MODELING OF SPACE CHARGE COMPENSATION IN THE RFQTS LEBT

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Abstract

A gas pressure- and gas species- dependent space charge compensation (SCC) model was developed in IBSimu for the RFQ Test Stand (RFQTS) to support the LANSCE Accelerator Modernization Project (LAMP). In LAMP, H^+ and H^- beams must be transported over an extended LEBT before RFQ injection, making SCC a key factor for beam emittance. The present work focuses on positive ion transport in the RFQTS and uses a steady-state approximation for direct comparison with beam measurements. For a 35 keV, 14 mA mixed beam condition, simulations show that a neutralization degree above 80% is required to suppress emittance growth during transport. Parameter scans indicate that the SCC-sensitive region is around 10^{-5}–10^{-6} Torr in Ar. These results define the operating window for upcoming RFQTS SCC experiments and provide input to LAMP front-end engineering design.

INTRODUCTION

The LANSCE Accelerator Modernization Project (LAMP) is replacing the front-end of the existing LANSCE accelerator, from the ion sources through the end of the 100-MeV drift tube linac (DTL) [1–3]. In the current LANSCE configuration, positive and negative hydrogen ions are independently accelerated to 750 keV immediately after extraction using separate Cockcroft-Walton (C-W) power supplies. This direct electrostatic acceleration up to 750 keV is advantageous because it mitigates beam blow-up caused by space charge effects [4]. In LAMP, however, the large C-W systems will be replaced by a single radio-frequency quadrupole (RFQ) capable of accelerating both positive and negative hydrogen beams from 65 keV to 2.1 MeV [5]. Unlike the existing configuration, LAMP requires transport of both beam polarities at 65 keV from the ion sources to the RFQ entrance. Because dual-polarity beams must be merged into a single beamline, the total beamline length reaches about 4 m. This is also the case for the RFQ test stand (RFQTS), a test stand associated with LAMP that is being used for technical maturation [6]. The RFQTS has a 35 keV low-energy beam transport (LEBT) and a 35 keV to 750 keV RFQ. Therefore, beam divergence and emittance growth during LEBT may be non-negligible.

In this study, we investigate the influence of space-charge effects on the RFQTS LEBT beam parameters. As an initial step, the effect of space-charge compensation (SCC) on the positive ion beam is investigated through both experiments and simulations. This paper reports the simulation work carried out to design the RFQTS experimental campaign.

EXPERIMENTAL APPARATUS

Figure 1 shows a sectional view of the Phase 1 configuration of the RFQTS. Positive hydrogen ion beams are generated by the LANSCE duoplasmatron ion source [7]. A coated nickel-strip filament emits thermionic electrons, which are focused downstream by a solenoid-based magnetic circuit. An arc plasma is formed by the characteristic double-sheath arc discharge and expanded into a boron-nitride plasma expansion cup through a 2.8 mm diameter anode aperture. This cools the plasma and improves its uniformity, resulting in lower emittance growth.

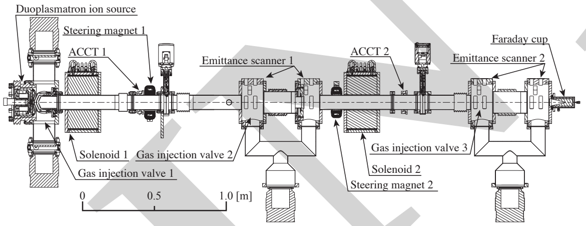

Figure 1: A schematic view of the RFQTS Phase 1 beamline, showing ion optics, diagnostics, vacuum pumps and neutralizer gas injection ports for SCC studies.

As shown in Fig. 2, positive ions are extracted through a 4.92 mm diameter aperture in the Pierce electrode (PE) by the extraction field between the PE and extraction electrode (EE) and are then accelerated to 35 keV using a conventional four-electrode system. A variety of ions are produced, with historical studies suggesting a fraction of 75% H^+, 20% H_2^+ and 5% H_3^+. The third electrode, a Repeller electrode (RE) biased at −2 kV, suppresses back-streaming low-energy electrons from the beam plasma formed downstream of the fourth grounded electrode (GE). Typical operating voltages are 22.6 kV for extraction and 12.4 kV for acceleration, resulting in a 35 keV beam. Although this potential distribution provides limited focusing at the EE exit, this extraction-dominant regime is selected to maximize extractable current while maintaining a low extractor aspect ratio and a broad perveance acceptance.

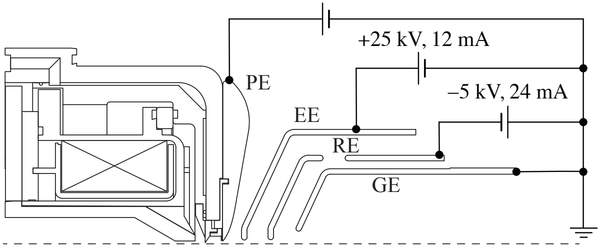

Figure 2: Electrode geometry for the RFQTS.

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The extracted beam is transported through a 4-inch beam pipe and focused by two solenoid magnets located 352 and 2298 mm downstream of the PE. Two sets of steering magnets enable deflection in the positive and negative x and y directions in case of misalignments. Beam current is measured by two AC current transducers (ACCT) made by bergoz (ACCT-S-122-2B) installed downstream of the first solenoid and upstream of the second solenoid. At approximately 3620 mm from the PE, the beam is intercepted by a positively biased, water-cooled Faraday cup. In addition to one Allison emittance scanner installed downstream of the first solenoid, two slit-scan emittance scanners measure both horizontal and vertical phase-space distribution at z = 1535 mm and 3134 mm. The entire beamline is pumped by four 920 L/s turbo pumps, and three neutralizer gas injection valves are installed for SCC experiments.

Currently, the RFQTS is intentionally being operated with the second emittance gear (and subsequent Faraday cup) in the location where the RFQ will be placed in the Future [8]. This enables a wider variety of LEBT studies, incluidng experimental measurement of the beam Twiss parameters at the RFQ entrance location to confirm that the beam is within the acceptance envelope of the RFQ before installation. out the RFQ (35 keV, 35 mA, Kress GmbH) [9] to focus on direct beam-based studies of beam transport and SCC in the LEBT.

MODELING OF SCC EFFECT

IBSimu, an open-source code with high flexibility for custom modeling, was used for beam trajectory simulations [10]. IBSimu can compute steady-state beam transport self-consistently through iterative field-particle calculations. In RFQTS, the beam energy is fixed at 35 keV. Assuming an background hyrogen pressure of $1{\times}10^{-6}$ Torr, the mean free time can be estimated as $\tau_{\mathrm{mft}} \sim 1/n_{\mathrm{gas}}\sigma v$, where n_{gas} is the background gas density, σ is the proton impact ionization cross section, and v is the beam velocity. Using a representative cross section for H_2, the resulting time scale is on the orders of several hundred µs. During operation, however, the introduction of neutralizer gas increases the local gas pressure by at least one order of magnitude, reducing the τ_{mft} to several tens of µs or less.

It should also be noted that the relevant cross sections in H_2 are typically smaller than those in heavier gases such as Ar or Kr, making this estimate conservative. Experimentally, the SCC time scale is experimentally known to be on the order of the τ_{mft} [11]. Therefore, by using the late plateau of the measured waveform, transient SCC effects can be reasonably neglected, and a steady-state comparison between simulation and experiment is justified.

Previous approaches include fully time-dependent particle in cell (PIC) simulations [12] and pseudo-transient Monte Carlo approaches [11], in which beam-plasma electrons and ions are generated and injected into the particle tracking database at each time step. However, these approaches are computationally expensive. In LEBT conditions, where phase-space behavior is strongly nonlinear with respect to meniscus shape, proton ratio, and gas line density, the computational cost be-comes particularly high. For this reason, and because the experiment targets steady-state beam conditions, a steady-state approximation is adopted in this study. In addition, rather than assuming a fixed neutralization degree (e.g., 90%), gas pressure- and gas species- dependent SCC is explicitly modeled to evaluate differences in SCC performance.

For positive ion beams, SCC is dominated by electrons. Focusing on electron density ne, the rate equation is written as

$$\frac{dn_e}{dt} = n_{\mathrm{beam}} n_{\mathrm{gas}} \sigma_{\mathrm{ion}} v_{\mathrm{beam}} - \frac{n_e}{\tau_{\mathrm{loss}}}. \qquad (1)$$

Here, τ_{loss} is introduced as an effective characteristic time that absorbs uncertain loss mechanisms, including electron transport/absorption and transient SCC degradation associated with ion loss to the wall. The τ_{loss} is on the order of the τ_{mft}, as commonly observed experimentally, although it may vary depending on electron loss, positive ion escape, and transport effects. Under steady-state conditions, the neutralization degree η can be written as

$$\eta = n_{\mathrm{gas}} \tau_{\mathrm{loss}} \langle \sigma_{\mathrm{ion}} v_{\mathrm{beam}} \rangle. \qquad (2)$$

By providing the gas-pressure distribution and proton impact ionization cross section data as inputs, η is evaluated locally at each mesh cell and applied to the local beam space charge. The resulting effective space charge is then used in the Poisson equation, enabling steady-state trajectory calculations with SCC.

SIMULATION RESULTS

Although the proton fraction can vary with source gas pressure, electron emission current, and arc power density, this work adopts the beam composition ratio of 75:20:5 reported experimentally at LANSCE beamline in Ref. [13]. The initial energy was set using a 5 eV plasma potential. The transverse thermal spread was set to T_t = 1 eV, assuming sufficient ion temperature reduction in the boron nitride expansion region.

Figure 3 shows the normalized emittance obtained from simulations from the PE (z = 0 mm) to the downstream edge of source/turbo-pump chamber (z = 170 mm), for a 35 keV, 14 mA beam. In this scan, a uniform neutralization degree η was assumed in the region downstream of the GE equipotential surface (45 mm ≤ z ≤ 170 mm). With SCC, the beam quality at z = 170 mm improves significantly: for $\eta > 80\%$, compared with the no-SCC case, the normalized emittance is reduced by about 42%, the rms divergence by 50%, and the rms beam size by 34%. For η in the range of 0-70%, strong beam divergence along the z-axis is observed. These results indicate that $\eta > 80\%$ is required to sup-press emittance growth in long-distance low-energy beam transport.

Based on this threshold, the gas-pressure-dependent SCC effect was evaluated for 35 keV beam transport in Ar gas at 300 K. The parameter scan used $p_{\mathrm{Ar}}\tau_{\mathrm{loss}}$ [Torr· s], where

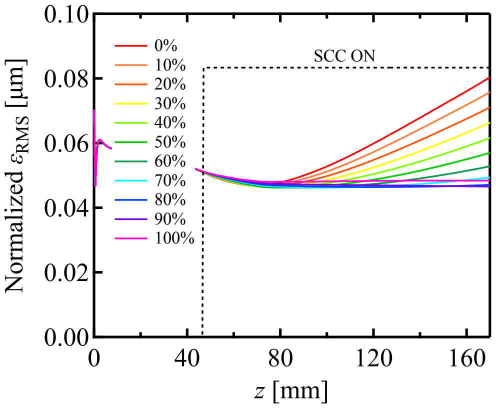

Figure 3: Simulated evolution of normalized rms emittance along the beamline for a uniform neutralization degree scan for a 35 keV, 14 mA beam.

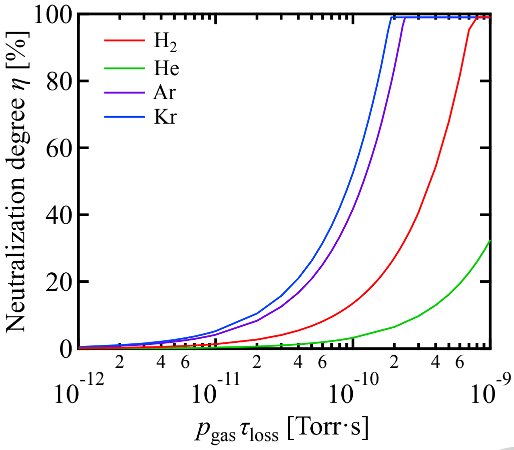

Figure 4: Simulated neutralization degree η as a function of $p_{\mathrm{Ar}}\tau_{\mathrm{loss}}$ for a 35 keV, 14 mA beam, showing the onset and saturation behavior of SCC in H_2, He, Ar, and Kr background gas.

τ_{loss} is the unknown characteristic loss time. The resulting neutralization degree as a function of $p_{\mathrm{Ar}}\tau_{\mathrm{loss}}$ is shown in Fig. 4. As shown, achieving $\eta = 80\%$ requires approximately $p_{\mathrm{Ar}}\tau_{\mathrm{loss}} = 2{\times}10^{-10}$ Torr· s. If τ_{loss} is on the order of the mean free time, the required uniform Ar pressure is predicted to be about $1{\times}10^{-5}$ Torr.

Experimentally, Ar will be introduced from three injection valves, and gas-pressure scans will be performed under conditions with as uniform a pressure distribution as possible by monitoring by ion gauges. This approach enables indirect estimation of τ_{loss} for the corresponding proton fraction, gas pressure, beam current, and beam energy. Because the proton impact ionization cross sections of He and Ne at 35 keV are about one order of magnitude lower than that of Ar, measuring the onset of the η rise in the $p_{\mathrm{Ar}}\tau_{\mathrm{loss}}$ scan may enable an absolute calibration of η. Conversely, if sufficient SCC saturation is not observed with Ar, additional experiments using Kr, which has a larger ionization cross section, are planned.

CONCLUSION

This paper presented a gas pressure- and species-dependent SCC model for direct comparison with RFQTS experiments, with the goal of demonstrating long-distance transport of low-energy H^+ beams in LAMP and providing feedback to the engineering design. The simulations indicate that, for 35 keV and 14 mA operation, a neutralization degree is expected to be most sensitive to Ar gas pressure is predicted to be approximately 10^{-6}-10^{-5} Torr range. In the experiment, additional effects are expected, including background pressure non-uniformity, molecular ion dissociation, and proton loss due to charge exchange (CX) loss. In particular, CX cross section for H_2 peaks near ~10 keV, so increasing gas pressure to enhance SCC may also introduce non-negligible CX beam loss. Although CX is not included in the present model, future work will incorporate measured axial gas-pressure profiles and evaluate z-directional beam loss including both SCC and CX processes.

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