., exceeding 5000 V), the deflected beam becomes entirely distinct from the primary beam in phase space. This separation enables the calculation of the emittance of the primary beam without any disturbances from the deflected component. With one plate grounded, the other chopper plate can be biased to either a positive or negative high voltage, corresponding to the positive-chopper and negative-chopper configurations, respectively. Since the chopper chamber is at ground potential, the electric field near the high-voltage electrode is

stronger. Consequently, H^- ions passing in the vicinity of the high-voltage electrode experience a larger deflection angle, as shown in Fig. 3(a). In the negative-chopper configuration, the H^- ions that require a larger deflection angle are precisely those traversing the region of a stronger electric field. This characteristic renders the negative chopper more effective at deflecting the beam outside the RFQ acceptance ellipse or even outside the RFQ front-end plate. Numerical simulation evidenced that the negative-chopper deflected beam with a larger deflected angle and position, as shown by Fig. 3(b). In addition, Faraday cup measurements observed steeper rising and falling edges of the chopped beam under the negative-chopper case, which also indirectly validates the simulation results. Detailed results are not presented here, as they fall beyond the scope of this paper.

Since the secondary H_2^+ ion cloud requires tens of microseconds to accumulate but dissipates within hundreds of nanoseconds under the transverse electric field of the chopper, SCC cannot be established in the vicinity of the chopper plates. Consequently, the space-charge effect dominates emittance growth during beam transport through the chopper field region. However, experimental results show that the negative chopper induces significantly greater emittance growth. As illustrated in Fig. 4, the beam emittance measured with the negative chopper is 0.28π mm mrad, corresponding to a 60% increase relative to the no chopper case. Under the same conditions with the positive chopper, the emittance growth remains below 20%. This observation suggests that the negative axial potential leads to more severe degradation of SCC.

To investigate the influence of the chopper electric field in more detail, a biased dc voltage instead of a square-wave voltage was applied to the upper chopper plate, while the lower plate was grounded. The applied dc voltage is limited to make the entire beam deflected by a small angle without increased beam loss on the metal shield plate. Compared to the square-wave voltage waveform, no effort is required to separate the deflected and undeflected beam components, particularly beneficial at low voltages. Figures 5(a) and 5(b) show the phase-space evolution for the barrier electrode under

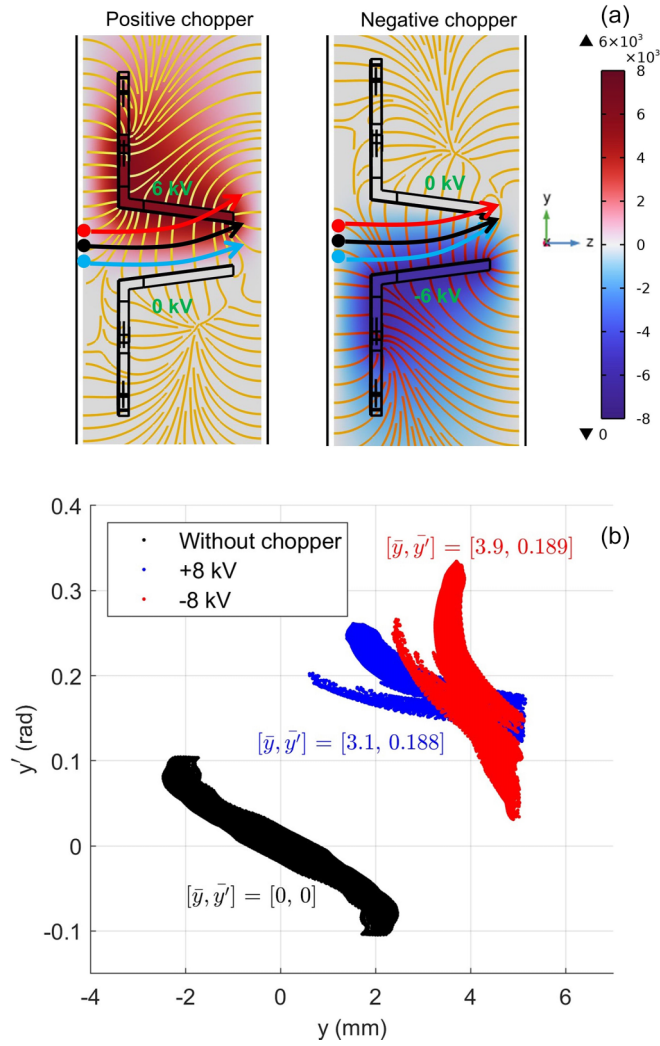


FIG. 3. (a) Schematic of the deflected H^- beam using positive and negative choppers. (b) Simulated phase space at the RFQ entrance for three cases: without chopper, +8 kV chopper, and -8 kV chopper.

positive and negative applied voltages, respectively. As the applied voltage increases, the changes in beam phase-space distributions suggest a change in beam focus during transmission. Figure 5(c) presents the emittance measurements with both positive and negative applied voltages; it is found that negative applied voltages always cause larger emittance growth than positive applied voltages. The findings further confirm that negative voltage can cause a wider range of SCC disruption. When a positive voltage is applied to the chopper plate, H_2^+ ions in its immediate vicinity are driven either toward the opposite grounded plate or upstream to regions of lower electric potential. As a result, SCC in other parts of the LEBT remains largely unaffected. In contrast, applying a negative voltage not only causes local H_2^+ ions to be absorbed by the electrode but also leads to axial depletion of H_2^+ ions generated farther from the chopper, as these ions migrate to replenish those lost near the electrode. This process can trigger widespread disruption of SCC throughout the beam line.

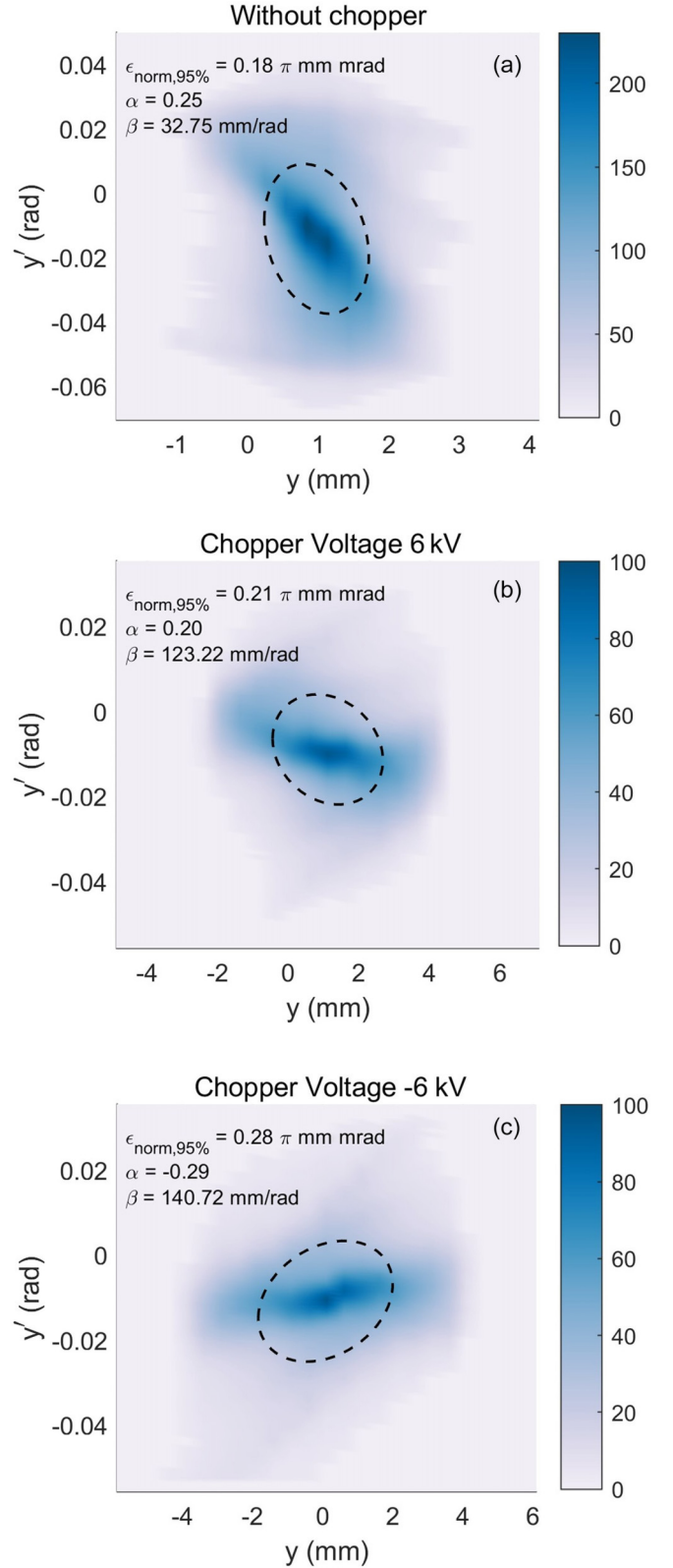


FIG. 4. Measured y - y' phase space of the H^- ion beam with the metal shield installed behind the chopper plates. (a) Beam with no chopper voltage applied. (b) Chopped beam with a +6 kV chopper voltage. (c) Chopped beam with a -6 kV chopper voltage. The Courant-Snyder parameters and the normalized rms emittance (5%-halo-removed rms emittance) are annotated. The black dashed lines represent the rms ellipses.

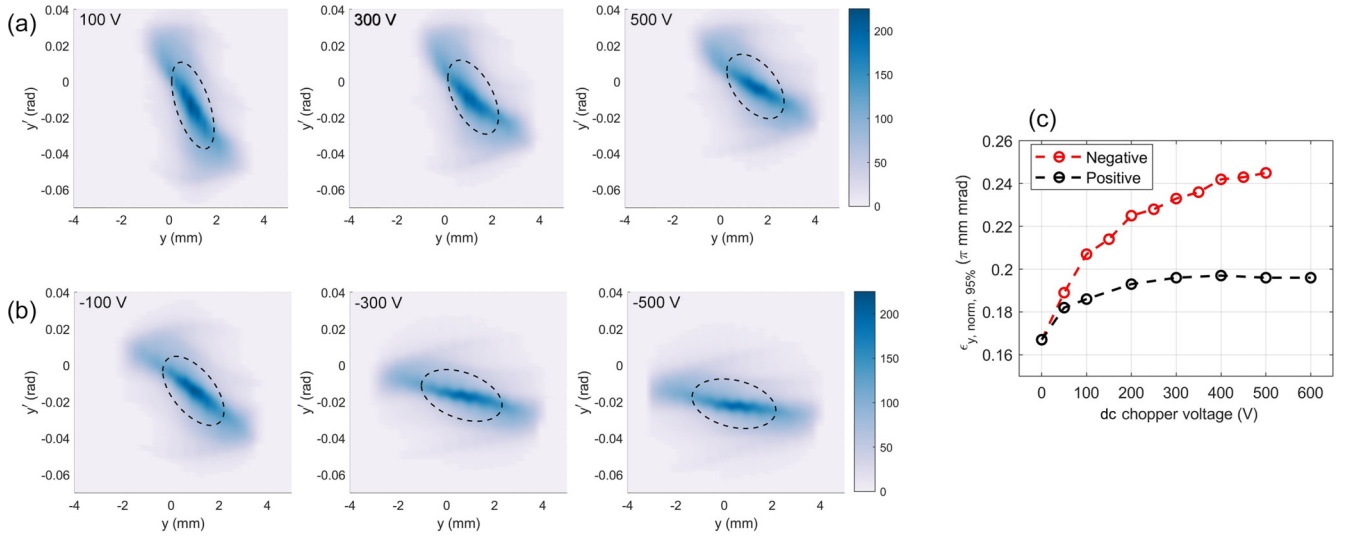


FIG. 5. Measured y - y' phase space of the H^- ion beam behind the chopper plates. The double-slit measurements were performed in Chamber 3 with the metal shield behind the chopper plates. (a) Positive dc voltage applied to the plate. (b) Negative dc voltage applied to the plate. (c) Normalized rms emittance (5%-halo-removed rms emittance) under both positive and negative voltage conditions. The black dashed lines represent the rms ellipses.

IV. CONFINE THE SECONDARY IONS BY BARRIER

To mitigate the severe disruption of SCC caused by the negatively biased chopper voltage, a barrier electrode was installed immediately upstream of the beam chopper (see Fig. 1). The effectiveness of the barrier electrode was evaluated with the chopper operating in pulsed mode at -5 kV, 1.02 MHz, and a 50% duty cycle. The barrier electrode was positively biased to suppress the negative fringe field and prevent axial loss of H_2^+ ions, as illustrated in Fig. 1(c). The ion source and LEBT parameters were kept identical to those in the previous measurements and the beam emittance was measured using the y -direction double-slit scanner installed in Chamber 3. Figure 6 shows the emittance of the undeflected primary beam as a function of the barrier electrode voltage. Notably, the emittance decreases with an increase in the positive barrier potential, whereas negative barrier

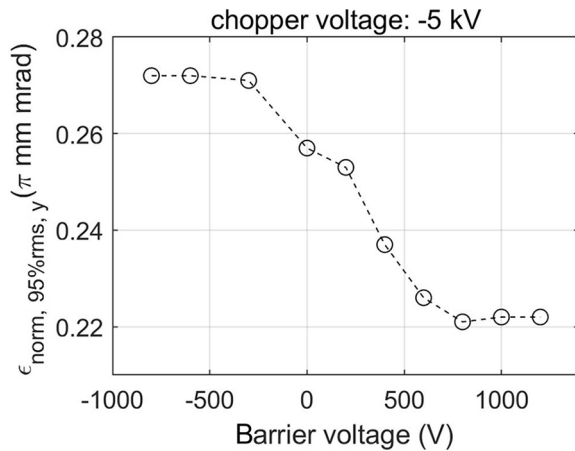


FIG. 6. Beam emittance as a function of barrier electrode voltage under a -5 kV chopper voltage. rms emittance calculated with 5% beam halo removed.

potentials lead to a significant increase in emittance. At a chopper voltage of -5 kV and with the barrier electrode grounded (0 V), the measured emittance is in good agreement with that obtained under dc-biased chopper conditions [cf. Fig. 5(c)]. Even at the optimal barrier voltage of 800 V, the minimum measured beam emittance (0.22π mm mrad) remains slightly above that achieved with a positive chopper [0.21π mm mrad; see Fig. 4(b)]. These results demonstrate that the incorporation of a barrier electrode offers a promising approach to simultaneously optimize beam chopper and preserve SCC in high-current ion-beam transport systems.

For facilities that transport H^- beams but do not incorporate a chopper in the LEBT, barrier electrodes can still play a role in confining secondary ions within the LEBT. For instance, a negative fringe field typically exists at the LEBT entrance, which continuously attracts secondary ions, thereby reducing their density in this region and consequently degrading the space-charge compensation, as shown in Fig. 1(b). To shield the fringe field and further confine the secondary ions axially, an additional barrier electrode was installed at the LEBT entrance, immediately downstream of the ground electrode, as illustrated in Fig. 1(a). The x -direction double-slit scanner and CTs in Chamber 2 are used to measure the beam emittance and beam current at various barrier electrode voltages. In this experiment, a 51 mA H^- beam is accelerated to an energy of 50 keV. Figure 7 shows the measured beam emittance and beam envelope versus the bias voltage on the barrier. Initially, as the bias voltage increases, both beam emittance and envelope size decrease; beyond an optimal point, they rise again. At the optimal barrier voltage of 3.5 kV, the beam envelope contracts by 40% and the emittance reduces by approximately 20%. Since the magnetic lens parameters were kept constant, the gradual decrease in the beam envelope indicates that the beam expansion caused by space-charge forces over the distance from the extraction region to the solenoid entrance was mitigated. This can only be attributed to an increase in the secondary ion density in this region.

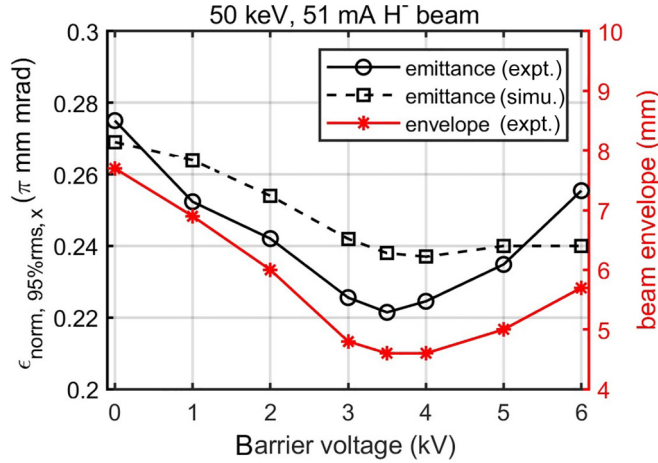


FIG. 7. Beam emittance and beam envelope diameter as functions of the barrier voltage: comparison between experimental and simulation results. rms emittance calculated with 5% beam halo removed.

Meanwhile, the reduction in emittance observed in the experiments is also an inevitable consequence of the weakened nonlinear space-charge forces and the reduced magnetic aberrations. The optimal barrier voltage depends on the beam's accelerating voltage and space-charge potential well. Underbiasing provides insufficient shielding of the negative potential of the ion source, while overbiasing repels H_2^+ ions far from the electrode, shortening the effective length of SCC.

V. NUMERICAL SIMULATION

To further investigate the evolution of secondary ions, we performed numerical simulations using the IBSIMU software package. This package is designed for modeling ion optics, plasma extraction, and space-charge-dominated ion-beam transport based on the Vlasov iteration method [30]. To accurately model space-charge compensation dynamics, a Monte Carlo collision algorithm was incorporated into the IBSIMU framework, enabling the generation and tracking of secondary ions and electrons in self-consistent electric and magnetic fields [27,31]. A 51 mA beam was initially modeled as a diverging Gaussian distribution, with a uniform residual gas pressure of 1 mPa assumed throughout the LEBT. The beam optics parameters, including the magnetic field of solenoids, were set to match the experimental conditions. Simulation results are presented in Fig. 7 alongside the measured emittance. The simulation results reproduce the overall trend of beam emittance variation with barrier voltage, despite deviations arising from imperfect modeling of experimental conditions and computational uncertainties. The effectiveness of the barrier electrode in suppressing emittance growth is thereby confirmed.

The influence of the barrier electrode on improving secondary ion confinement was further simulated under a higher background gas pressure of 7 mPa [Fig. 8(b)]. At a residual gas pressure as low as 1 mPa [Fig. 8(a)], the barrier electrode voltage exhibits a more pronounced effect on the number of trapped secondary ions compared to the case at 7 mPa. A high gas pressure results in a higher generation rate of secondary

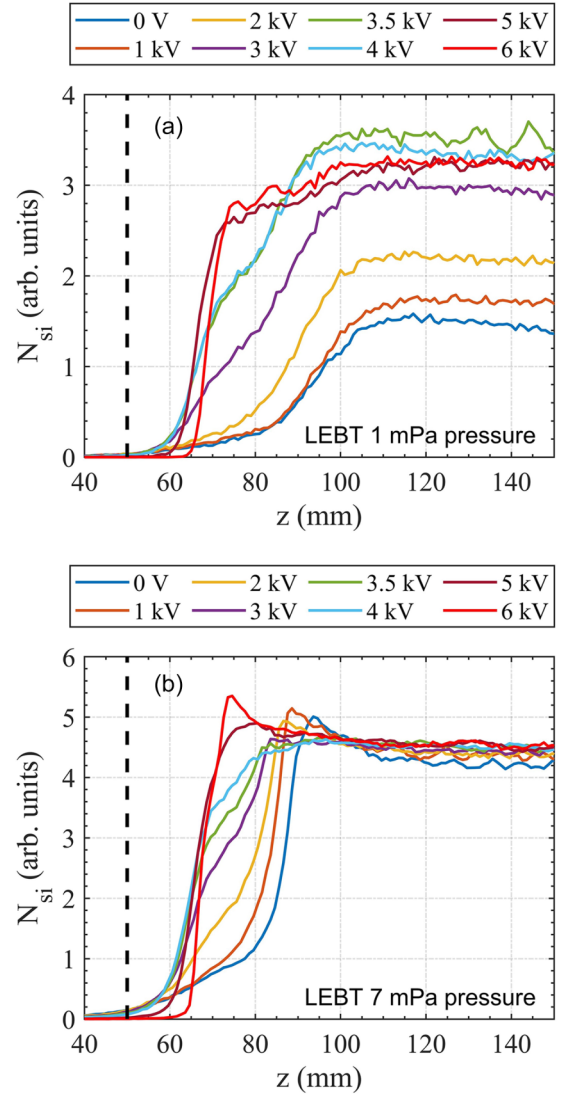


FIG. 8. Simulated distributions of the secondary ions (steady state) vs the barrier voltage in LEBT with (a) 1 mPa uniform gas pressure and (b) 7 mPa uniform gas pressure. The dashed black lines represent the position of the barriers.

ions, therefore enabling almost full compensation, i.e., zero potential inside the beam, over an extended region of the LEBT. When the secondary-ion generation rate sufficiently balances the axial losses induced by the fringe field, the effectiveness of the barrier electrodes degrades. Nevertheless, to minimize stripping losses of the primary beam and maintain high vacuum conditions in the RFQ, standard LEBTs are operated at lower pressures, under which the barrier electrode still retains substantial effectiveness.

VI. SUMMARY AND OUTLOOK

In summary, the axial loss of secondary ions responsible for space-charge compensation near the acceleration electrode and the transverse deflecting chopper electrode has been investigated. Both cases demonstrate that electrostatic potential barriers, designed to trap the secondary ion cloud, effectively suppress emittance growth during beam transport. For a

deflecting chopper, biasing an electrode opposite to the beam charge (i.e., positive for an H^- beam) is beneficial for minimizing SCC destruction. Unlike gas injection methods, which enhance SCC by increasing the residual gas density but can also increase beam scattering and stripping losses, the barrier electrode approach enhances SCC by increasing the density of secondary ions through electrostatic confinement without introducing additional gas into the beam line. Consequently, this technique improves SCC while having no adverse effect on beam current. This study suggests that barrier electrodes can be applied in high-intensity ion beam linacs for low-energy beam transport, provided that either the pulse duration is much longer than the SCC buildup time or the beam is continuous.

The proposed barrier-electrode confinement strategy is not restricted to accelerator beamlines; it is also applicable to magnetic-confinement fusion NBI systems and high-current ion implanters. For fusion NBI, beams extracted from radio-frequency H^- ion sources typically exhibit substantially larger initial emittance than theoretical predictions [5,32], which renders effective emittance control highly critical. Recent simulation work has demonstrated that residual electric fields can exert a detrimental impact on SCC [22]. In this context, the potential-barrier-electrode confinement scheme presented in this work is expected to shield the extracted beam from fringe-field-induced degradation of SCC, and could therefore help improve the ultimate beam quality of NBI systems. For high-current ion implantation systems, precise divergence control is critical for stable, high-precision ion doping and material processing. SCC is also essential for efficient beam transport

in low-energy, high-current ion implanters [33]. Heavy-gas injection can boost transmitted beam current, yet it generates undesired by-product ions [34]. These by-products conflict with the systems' stringent impurity-control requirements. Through axial confinement of secondary ions, the barrier-electrode-based scheme realizes effective SCC under minimal gas injection, suppressing harmful by-products while sustaining high beam transport efficiency.

ACKNOWLEDGMENTS

The authors express their gratitude to Taneli Kalvas for providing the IBSimu code through the webpage, which facilitated the beam optics simulation in this study. This work was supported by the National Natural Science Foundation of China (Grant No. 12505185), China Postdoctoral Science Foundation (Grant No. 2024M761760), Guangdong Basic and Applied Basic Research Foundation (Grant No. 2024B1515120028), and Xiejialin Foundation (Grant No. E55468U2).

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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