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उच्च-तीव्रता वाले प्रोटॉन त्वरकों के लिए अंतराकाशी आवेश क्षतिपूर्ति अध्ययन

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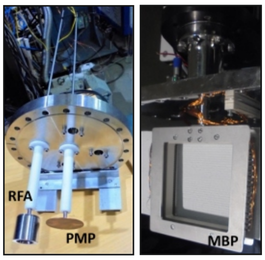

एल. ई. बी. टी. बीम डायग्नोस्टिक चैंबर-1 में आर. एफ. ए., पी. एम. पी. और एम. बी. पी. विधानसभाओं को तैनात किया गया है

सारांश

यह लेख उच्च-तीव्रता वाले प्रोटॉन त्वरकों में मजबूत विफोकसन बलों को कम करने के लिए लेहिपा सुविधा में संचालित व्यापक अंतराकाशी आवेश क्षतिपूर्ति (एससीसी) अध्ययन प्रस्तुत करता है। 3डी पार्टिकिल-इन-सेल और मोंटे कार्लो टक्कर (पीआईसी-एमसीसी) अनुकरण को एक स्वदेशी रूप से विकसित नैदानिक सुइट के साथ जोड़कर-एक नए, गैर-आक्रामक कण मॉनिटर प्रोब (पीएमपी) द्वारा हाइलाइट किया गया-कणपुंज उदासीनीकरण की क्षणिक और स्थिर-स्थिति गतिशीलता को सफलतापूर्वक चिह्नित किया गया। क्षतिपूर्ति करने वाले गैस मापदंडों के लक्षित अनुकूलन ने लगभग पूर्ण क्षतिपूर्ति (η~0.96) हासिल की, जिससे सीधे अनुवर्ती आरएफक्यू कणपुंज संचारण में 65 प्रतिशत से 85 प्रतिशत तक सुधार हुआ। अंततः, यह अंतर्दृष्टि अगली पीढ़ी के त्वरक प्रणालियों में निम्न ऊर्जा कणपुंज परिवहन (एलईबीटी) अभिकल्पन एवं प्रचालन का इष्टतमीकृत एक मजबूत, भावी ढांचा प्रदान करता है।

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Space Charge Compensation Studies for High-Intensity Proton Accelerators

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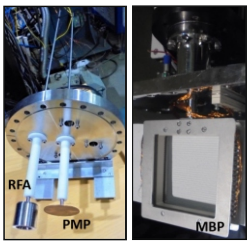

RFA, PMP and MBP assemblies deployed in LEBT Beam Diagnostic Chamber-1

ABSTRACT

This article presents comprehensive Space Charge Compensation (SCC) studies conducted at the LEHIPA facility to mitigate strong defocusing forces in high-intensity proton accelerators. By combining 3D Particle-in-cell & Monte Carlo Collision (PIC-MCC) simulations with an indigenously developed diagnostic suite highlighted by a novel, non-invasive Particle Monitor Probe (PMP) the transient and steady-state dynamics of beam neutralization were successfully characterized. Targeted optimization of compensating gas parameters achieved near-complete compensation (η~0.96), directly improving downstream RFQ beam transmission from 65% to 85%. Ultimately, these insights offer a robust, predictive framework for optimizing Low Energy Beam Transport (LEBT) design and operation in next-generation accelerator systems.

KEYWORDS*: Space Charge Compensation (SCC), Particle Monitor Probe (PMP)*

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Introduction

The Front-End Challenge

In high-intensity proton accelerators, one of the most critical regions is the front-end, where the beam energy is low (typically tens of keV) and the current is high. At these non-relativistic velocities, the electrostatic repulsion between particles is not mitigated, allowing strong space charge forces to dominate beam dynamics. Consequently, the beam experiences severe defocusing, leading to rapid transverse expansion, emittance growth, and halo formation.

If these effects are not controlled at the LEBT stage, they propagate downstream and cause significant beam losses and component activation. Therefore, preserving beam quality via SCC is essential. A diagnostic-guided SCC optimization in the Low Energy High Intensity Proton Accelerator (LEHIPA) facility directly improved transmission through the 3 MeV Radio Frequency Quadrupole (RFQ) from 65% to 85%. Crucially, the diagnostics developed for this are completely indigenous, showcasing deep *atma nirbhar* capabilities in advanced accelerator technologies.

The LEHIPA Facility and SCC Physics

At the Bhabha Atomic Research Centre (BARC), the LEHIPA serves as a testbed to study these phenomena. Its compact ~2.7 m dual-solenoid LEBT (Fig.1) transports and matches the high-intensity proton beam from the ECR ion source to the RFQ. To study the dynamics of beam neutralization, the “gas feed” port in LEBT injects controlled amounts of compensating gas (H_2, N_2 or Ar). This allows systematic variation of gas type and its pressure, enabling detailed parametric studies of SCC.

SCC arises when the primary beam ionizes this residual gas [1]. The produced electrons are rapidly trapped within the beam potential, progressively neutralizing its space charge and reducing transverse defocusing forces. This dynamic process is characterized by two key parameters:

- **Degree of Compensation (η):** Indicates the level of neutralization, where $\eta \rightarrow 1$ means near-complete compensation. $\eta = 1-\phi_c/\phi_0$, where ϕ_c and ϕ_0 are the compensated and uncompensated on-axis beam potentials.

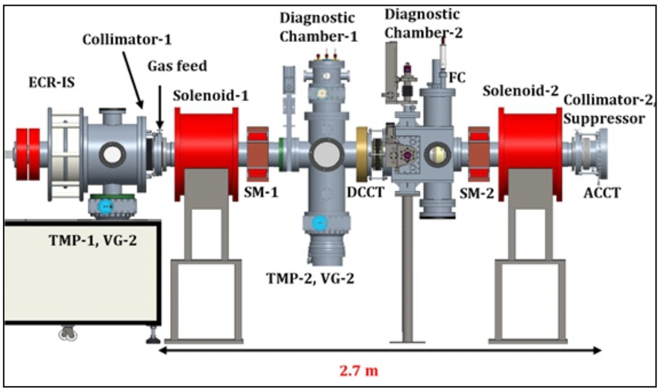

Fig.1: Schematic of LEHIPA LEBT. ECR Ion Source (ECR-IS), Turbo Molecular Pump (TMP), Vacuum Gauge (VG), Steerer Magnet (SM), Faraday Cup (FC), Current Transformer (CT).

- **Characteristic Timescale (τ_{scc}):** The time required for compensation buildup. $\tau_{scc} = 1/(\sigma_i(E).n_g.\beta c)$, where $\sigma_i(E)$ is the ionization cross-section, n_g the gas density, and βc the beam velocity.

Integrated Modelling: PIC-MCC Simulations

To fundamentally understand these complex beam-plasma interactions, comprehensive 3D Particle-In-Cell Monte Carlo Collision (PIC-MCC) simulations were performed [2,3]. These models track the ionization of the residual gas and the kinematics of generated secondary electrons and slow ions. By resolving the trapping of neutralizing electrons and the radial expulsion of positive ions, the framework captures the transient buildup and steady-state plasma. Fig.2(a) shows the clear reduction in beam potential at 2 μs and 4 μs as SCC progresses. Furthermore, in Fig.2(b), the simulations confirm that τ_{scc} corresponds directly to electron density saturation and beam size stabilization.

The Space Charge Compensation Diagnostic Suite

Understanding transient SCC is critical, but conventional beam size measurements are intrusive and can perturb the SCC process via secondary electron emission. To overcome

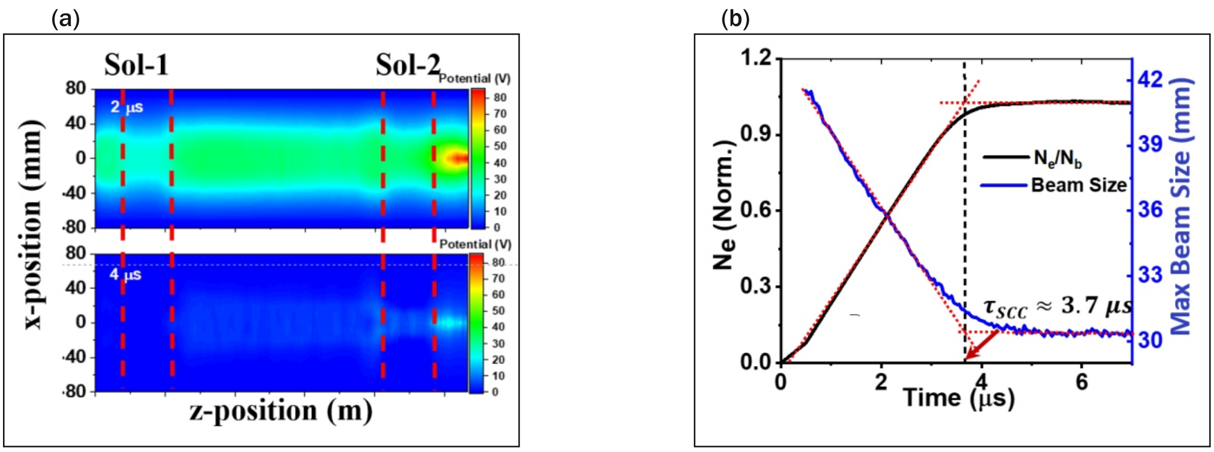

Fig.2: For 5×10^{-5} Torr N_2: (a) beam potential evolution; (b) temporal evolution of normalized electron density (N_e/N_b, left axis) and maximum beam size (right axis).

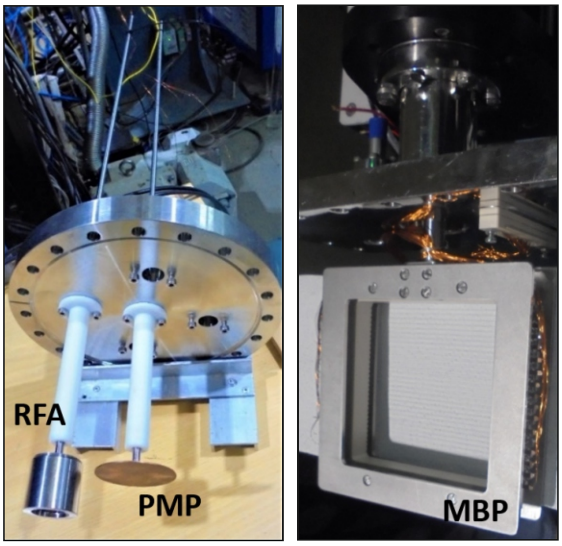

Fig.3: RFA, PMP and MBP assemblies deployed in LEBT Beam Diagnostic Chamber-1.

this, a dedicated, non-invasive diagnostic suite, comprising the PMP [2,3] Retarding Field Analyzer (RFA) [3] and Multiwire Beam Profiler (MBP)[3] was developed and deployed in a diagnostic chamber downstream of the first solenoid (Fig.3).

Particle Monitor Probe (PMP)

The novel PMP operates non-invasively by measuring the radial flux of secondary plasma particles expelled during SCC buildup. Utilizing a specialized cylindrical pick-up electrode, it boasts a fast response time (~1.3 ns) for high temporal resolution during initial transient phases [3]. Simulations (Fig.4(a)) predict a distinct rise-peak-decay profile for the transverse electron current, where the subsequent minimum marks steady-state compensation. Experimental measurements with the PMP capture this exact temporal minimum, yielding a direct measurement of τ_{scc} (Fig.4(b)). Benchmarking against a Multi-Pixel Photon Counter (MPPC) demonstrated a comparable response without beam perturbation, establishing the PMP as a highly robust diagnostic.

Retarding Field Analyzer (RFA)

To complement the PMP's transient data, the RFA quantifies the steady-state degree of space charge compensation [3]. By measuring the energy distribution of secondary ions repelled radially from the beam core, the maximum kinetic energy serves as a direct, experimental proxy for the compensated on-axis beam potential (Fig.5 (a)).

Multiwire Beam Profiler (MBP)

The MBP completes the suite by providing reliable measurements of the transverse beam profile in the steady state [3]. It actively tracks beam size reduction and profile evolution toward a Gaussian distribution during compensation (Fig.5(b)).

Experimental Results

The primary objective of these studies was to systematically identify the optimal compensating gas species and flow rates to maximize downstream RFQ transmission [3].

Initial investigations characterized compensation dynamics across different species. As shown in Fig.6, τ_{scc} decreases with increasing gas pressure, strictly depending on the injected gas's ionization cross-section. While experimental values are marginally higher than ideal simulations due to realistic effects (finite beam rise time, electron losses, localized pressure gradients), the accurately reproduced scaling behavior provided the empirical data needed to select the best gas for rapid neutralization.

Next, optimizing the localized gas flow was critical to balance necessary compensation pressure against beam degradation from scattering. By tracking the transverse profile across various flow rates (Fig.5(b)), MBP data identified the ideal flow regime yielding the most tightly focused, well-matched beam.

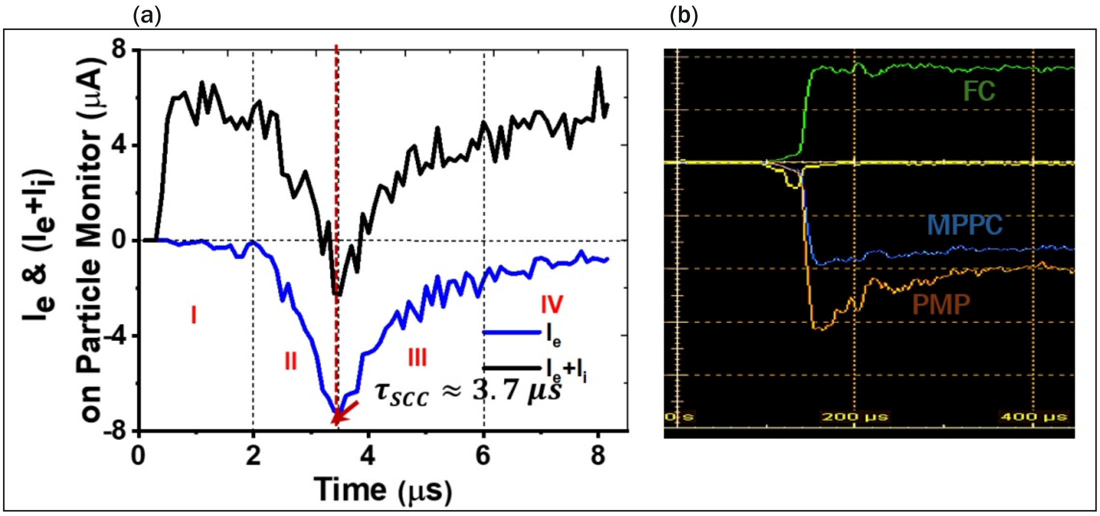

Fig.4: (a) Time evolution of the simulated transverse electron current (I_e) and total current (I_e+I_i) on particle monitor; (b) measurement plots of Particle Monitor Probe (PMP), Multi-Pixel Photon Counter (MPPC) and beam current signal on Faraday Cup (FC).

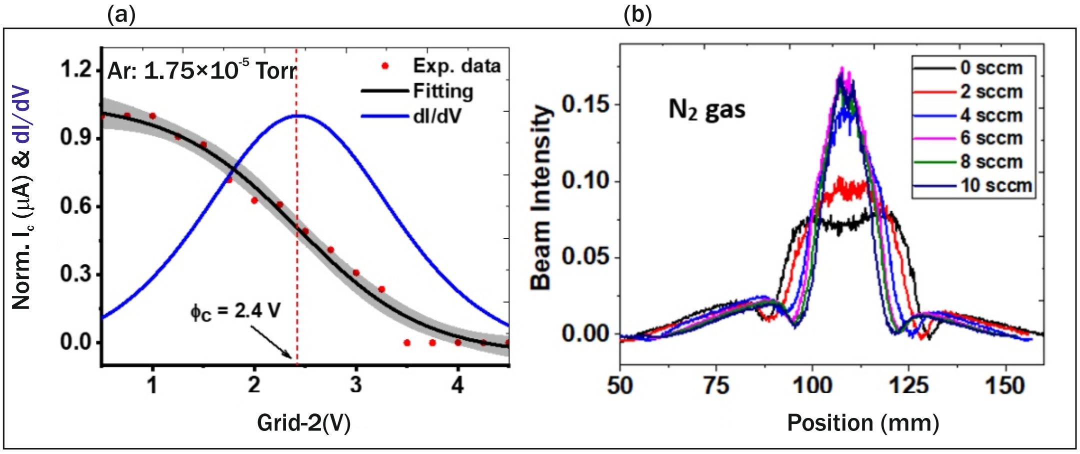

Fig.5: (a) RFA I–V characteristics and corresponding energy distributions for Ar gas. (b) MBP plots for different residual gas flow rates.

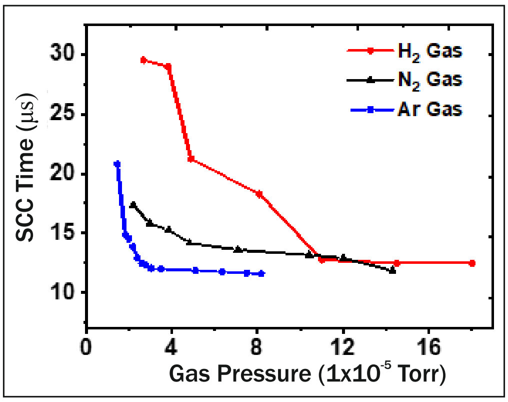

Fig.6: Variation of τ_{scc} with gas pressure for H_2 (red), N_2 (black) and Ar (blue) gases.

Under these optimized conditions, the LEHIPA LEBT achieves near-complete space charge compensation (η~0.96). The RFA independently verified this highly neutralized state (Fig.5(a)), recording a dramatic beam potential drop from an uncompensated ~70 V to just ~2 V. This targeted optimization directly facilitated maximum matching efficiency and transmission through LEHIPA RFQ.

Conclusion

The LEHIPA studies establish a consistent, predictive understanding of SCC through integrated PIC-MCC simulations and targeted diagnostics. The non-invasive Particle Monitor Probe successfully overcomes the limitations of conventional techniques by enabling direct, fast measurement of SCC time. These practical insights into gas selection, pressure optimization, and diagnostic strategy are directly relevant for designing and operating next-generation high-intensity proton accelerators, ensuring the precise beam control essential for reliable performance.

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