

Beam transient studies in high-intensity linacs

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(Received 24 March 2026; accepted 29 September 2026; published 14 October 2026)

Space charge is one of the main challenges for high-intensity linear accelerators (linacs). To overcome this, most linacs have adopted the space charge compensation (SCC) scheme at the low-energy beam transport (LEBT). However, SCC is a buildup process that produces beam transients, i.e., nonoptimal beam conditions, which can lead to significant beam degradation and losses. Furthermore, most LEBTs are equipped with a chopper to provide a beam structure intended for the downstream sections and for the gradual ramp-up of power. However, operation of the chopper will destroy the SCC, leading to additional beam transients. SCC studies on beam transients focus primarily on the LEBT section, resulting in insufficient analysis of the downstream section, where beam transients can cause significant losses. This work addresses this gap by analyzing beam transients generated in the LEBT and their propagation throughout the linac to assess beam losses. This analysis challenges conventional notions by revealing that the worst-case scenario does not occur when the SCC is zero, but rather within twice the compensation time (τ^*). This is because, although mismatch and emittance growth are at their maximum at the beginning, 80% and 450%, respectively, the current transmitted to the superconducting linear accelerator is minimal (30%); consequently, beam instabilities caused by the mismatch are less severe. Most nonoptimal beams were intercepted by the cone collimator and the radio-frequency quadrupole at energies below the activation threshold (2.16 MeV), with a peak power loss density that remained within cooling capacity limits. Furthermore, any residual risk was safely eliminated by the collimators in the medium-energy beam transport. As a result, transient losses in the superconducting linac were estimated to be below 1 W/m and were confined to the low-energy section.

DOI: [10.1103/shnn-b3rn](https://doi.org/10.1103/shnn-b3rn)

I. INTRODUCTION

The Japan Atomic Energy Agency (JAEA) is designing an accelerator-driven subcritical system (ADS) aimed at reducing the geological burden of nuclear waste by transmuting minor actinides. The JAEA-ADS utilizes a 30-MW continuous-wave (cw) superconducting proton Linear Accelerator (linac) to generate neutrons through spallation using a lead-bismuth eutectic target. This system is designed to integrate with an 800-MW thermal power subcritical reactor [1]. Figure 1 presents the conceptual design of the JAEA-ADS project and Table I.

Space charge (SC) is the primary cause of uncontrolled beam size growth, leading to particle loss in high-intensity accelerators [3,4]. As the beam is transported downstream, stricter limits are imposed on the beam loss fraction to

prevent component activation [5,6]—a factor that can limit operational linac performance. Since SC effects vary inversely with energy, their impact is most severe at low energies. Consequently, the low-energy beam transport (LEBT) system is crucial for transporting and matching the beam from the ion source to the radio-frequency quadrupole (RFQ) while minimizing emittance growth due to SC.

Prost summarized a list of high-intensity LEBT systems for light ions, covering both existing and future designs [7]. He analyzed the magnitude of the SC by quantifying the generalized beam perveance [8] and the potential for emittance growth. The generalized beam perveance values range from 6×10^{-4} to 7×10^{-3} . For the JAEA-ADS LEBT, the perveance value is 2×10^{-3} , which is considered a moderate value. The study concludes that the trend in high-intensity LEBTs favors the use of solenoid configurations, known as magnetostatic LEBTs. This preference is not only due to the ability to leverage space charge compensation (SCC), which permits operation at higher generalized perveance, but also because potential emittance growth caused by phase-space distortions due to

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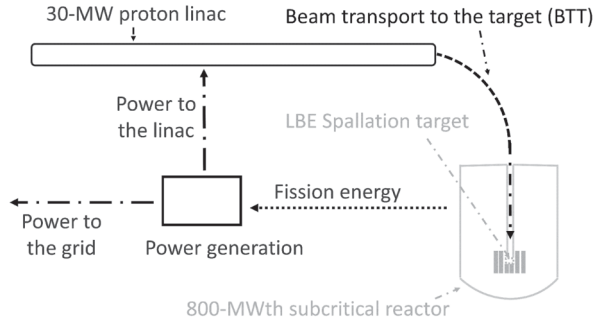


FIG. 1. General scheme for the JAEA-ADS.

SC nonlinearities and relatively large tune depressions associated with realistic beam distributions.

However, SCC is not an instantaneous process; it involves a buildup process that generates beam transients. Since the linac optics are optimized for specific steady-state beam conditions to ensure that beam losses remain below 1 W/m. Beam transients pose a significant risk to maintaining low beam loss levels. In addition, several magnetostatic LEBTs have a chopper to adjust the beam time structure. Consequently, this will disturb the SCC, generating additional beam transients that will need to be evaluated.

In the last decades, extensive research has been conducted on the SCC, focusing on the development of high-fidelity particle-in-cell (PIC) 3D models [9–13] that can accurately reproduce measurements and noninvasive diagnostics [14,15]. Regarding the beam transients, the focus is to reduce the buildup time by injecting high-cross section gases, e.g., Ar, operating at relatively high pressure [12,14] to enhance the electron production by ionization. However, the reported SCC studies simulated only a single type of residual gas at a time [12,15,16], missing how multiple gas ionizations affect the SCC formation. This study is the first to present the simultaneous simulation of both the residual gas from the beam source and the injected residual gas.

TABLE I. Main characteristics of the JAEA-ADS accelerator [2].

Parameter	
Particle	Proton
Beam current (mA)	20
Beam energy (GeV)	1.5
Duty factor (%)	100 (cw)
Beam loss ^a (W/m)	<0.02
$\epsilon_{\text{norm,rms},x}^b$ (mm mrad)	0.20/0.26
$\epsilon_{\text{norm,rms},y}^b$ (mm mrad)	0.21/0.29
$\epsilon_{\text{norm,rms},z}^b$ (μMeV deg)	0.07/0.08

^aAt the entrance of the first HWR cryomodule obtained from beam tracking simulations [2].

^bAt the main linac entrance/end obtained from beam tracking simulations [2].

Furthermore, the analysis of SCC transients is currently limited to the LEBT [17] and RFQ [18], and the potential impact of beam loss in the downstream region has not yet been analyzed. This work aims to address this gap by analyzing beam transients generated in the LEBT and their propagation downstream through the linac to assess potential beam losses.

In this manuscript, Sec. II provides an overview of the linac accelerator, focusing on the LEBT design. Section III describes the simulation model for beam transients. The results are presented in Sec. IV, while Sec. V offers the conclusions.

II. LINAC

The JAEA-ADS linac is composed of a normal conducting part and a superconducting one, as displayed in Fig. 2. The detailed description of the linac is provided elsewhere [2,19–22].

A. Beam loss budget

Along the linac, the allowable beam loss fraction changes with beam energy and depends on whether the losses are controlled (intercept or dump in collimator) or uncontrolled (vacuum chamber or cavities). (i) LEBT: At 35 keV, protons do not cause nuclear activation in the beam tubes or the cone collimator [23]. Most of the intercepted beam will impact the cone collimator. The maximum power density in the cone collimator is less than 10 kW/cm² [24], utilizing water-cooled channels to dissipate the thermal load. (ii) RFQ: For energies exceeding 2.16 MeV, which is the threshold for nuclear activation for protons in copper [23], beam losses are limited to less than 0.002%. At lower energies, a beam loss of up to 10% is acceptable for high transmission with a maximum local power density (any single loss point) below 30 W/cm². This limitation is necessary to ensure effective cooling, based on the performance of current high-power RFQs [25]. (iii) Medium-energy beam transport (MEBT): Uncontrolled beam losses are set to less than 1 W/m to avoid activation, controlled losses at the collimator must be below 100 W. (iv) Superconducting linac: Beam losses are set to less than 1 W/m to avoid activation and cavity quench. (v) Beam transport linac: Beam losses outside the reactor vault (the first part of the transport line [26]) are limited to less than 1 W/m. Beam losses inside the reactor vault are allowed to exceed 1 W/m, as remote handling will be used.

B. LEBT design

LEBT designs are classified as either electrostatic or magnetostatic, with the primary difference being the way to manage SC [9,27]. The electrostatic LEBT employs strong electrostatic fields—typically generated by Einzel lenses [28]—that sweep away background ions or

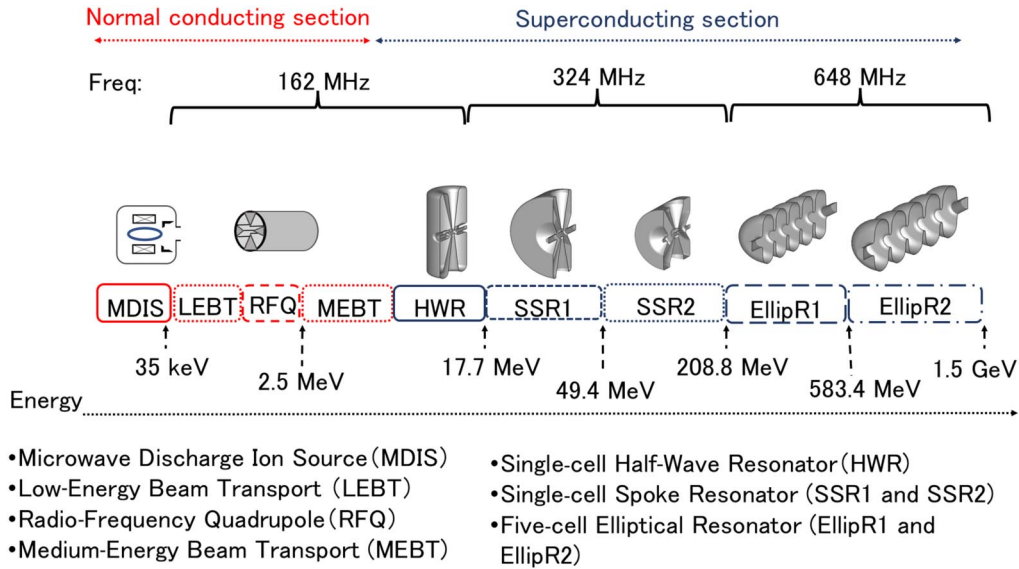


FIG. 2. Schematic for the JAEA-ADS linac.

electrons. Consequently, this design operates without SCC. This eliminates the transit time associated with SCC, enabling rapid beam chopping. While the design is highly compact to minimize emittance growth, the use of high voltages makes it more susceptible to high-voltage breakdown and beam trips [9,27]. The magnetostatic system uses solenoid magnetic fields that do not remove background ions or electrons [29]; instead, these fields allow the accumulation of oppositely charged ionized particles within the beam potential well (known as SCC), facilitating the transport of high-intensity beams. The footprint of the magnetostatic design is larger than that of the electrostatic one, allowing for the inclusion of diagnostic systems and choppers. Additionally, magnetic deflection, due to the particle momentum-to-charge ratio, enables the filtering of ions with greater masses produced by the ion source. However, magnetostatic systems can experience transients caused by SCC and beam chopping operations.

A magnetostatic LEBT was chosen [30] because it is the most established design for high-intensity LEBTs [12–14,17,29,31–35], offering a more robust design. Furthermore, magnetostatic LEBT systems are preferred [15,24,30,36] since they are less prone to beam trips, which are necessary to avoid thermal stress in the reactor structure [37]. The SNS linac, which uses an electrostatic LEBT, is considering switching to a magnetic LEBT due to significant beam loss at the exit aperture of the LEBT [38].

The JAEA-ADS LEBT not only transports and matches the beam to the RFQ but also plays a vital role in managing beam power. This section is particularly suited for safely adjusting beam power by controlling the beam length and for dumping the beam during incidents using a chopper. Furthermore, to measure the reactor's subcriticality, it is necessary to generate short beam tails (less than 1 μ s) to monitor the neutron population within the reactor [39].

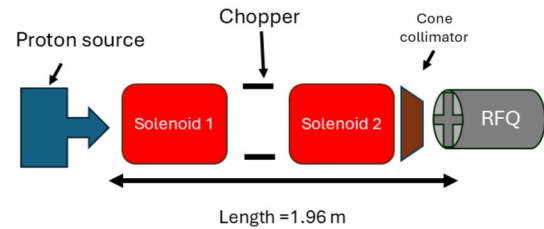


FIG. 3. JAEA-ADS LEBT design.

Figure 3 illustrates the configuration of the LEBT system. This includes two solenoids, an electrostatic chopper, and a cone collimator; however, the beam diagnostic is not included in this depiction. The configuration has been optimized to achieve the following objectives: (i) to provide a steady-state beam that enables effective transport downstream of the linac, maintaining the required current while keeping losses below 1 W/m; (ii) to manage the beam dump effectively using a voltage chopper operating at less than 6 kV, with a peak power density at the cone collimator kept below 10 kW/cm²; and (iii) to minimize disturbance in the formation of the SCC.

The solenoid positions are located close to the end parts, so that the first solenoid must capture most of the high divergence from the ion source, and the second can provide a high-converging beam to the RFQ. The first solenoid is positioned farther downstream than the second, allowing most of the high-charge particles to remain unfocused and providing space for the vacuum gauge and gas injector. The second solenoid must ensure enough space for the cone collimator, the vacuum gauges, and maybe the chopper. The distance between solenoids is about 1 m to ensure diagnostics. The chopper location has strong impact on the SCC, the initial design using a

macroparticles tracking code [20] proposed placing the chopper directly in front of the cone collimator as when the chopper is on this will limit the area in which the SCC is affected. However, after a more detailed analysis using a self-consistent PIC code [21], it was determined that placing the chopper between the two solenoids and moving downstream the second solenoid allows for a more convergent beam at the RFQ entrance, achieving a transmission of over 95% through the RFQ. Moreover, the voltage required for the chopper is approximately 4 kV; in contrast, for the chopper located immediately after the cone collimator, the voltage needed to deflect the beam is approximately 7 kV. Reducing the voltage operation will also decrease the probabilities of beam trips. Furthermore, when the beam is deflected before being focused by the second solenoid, it experiences an expansion effect. As a result, the size of the beam that hits the cone collimator is about 3 times larger compared to when the chopper is placed after the final solenoid. In the case of the chopper after the solenoid, the beam is strongly focused by the field of the final solenoid before it is deflected by the chopper. Consequently, the increase in beam size by a factor of 3 reduces the peak power density value by a similar proportion. It is worth noting that the cone collimator's geometry has been optimized to achieve a low peak power density of 2.4 kW/cm², one quarter of the maximum accepted by the other ADS cone collimator [24]. Another relevant point is that the chopper is located close to solenoid 1 to take advantage of lower-voltage operation and a low beam power peak and make room for diagnostics between solenoids. However, coupling between the solenoid fields and the chopper electric fields can produce transverse coupling that will affect the downstream beam. Table VI provides the details of the configuration.

III. BEAM OPTICS MODEL

SCC occurs when a primary beam collides with the molecules of the residual gas inside the beam pipe, produced by the ion source or intentionally injected. This process generates oppositely charged particles, referred to as neutralizing particles, which accumulate in the beam's potential until reaching a stable state. This process produces a shield against SC forces, thereby reducing the effective SC force.

A. Physics process

SCC is a complex phenomenon involving interactions between the primary beam, residual gases, the created particles, and their environment. Therefore, accurately describing it requires including the various processes; however, increasing the number of interactions will make the computational time required unmanageable. Therefore, to achieve both high accuracy and manage acceptable computational required time, we discussed and

implemented the most important processes: (i) Ionization: Charged particles interact with the neutral gas, transferring energy during the collision, which results in the removal of one or more electrons from the gas. This process is the main mechanism for generating compensating particles and is the most common method used in SCC simulations. Here, we not only consider the ionizations of the proton beam with the residual gas, $H^+ + A^0 \rightarrow H^+ + A^+ + e^-$, but also the ionization of the electrons with the residual gas, $e^- + A^0 \rightarrow e^- + A^+ + e^-$. Experimental data were used [40–42] to simulate these processes. (ii) Charge exchange: The charge exchange process, often referred to as electron capture when dealing with positive primary beams, involves either the capture or loss of an electron from the primary beam, resulting in the transformation of the primary beam into a neutral gas ($H^+ + A^0 \rightarrow H^0 + A^+$) [40]. This process is significant because high pressure is frequently used to speed up the SCC buildup. However, this can lead to a reduction in the transmission of the primary beam, i.e., beam loss. (iii) Secondary electron emission from the surface: When primary particles or secondary electrons collide with the metal, they transfer their kinetic energy to the material's free electrons. This transfer enables the electrons to overcome the atomic bonding forces allowing them to escape into the surrounding environment. This interaction takes place at the beginning of the operation when the SC force is high, resulting in a large beam that strikes the cone collimator. It also occurs during chopper operation when the primary beam is intentionally aimed at the cone collimator. The secondary emission yield (δ), defined as the number of electrons emitted per incident particle, was 1.3 for this study. This yield corresponds to the impact of a 35-keV proton beam on copper [43].

Elastic scattering was not included because the particles involved in the interaction remain unchanged; therefore, it is not relevant for the SCC. Similarly, the excitation process resulting from the beam-gas interaction was also not considered, as the energy transferred to the gas does not remove the electrons from the gas.

Previous studies have included—in addition to ionizations by the primary beam—electron-induced ionizations [34], or charge exchange [44], or secondary electron emission [15]; however, this work is the first to report the inclusion of primary-beam and electron-induced ionizations, primary-beam charge exchange, and secondary electron emission from the surface.

B. Figures of merit

Beam transients are an outstanding issue in the final design of the JAEA-ADS linac. Therefore, for the LEBT optimization to achieve acceptable performance (ensuring sufficient beam quality to achieve a 30-MW proton beam with acceptable losses and short beam transients), it is important to define a figure of merit.

1. SCC degree (η)

SCC degree (η) is commonly expressed as a function of the beam potential [9,45] or the number of particles trapped over a certain beam cross section area [46].

For the former, $\eta(\phi, s, t)$ is represented as

$$\eta(\phi) = 1 - \frac{\phi_{\text{SCC}}(s, t)}{\phi_{\text{NoSCC}}(s, t)}, \quad (1)$$

where $\phi_{\text{SCC}}(s, t)$ is the potential in the center of the beam for the SCC case as a function of the position (s) and certain time (t). Similarly, $\phi_{\text{NoSCC}}(s, t)$ is the potential for the uncompensated case.

We adopted the latter definition:

$$\eta(\sigma_{\text{beam}}) = \frac{\#e^-(\sigma_{\text{beam}}, s, t)}{\#H^+(\sigma_{\text{beam}}, s, t) + \#A^+(\sigma_{\text{beam}}, s, t)}, \quad (2)$$

where $\sigma_{\text{beam}}(s, t)$ indicates the transverse size of the beam for a certain position (s) and time (t), e^- stand for electrons, H^+ for protons, and A^+ for the positive ion produced, e.g., Kr^+ .

Figure 4 illustrates the behavior of $\eta(\sigma_{\text{beam}})$ for various beam cross section sizes along the LEBT. $\eta(\sigma_{\text{beam}})$ remains relatively uniform across the beam's cross section throughout the LEBT; however, some differences are noticeable in the solenoid regions, particularly around 0.5 and 1.68 m.

$\eta(\sigma_{\text{beam}})$ begins at 0.2 and increases to 0.94 at the first solenoid. Between the solenoids, the SCC stabilizes, then decreases as it approaches the RFQ. Some discontinuities are observed at the entrance and exit of the solenoids, which are attributed to the transverse kick of the solenoid's fringe fields. A sensitivity analysis of Eq. (2) is presented in Appendix A.

2. Compensation time (τ^*)

To describe the SCC process time, two-time parameters are adopted: stabilization time (τ_{ss}) and compensation

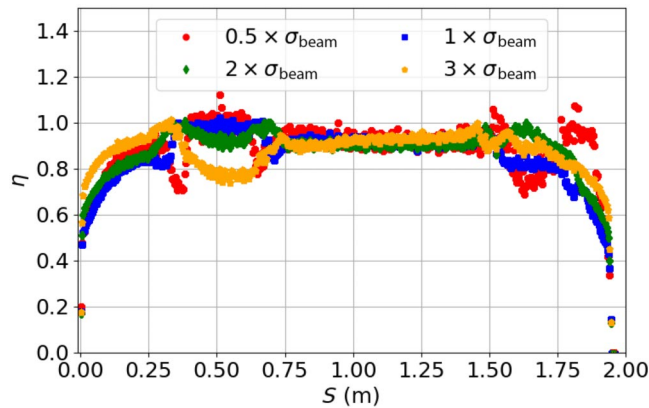


FIG. 4. SCC degree at different beam transverse for the SCC buildup case at 110 μs .

time (τ). τ_{ss} refers to the total time necessary to achieve a steady-state equilibrium in the SCC process, while the τ is the associated time required for the beam to ionize the gas to produce the neutralizing particles (i.e., the opposite beam polarity particles).

As a rule of thumb [9,12,47], the relationship between τ_{ss} and τ is given by

$$\tau_{ss} \approx 2 \sim 3 \times \tau = 2 \sim 3 \times \frac{1}{n_g \sigma_i v_b}, \quad (3)$$

where n_g is the gas number density in the beam line, σ_i is the cross section of the gas, and v_b is the speed of the beam.

τ can be derived from the relation between the mean free path between collisions (λ) and v_b by [48,49]:

$$\tau = \frac{\lambda}{v_b} = \frac{1}{\nu} = \frac{1}{n_g \sigma_i v_b}, \quad (4)$$

where ν is the collision frequency.

In 1971, Evans and Warner [50] used Eq. (4) to select the residual gas pressure that ensured the required time for electron accumulation was shorter than the pulse duration. One decade later, Baconnier *et al.* [46] presented a general formula to consider the contribution of multiple residual gases:

$$\frac{1}{\tau_t} = \sum_i \frac{1}{\tau_i}, \quad (5)$$

where the index i represents different gases. This is obtained by considering the independence of collision events, such that the total collision frequency is the sum of all individual contributions:

$$\nu_t = \sum_i \nu_i = \sum_i \frac{1}{\tau_i}. \quad (6)$$

We took a further step and included the contribution of neutralizing particles, also considering the independence of the events:

$$\begin{aligned} \frac{1}{\tau^*} &= \sum_{i=1} \frac{1}{\tau_{b,i}} + \sum_{i=1} \frac{1}{\tau_{n,i}}, \\ &= \sum_{p=b}^n \sum_{i=1} \frac{1}{\tau_{p,i}}, \\ &= \sum_{p=b}^n \sum_{i=1} \frac{P \sigma_i v_p}{k_B T}, \end{aligned} \quad (7)$$

where the index p represents different types of particles: the primary beam b and the neutralizing particles n . The index i refers to the cross section of the injected gases.

TABLE II. Testing cases. The pressure was 5×10^{-4} Pa.

Case	Process	Residual gas
M1	$H^+ + A^0 \rightarrow H^+ + A^+ + e^-$ $e^- + A^0 \rightarrow e^- + A^+ + e^-$	Kr
M2	$H^+ + A^0 \rightarrow H^+ + A^+ + e^-$ $e^- + A^0 \rightarrow e^- + A^+ + e^-$	Kr + H ₂

The residual gases are assuming as ideal gases:

$$n_{g,i} = \frac{P}{k_B T}, \quad (8)$$

where k_B denotes the Boltzmann constant, T is the temperature of the residual gas, and P represents the pressure.

To evaluate how well Eq. (7) describes the evolution of the beam parameters, we compared with the decay time (τ_{decay}) obtained by fitting the emittance evolution in the simulations, i.e., $\varepsilon(t) \propto \exp(-t/\tau_{\text{decay}})$ [12,17,35].

The testing cases considered the proton beam and electron ionization processes for using single and double residual gases, Table II. A sensitivity analysis of Eq. (7) is presented in Appendix A.

Figure 5 shows the horizontal normalized rms emittance and their corresponding fit for the simulations.

Equation (7) was evaluated using the data presented in Table III. The cross section depends on particle energy, in the case of protons, the beam energy was 35 keV, while for the electrons, the average value obtained from the simulations in both scenarios was about 8.5 eV. In the case of H₂ gas, a factor of 2 was considered in the density as suggested by Batygin *et al.* [35].

The results displayed in Table IV indicate that $\tau^* \approx 2 \times \tau_{\text{decay}}$, similar result was presented by Valerio-Lizarraga *et al.* [12]. Generally, the stability of an

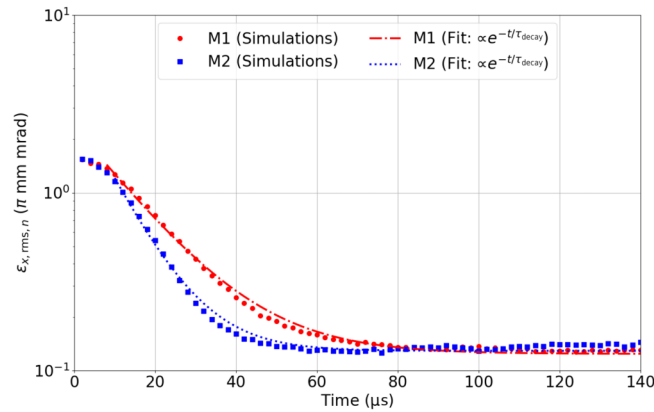


FIG. 5. Evolution of the horizontal normalized emittance for M1 (red) and M2 (blue) cases. The points are the simulation results, and the lines are the fits using an exponential decay.

TABLE III. Parameter to estimate the SCC. The speed of the electron, v_{electron} , is computed as the average energy of the electron in the simulation.

Parameter	Value
P (Pa)	5×10^{-4}
T (K)	300
k_B (J/K)	1.38×10^{-23}
v_{proton} (m/s)	2.59×10^6
$\sigma_{H_2,\text{proton}}$ (m ²)	1.75×10^{-20} [40]
$\sigma_{Kr,\text{proton}}$ (m ²)	7.09×10^{-20} [40]
v_{electron} (m/s)	5.3×10^6
$\sigma_{H_2,\text{electron}}$ (m ²)	2.77×10^{-20} [41]
$\sigma_{Kr,\text{electron}}$ (m ²)	4.38×10^{-20} [42]

TABLE IV. Time comparison.

Case	τ^* (μ s)	τ_{decay} (μ s)
M1	31.8	15.1
M2	18.8	9.6

exponential decay is achieved about $5 \times \tau_{\text{decay}}$, which falls between 2 and $3 \times \tau^*$. Additionally, Figs. 18 and 37 indicate that after 60 μ s ($\approx 3 \times \tau^*$), the parameters reached a nearly stable state. This level of variation can be effectively regarded as a near-steady state. Therefore, the value of τ^* discussed in this work is consistent with the SCC studies published in the literature [9,12,47].

It should be noted that this study simulated the SCC considering not only the processes presented in Table II but also proton charge exchange and secondary emission. However, these mechanisms have a limited impact, resulting in a slight increase in τ_{decay} , 11 μ s. This is 15% larger than M2 cases.

C. Pressure

A key factor in reducing τ^* is pressure, as highlighted in the sensitivity analysis in Appendix A. While higher pressure speeds up the process, it can also decrease beam transmission by intensifying charge-exchange interactions and increasing the likelihood of RFQ trips. Figure 6 compares the variation of τ^* varies and the beam transmission as a function of the pressure.

Beam transmission was computed by using the Beer-Lambert law [51]:

$$T = \exp\left(-\left(\frac{\sigma_c PL}{k_B T}\right)\right), \quad (9)$$

where σ_c is the ion-capture cross section for the residual gas, P is the pressure, L is the LEBT length, k_B is the Boltzmann constant, and T is the temperature. High proton

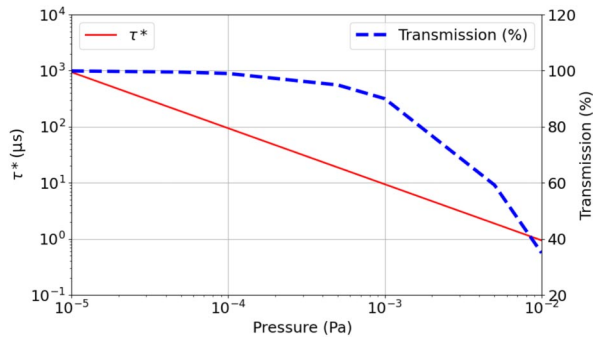


FIG. 6. Comparison of changes in τ^* and transmission as a function of the pressure.

transmission (exceeding 95%), a short time τ^* —on the order of a few tens of microseconds—and a relatively low pressure (close to 10^{-4} Pa) were considered to reduce RFQ trips. For this study, a pressure of 5×10^{-4} Pa was selected as a compromise among the various requirements.

D. Residual gases

As mentioned above, operation at low pressure is planned; therefore, the injected residual gas plays a significant factor influencing the SCC buildup. In SCC studies, it is common practice to inject noble gases (e.g., Ar or Kr) due to their larger cross sections [40], which result in high electron production via ionization. However, the beam source itself constitutes an additional source of residual gas. To analyze how multiple gas ionizations affect SCC formation, this study simultaneously simulates the contribution of beam source waste gas and injected waste gas. In the case of the JAEA-ADS linac, the proton source is expected to generate a certain amount of H_2 . As for the injected gas, three gases were considered: Ar, Kr, and Xe. Xe has the largest cross section, making it the most effective for ionization but also for proton capture. Ar and Kr are the most used gases in LEBTs, providing several benchmark studies [12,14,15,52]. Among them, Kr was selected because it offers a good balance between high electron production and acceptable proton capture at low pressure.

E. Heavy-mass parasitic ion species

Hydrogen-fed proton sources not only generate a proton beam but also produce heavy-mass ion impurities such as H_2^+ and H_3^+ . The ion source model at JAEA-ADS delivers a proton current of 25 mA, along with parasitic currents of 2.5 mA for H_2^+ and 1.25 mA for H_3^+ [19]. The total beam power amounts to 933 W, which consists of 875 W from protons, 44 W from H_2^+ , and 15 W from H_3^+ .

Due to differences in mass-to-charge ratios and energy levels between the parasitic ions and the proton beam, the parasitic ions will not be properly focused by the solenoids in the LEBT. Consequently, these parasitic ions will create

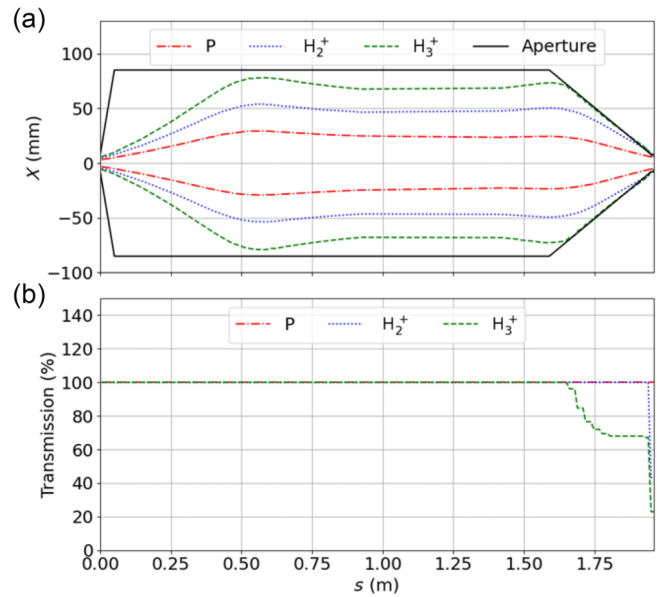


FIG. 7. Horizontal envelopes (a) transmission (b) at the LEBT. The dashed-dotted red line is for proton, dot blue line for H_2^+ and dashed green line H_3^+ .

a more diffuse envelope compared to the concentrated and abundant proton beam, resulting in less effective interaction with the gas, as shown in Fig. 7(a).

Most of the lost parasitic ions will be removed at the cone collimator [Fig. 7(b)] and at the initial section of the RFQ (Fig 8), as reported by other injectors [53,54]. The distribution of beam loss at the cone collimator and the RFQ will vary as the SCC builds up. Initially, when SCC is nearly zero, most of the parasitic ion beam will be uniformly intercepted by the cone collimator, resulting in a maximum average power density of less than 1 W/cm². As SCC grows, most parasitic ions will be transported through the RFQ; however, they will be lost in the first RFQ cells due to falling outside the acceptance phase,

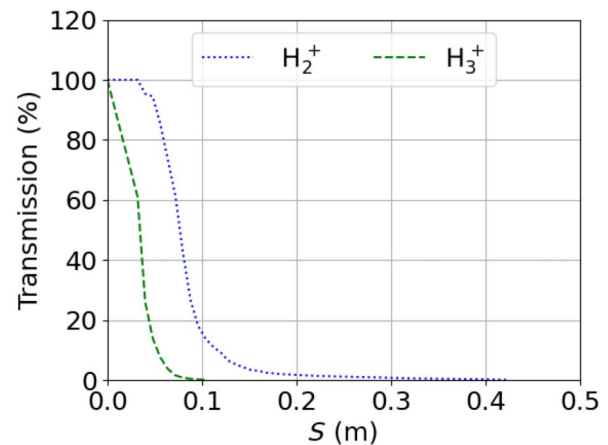


FIG. 8. RFQ transmission for H_2^+ (dotted blue line) and H_3^+ (dashed green line).

leading to a maximum local power loss density of less than 0.4 W/cm^2 . The contribution of these beam losses does not pose a problem for the beam loss budget in the cone collimator and the RFQ. These parasitic ionic species were excluded from the simulations because their contribution to the SCC is not significant, as noted by other authors [15]. Additionally, including them would increase computation time.

F. Field maps

The model employed 3D field maps of both the solenoid and the electrostatic chopper to simulate fringe field effects. This is crucial due to the proximity of solenoid 1 to the chopper; the axial field of the solenoid can leak into the chopper, leading to field coupling that may adversely affect beam performance.

The solenoid model was developed in CST studio [55], based on the J-PARC solenoids, and has been utilized since the initial studies [30] (see Fig. 9).

The electrostatic chopper model is based on the SPIRAL2 and ESS choppers [56,57]. Figure 10 illustrates the electrode geometry at the top and the normalized deflecting electric field at the bottom. The bottom electrode is grounded and slightly curved, forming an angle of 7.7° with the xz -plane. This design reduces the fringe field length by 3% compared to a flat electrode.

In the model, the rise and fall of the chopper's voltage will follow an exponential curve as a first-order RC circuit:

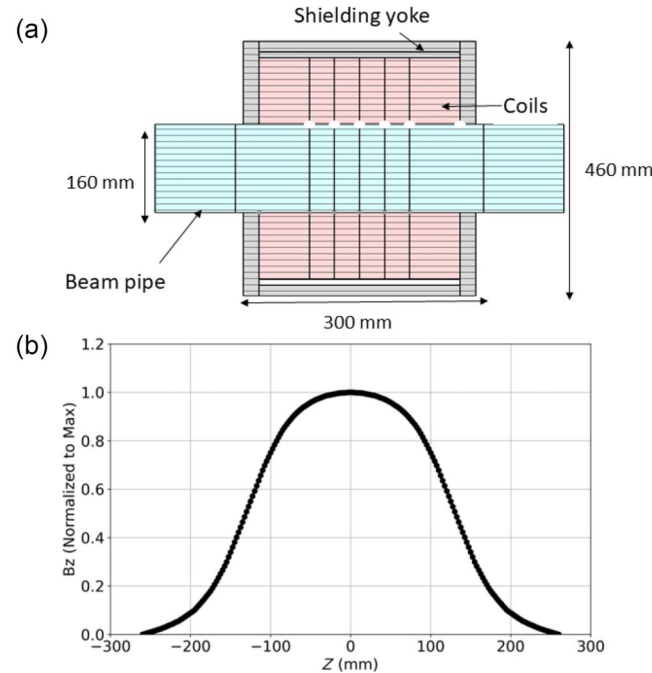


FIG. 9. 3D Solenoid model: geometry dimensions (a) and the normalized longitudinal magnetic field at the center (b).

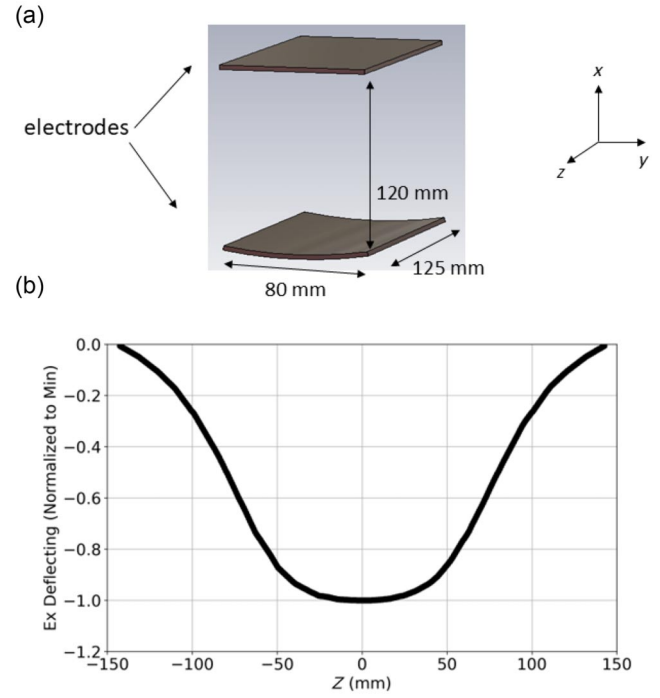


FIG. 10. 3D electrostatic chopper model: geometry dimensions (a) and the normalized deflecting electric field at the center (b).

$$V(t) = \begin{cases} V_0(1 - \exp(-t/\tau_{\text{chop}})) & \text{rise} \\ V_0 \exp(-t/\tau_{\text{chop}}) & \text{fall} \end{cases}, \quad (10)$$

where $\tau_{\text{chop}} = R_T C_T$, R_T is the impedance of the system and C_T is the total load capacitance. C_T comprises the capacitance of the electrodes (C_{elec}), the high-voltage switch (C_{HV}), and the coaxial feedthroughs (C_{Feed}). Since the SPIRAL2 and ESS choppers [56,57] are suitable for the operation of our chopper, we will adopt the same electrical design configuration, which involves a direct connection between the feedthrough and the high-voltage switches. The main distinction in our choppers lies in the shape and spacing of the electrodes when compared to the SPIRAL2 and ESS choppers, consequently the main variation will be in C_{elec} . In our model, the value of C_{elec} is approximately 5 pF, which is lower than the capacitance associated with the SPIRAL2 design described in [58]. After discussions with the colleague responsible for designing the choppers for SPIRAL2 and ESS, we estimate that the C_T of our system will be around 60 pF [59]. Consequently, 50- Ω impedances lead to a $\tau_{\text{chop}} \approx 3 \text{ ns}$. Therefore, the rise and fall times are approximately $5 \times \tau_{\text{chop}} \approx 15 \text{ ns}$. While this may seem like a strong assumption, it is worth noting that discussions with chopper designers [59]—and the fact that other chopper designs have reported comparable times [60,61]—indicate that it is a viable assumption.

Figure 11 shows the one-dimensional field maps for the solenoids and the chopper. The electric field produced by

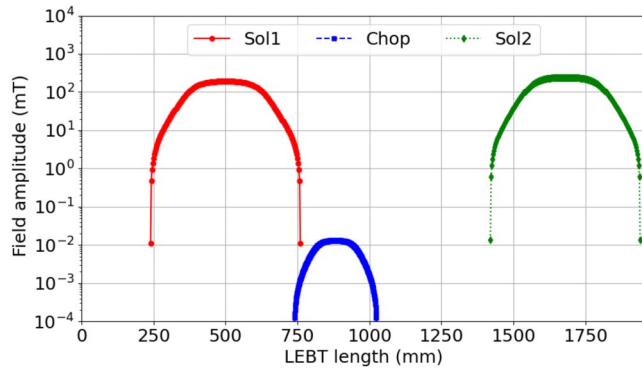


FIG. 11. 1D field maps in the LEBT.

the chopper has been converted to mT to facilitate direct comparison with the solenoid fields. There is an overlap between solenoid 1 and the chopper that spans approximately 30 mm. In this overlapping region, the maximum field amplitude is less than 1×10^{-2} of the overall maximum amplitude. Since this overlap is confined to low amplitudes and only occurs when the chopper is on, simulations indicated that coupling effects lead to an increase of less than 3% in emittance growth compared to the uncoupled fields case.

G. PIC program and conditions

An early study [30] was done considering a constant SCC by parts, e.g., from the LEBT's entrance to the first solenoid, the SCC was 60%, using TRACEWIN program [62]. As a step forward, we envisaged a self-consistent SCC process by simulating the particle-gas and particle-environment interactions.

The SCC process has been simulated in programs such as WARP [63], IBSimu [64], SOLMAXP [65], Cartago [47], and Bender [11]. Of these programs, WARP was selected because it has been benchmarked with experiments [13,16,31,44,52,66–68], can be run in parallel reducing the simulation time, and is open-source software allowing the implementation of special functions.

WARP is an open-source PIC package designed to simulate plasmas and high-current particle beams in a variety of applications. WARP adopts the latest programming techniques, such as object-oriented programming, parallelism, and PYTHON scripting. Figure 12 depicts the PIC loop in WARP. Between steps 1 and 2, the interactions between the particle-gas and particle-environment were simulated using Monte Carlo methods. The external fields, i.e., solenoid fields, were applied between steps 4 and 1. Itagaki *et al.* provided us with an example of the WARP code used for LIPAC LEBT studies [52]. The script was modified to include charge exchange processes, implement double gas simulations, and incorporate post-processing tools, such as tracking emittance and Twiss parameters.

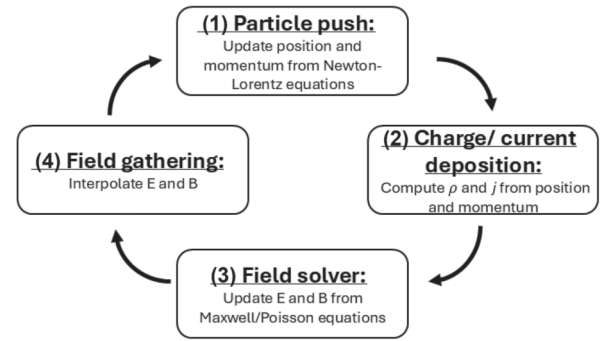


FIG. 12. WARP's standard PIC loop [69].

To ensure accuracy and stability in the PIC simulation, the mesh size (Δr) and time step (Δt) were chosen to solve the equation of motion of the physical phenomenon properly by considering the shortest timescale defined by the electron plasma frequency ($\omega_{p,e}$) and the plasma length scale [i.e., Debye length (λ_D)]. The changes in beam size along the LEBT produce differences in the scale space and time in which the motion equations are solved. Therefore, we used mesh refinement [70] as an efficient way to overcome the variation in space and time at the different zones of the simulation domain. The JAEA-ADS LEBT model mesh is composed of a main mesh with a size of 4 mm plus three refinement meshes, each of them with half the mesh size of the preceding mesh, as presented in Fig. 13.

The last refinement mesh, mesh size of 0.5 mm, is applied in the region where the beam distribution is more concentrated; consequently, λ_D is the smallest: at the entrance, first 500 mm, and the exit, last 250 mm. Most of the beam is simulated with a mesh size no larger than 2 mm.

In addition, to improve the accuracy of the results, it was necessary to simulate a large number of macroparticles per

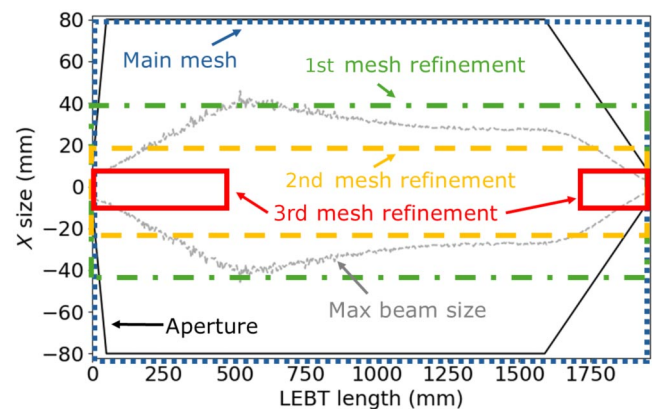


FIG. 13. Mesh distribution for the JAEA-ADS LEBT model in WARP. The main mesh (blue-dotted line) has a mesh size of 4 mm; the first refinement mesh (green-dashed-dotted line), 2 mm; the second one (orange-dashed line), 1 mm; and the third refinement mesh (red-solid line), 0.5 mm.

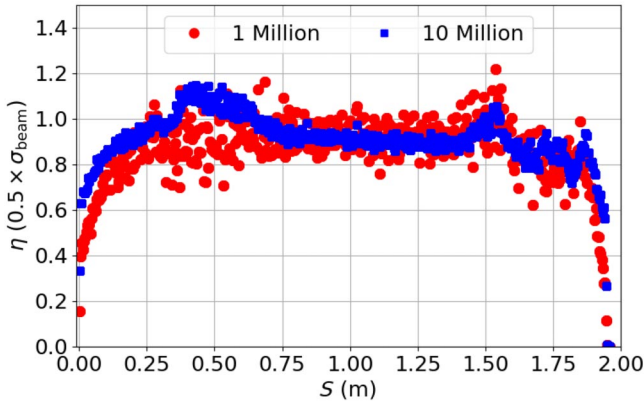


FIG. 14. Comparison of the η for the beam center along the LEBT for 1 million (red circle) and 10 million (blue square) macroparticles.

mesh cell to reduce artificial numerical heating [71], as shown in Fig. 14. Table V presents the simulation conditions adopted by the LEBT studies based on the literature [72].

Figure 15 shows the energy and beam loss rate for 1-W loss in the JAEA-ADS linac. At 30 MW beam power, which is the last part of the linac, a distribution of 3×10^7 macroparticles is necessary to estimate beam losses on the order of 1-W at the end of the accelerator. However, due to a computational resource constraint, we decided that a beam distribution of 10^7 macroparticles would suffice for a proper beam loss estimation close to the end of EllipR1, which covers most of the problematic sections of the main linac. The beam simulation studies showed a ratio of acceptance to maximum envelope size—almost a factor of 2 at the EllipR1 and EllipR2 sections, see Figs. 24, 27, 36, and 44. This suggests that increasing by a factor of 3 the number of macroparticles will not dramatically increase the beam size envelopes, as the particles are likely to occupy both the halo and the core. Instead, we anticipate that the artificial growth of the beam will be minimized, which will subsequently improve the accuracy of the beam size. As a result, no beam losses are expected. The same assumption was used for the beam optimization of the main linac [2].

A 35-keV proton beam takes approximately $0.8 \mu\text{s}$ to travel the 1.96 m length of the LEBT. Therefore, the data points were initially stored every $1 \mu\text{s}$. However, since SCC buildup requires simulating a beam time of tenths of

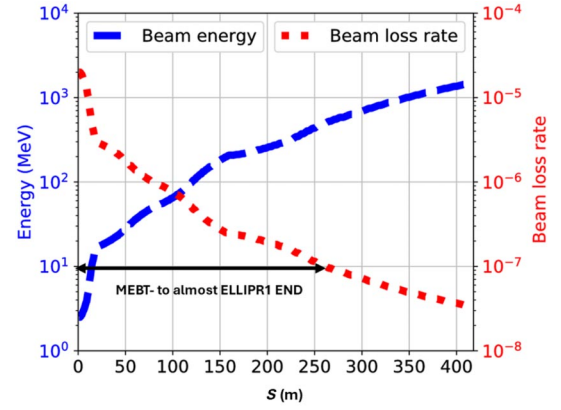


FIG. 15. Beam energy of the linac (blue dashed line) and 1 W/m beam loss rate (red dotted line).

μs (see Fig. 19), the computation time increases to several hours, as does the storage of the saved data to several gigabytes. Therefore, we selected a storage interval of $2 \mu\text{s}$, as a compromise between a short step size and the available computational resources.

The LEBT simulation conditions were established according to the previous discussion. Table VI presents

TABLE VI. Main parameters for the SCC JAEA-ADS LEBT simulations.

Parameter	
Primary beam	Proton
Beam current (mA)	25
Beam energy (keV)	35
Process	Ionization ^a Charge exchange ^b Secondary electron emission from the surface ^b
Residual gases	H ₂ and Kr
Pressure (Pa)	5×10^{-4}
Solenoid 1 field (mT)	191
Solenoid 1 position (m)	0.5
Solenoid 2 field (mT)	242
Solenoid 2 position (m)	1.68
Chopper location (m)	0.862
Chopper voltage (kV)	4
Length (m)	1.96

^aFor protons and electrons.

^bOnly for protons.

TABLE V. PIC simulations conditions.

Condition	Reason	Adopted value
$\Delta r < 3.4\lambda_D$ (5–0.6 mm)	Avoid numerical instabilities	$4 \text{ mm} \geq \Delta r \geq 0.5 \text{ mm}$ (Mesh refinement)
$\Delta t < 2/\omega_{p,e}$ ($> 1 \text{ ns}$)	Avoid aliasing	$\Delta t = 0.1 \text{ ns}$
$v_{\text{beam}} (= 2.56 \times 10^6 \text{ m/s}) < \Delta r/\Delta t$	Ensure convergence	$\Delta r_{\text{min}}/\Delta t = 5 \times 10^6 \text{ m/s}$
Large number of macroparticles	Reduce numerical heating	Number of macroparticles $> 10^7$

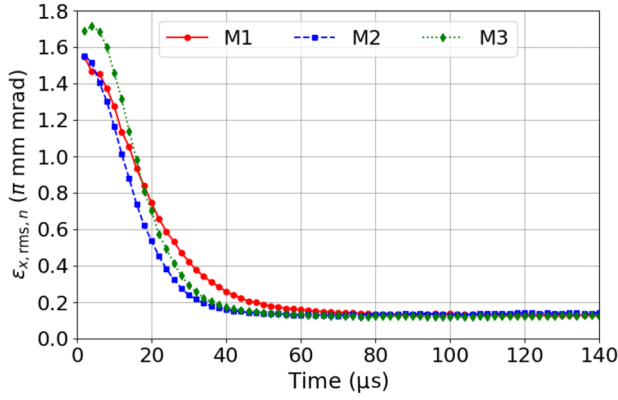


FIG. 16. Horizontal normalized rms emittance ($\epsilon_{\text{norm}, \text{rms}, x}$) transients for the three models. M1 simulated the proton and electron ionization for Kr gas. M2 utilized the same ionization as M1 but simultaneously used two gases: Kr and H_2 . Finally, M3, in addition to the process performed by M2, considered the proton charge exchange and the secondary electron emission.

the details. Figure 16 shows the emittance transients for three cases. In all cases, the proton and electron ionization contributions are simulated. In case M1, only the ionization process and Kr as the residual gas were considered. M2 is similar to M1 but includes the residual gas H_2 . Finally, M3 is a more complete version of M2, to which charge exchange and secondary electron emission have been added. It is noticeable that M2 cases reached the stability about 40 μs , which is roughly two-thirds faster than M1 due to the ionization of H_2 . M3 starts with a higher emittance compared to the previous cases, primarily due to secondary emission electrons generated by the impact of the large beam size on the collimator. These additional electrons are mainly trapped in the outer part of the beam, resulting in a hollow beam profile that ends in a larger emittance beam. Over time, the distribution of electrons becomes more uniform throughout the beam, leading to a more convergent beam that produces fewer secondary electrons. Ultimately, M3 stabilizes around the same time as M2.

IV. RESULTS

A. SCC buildup

Figure 17 shows the effect of the SCC on the horizontal distribution in the initial part of the simulation, where the SCC is basically zero (top) and then when it reaches a stable SCC (bottom) at the LEBT.

The evolution of the beam parameters at the exit of the LEBT is presented on Fig. 18. Around 60 μs , which corresponds to $3 \times \tau^*$ for this model, the emittance and α and β Twiss parameters reached certain convergence, which the variation is less than 5%, except for the longitudinal Twiss parameter α , which remains around 7%. Figure 19 shows the value of η at the center of the beam

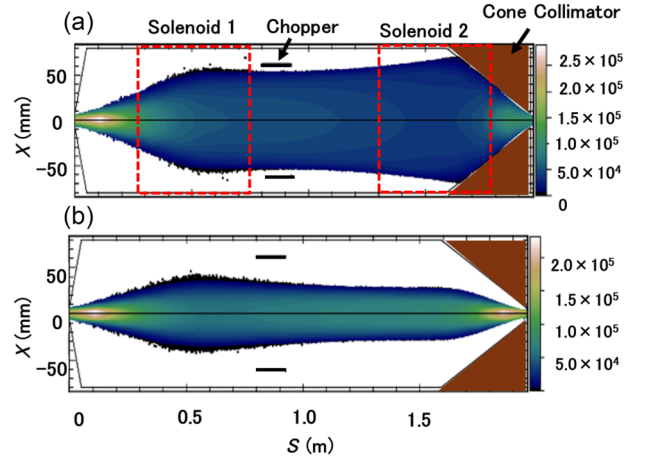


FIG. 17. Beam horizontal distribution at 2 μs (a) and 110 μs (b). The red dotted rectangles indicate the area of the solenoid fields.

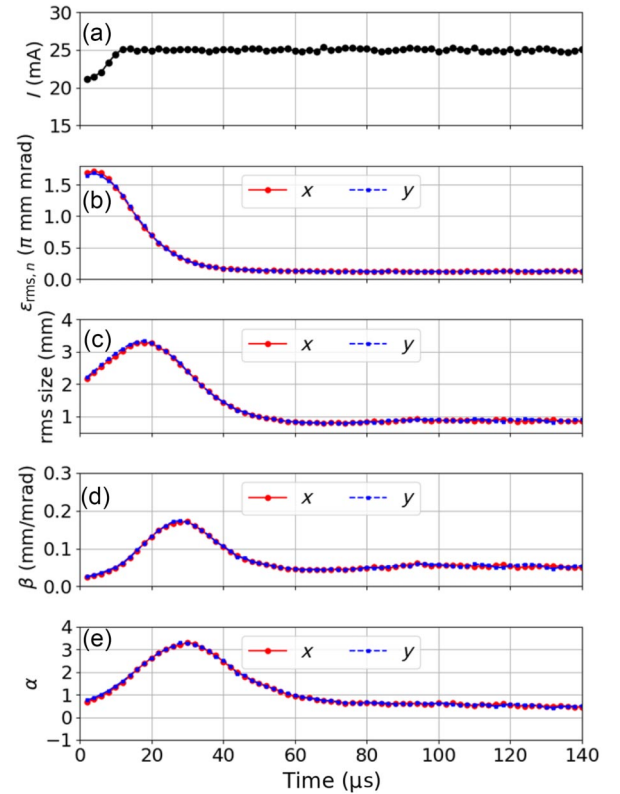


FIG. 18. Beam transient parameters at the end of the LEBT during the SCC buildup. Current (a), normalized rms emittance (b), rms size (c), β -Twiss (d), and α -Twiss (e).

along the LEBT. It can be observed that the value of η nearly reached stability after 40 μs ($2 \times \tau^*$). The value of η in the latter part, between the second solenoid and the RFQ, takes longer to stabilize, which explains the slow convergence of α parameter [Fig. 18(e)].

The output beam distributions from the LEBT simulations were used as input for the RFQ simulations. The

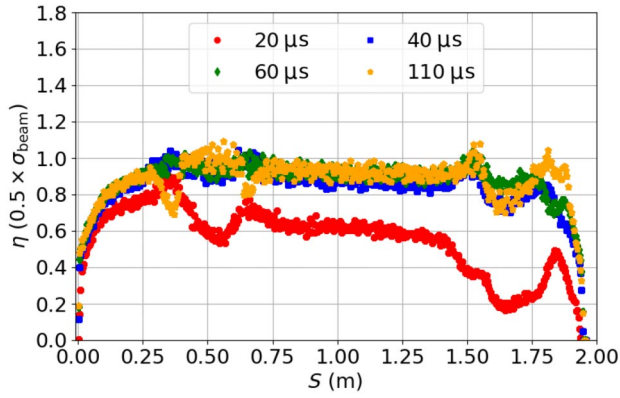


FIG. 19. SCC degree for the beam center during the SCC buildup.

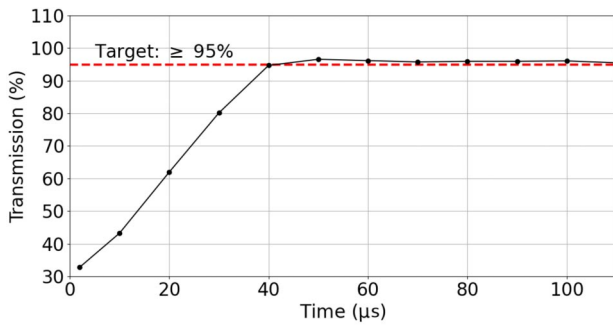


FIG. 20. RFQ transmission as a function of time during the SCC buildup. The red dotted line shows the target transmission, $\geq 95\%$.

JAEA-ADS RFQ simulations were done in RFQGEN code [73]. The RFQ studies found the beam reached its target transmission, $\geq 95\%$, after 40 μs , as is shown in Fig. 20.

Figure 21 presents the distribution of current losses as a function of the beam energy and time in the RFQ. All the losses occurred below 2.16 MeV, which prevents copper activation from proton loss. Two current loss peaks are located at energies around 216 and 400 keV, these peaks

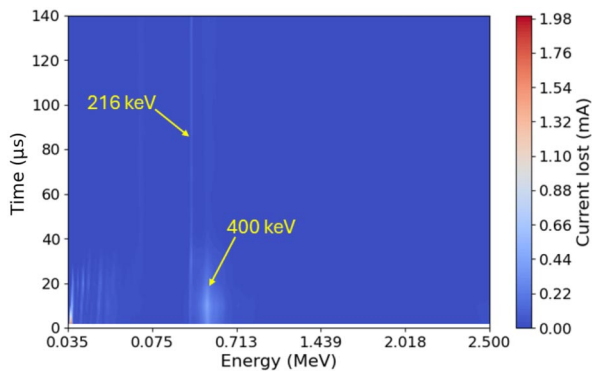


FIG. 21. Current losses distribution in the RFQ as a function of the beam energy and time during the SCC buildup.

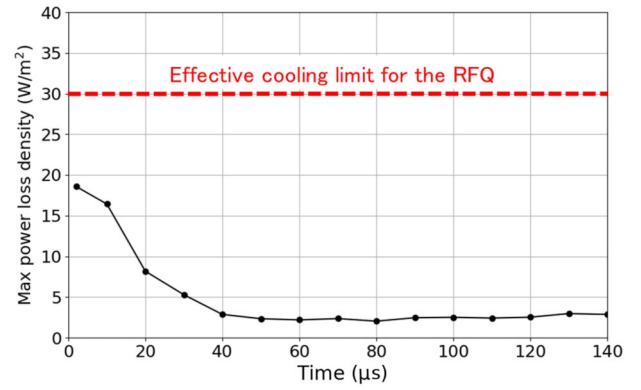


FIG. 22. Maximum power loss density in the RFQ as a function of the time.

remain, however, the losses have narrowed as the steady state is reached. The maximum local power loss density in the RFQ reached two-thirds of the limit for an efficient cooling in the RFQ, showing that the transient losses do not represent a threat for the RFQ operation, shown in Fig. 22.

The evolution of the output beam parameters in the RFQ is presented in Fig. 23. The transverse emittance and Twiss parameters fall within the acceptable tolerances established for the main linac [2] starting from 40 μs . Additionally, from 60 μs onward, both the longitudinal emittance and the Twiss parameter β are within acceptable limits; only α continues to exceed the threshold by 2%.

Finally, the beam is transported from the MEBT to the target using TRACEWIN program, see Fig. 24. The beam power is calculated under the assumption that the beam parameters remain constant over a time window of 10 μs . This is a conservative estimate for the first 60 μs but reasonable for the time that follows.

Figure 25 shows the beam loss transients that occur during the SCC formation from the MEBT to the reactor target. Losses in the superconducting linac were limited to the first 40 μs and the initial 100 m, specifically at the entrance of the second HWR cryomodule and the sixth SSR2 cryomodule. At this region, the number of macro-particles was sufficient to provide enough statistics for estimating the loss at a level of 1 W/m, and these losses remained below the maintenance limit. The results indicate that the most critical point happens not at the start—when the SCC reaches its minimum—but approximately 20 μs ($1 \times \tau^*$) after the process begins, as shown in Fig. 26. At the beginning of SCC buildup, the mismatch and emittance growth are the highest compared to the steady-state conditions. At this time, the majority of the nonoptimal beam is intercepted at low energy by the conical collimator and the RFQ. Similar approach, exploiting the RFQ acceptance to remove stripping protons for the linac, was used for CSNS colleagues [74]. As a result, the transported current downstream is smaller, 30% at Zero SCC. Thus, at low space charge, the beam instabilities caused by the mismatch are

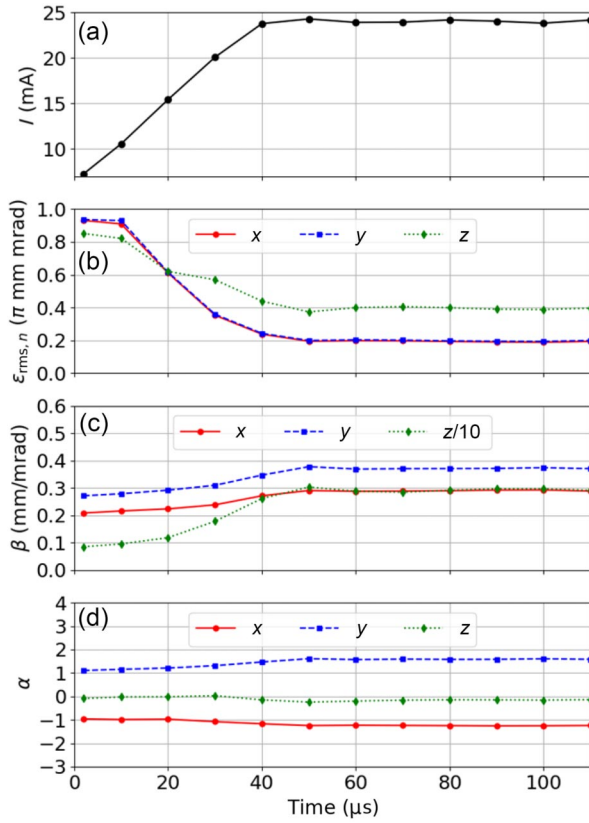


FIG. 23. Beam transient parameters at the end of the RFQ during the SCC buildup. In the β graph (c), the amplitude in the z -plane was scaled down by a factor of 10 to match the scale of the transverse plane. Current (a), normalized rms emittance (b), rms size (c), β -Twiss (d), and α -Twiss (e).

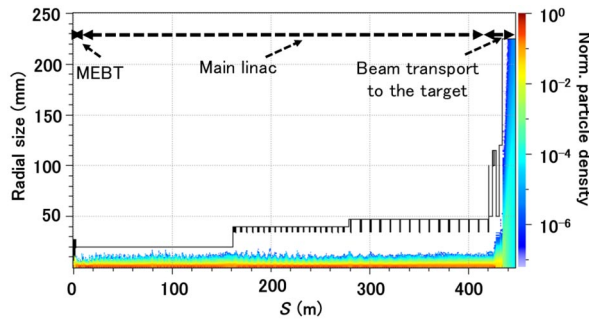


FIG. 24. Radial beam distribution from the MEBT to the target after reaching 110 μs.

less severe. At 20 μs, the beam current was approximately 60% of its nominal value, with beam mismatches around 25% and emittance growth of 100%. Noteworthy, the beam loss time confinement shows that, once transverse tolerances (such as emittance and Twiss parameters) are satisfied and the longitudinal tolerances are close to being met, the beam can be transported without losses.

The maximum radial size at times of 2, 20, and 110 μs is plotted and compared in Fig. 27. It can be observed that at

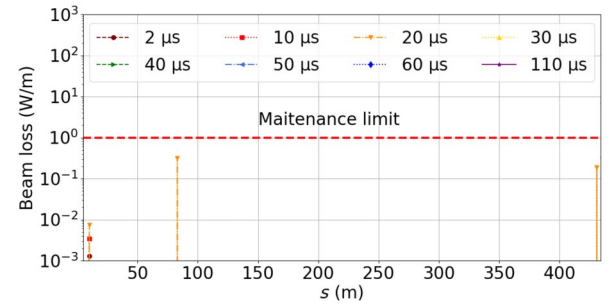


FIG. 25. Beam transient losses from the MEBT to the target during the SCC buildup. The transients correspond to the first 60 μs, where the parameter variations are more noticeable, while data for up to 110 μs are included.

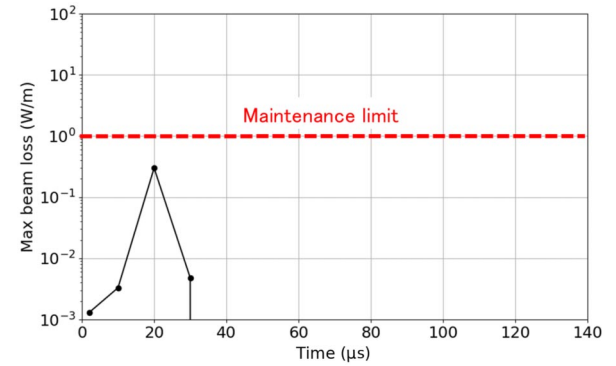


FIG. 26. Maximum local loss as a function of time during the SCC buildup.

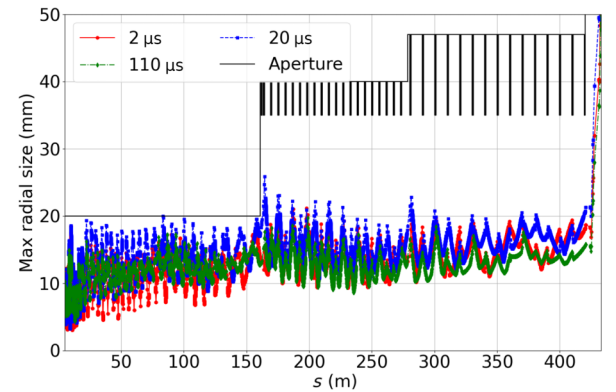


FIG. 27. Maximum radial beam size from the MEBT to the beam transport. The initial stage, the lowest SCC compensation level, 2 μs, is plotted in a solid red line, the case with higher losses, 20 μs, in a dashed blue line, and the 110 μs, dotted-dashed green line.

20 μs, the beam envelopes exhibit the greatest amplitudes as they approach the beam aperture in the low-beta section (the first 170 m). Regarding the proper assessment of beam loss at the end of the linac, the ratio between the aperture and the maximum envelope is approximately two to one.

This suggests that beam losses are unlikely, even if the number of macroparticles is tripled. Increasing the number of macroparticles improves the precision and stability of the simulated beam envelope without causing a significant increase in its size.

In the beam transport section, a loss of less than 0.2 W/m was recorded for the 20 μ s. While this loss could increase with a higher number of macroparticles, it occurs within the reactor vault, where transient losses exceeding 1 W/m are acceptable due to remote handling operation.

B. Chopper on

Figures 28 and 29 show that, 440 ns after chopper activation, beam transmission is zero. Due to the variability in the timescale at which the beam changes during chopper activation, data were saved at different intervals ranging from 100 to 5 ns, see Fig. 28.

Figure 30 illustrates η at the center of the beam for the time intervals mentioned earlier. It can be seen how rapidly the SCC is destroyed as time passes. However, due to the solenoid shielding and the fact that the beam shape remains unchanged, η remains virtually constant during the initial part of the LEBT.

The simulations in the RFQ model, the current losses distribution, Fig. 31, indicate an increase in the losses

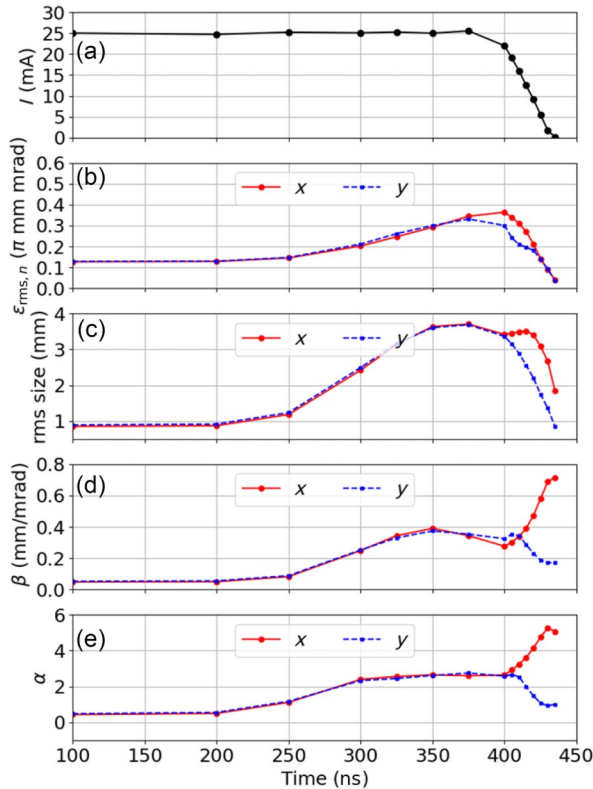


FIG. 28. Beam parameter transients at the end of the LEBT due to turning on the chopper. Current (a), normalized rms emittance (b), rms size (c), β -Twiss (d), and α -Twiss (e).

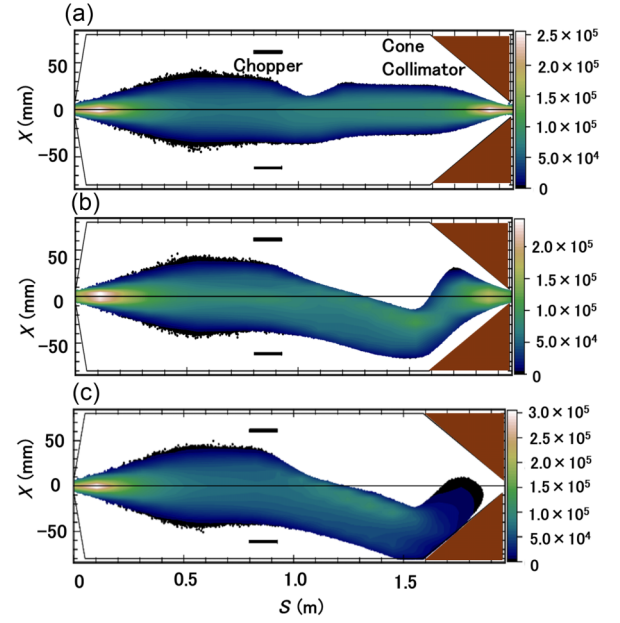


FIG. 29. Horizontal distribution along the LEBT at different times when the chopper is on. (a) 100 ns, (b) 250 ns, and (c) 440 ns after the chopper is turned on.

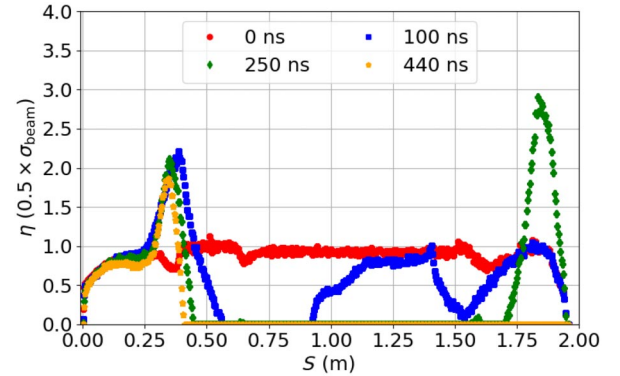


FIG. 30. SCC degree for the beam center after the chopper was turned on.

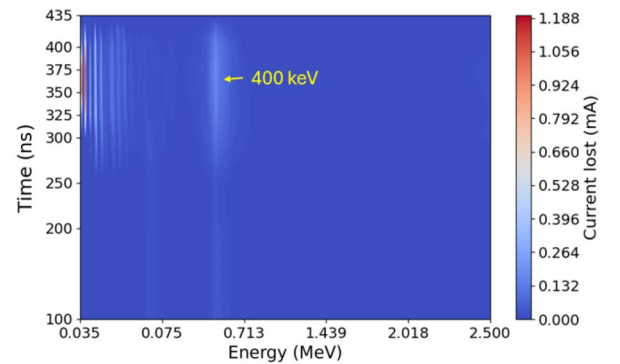


FIG. 31. Current losses distribution as a function of the energy in RFQ and time due to turning on the chopper.

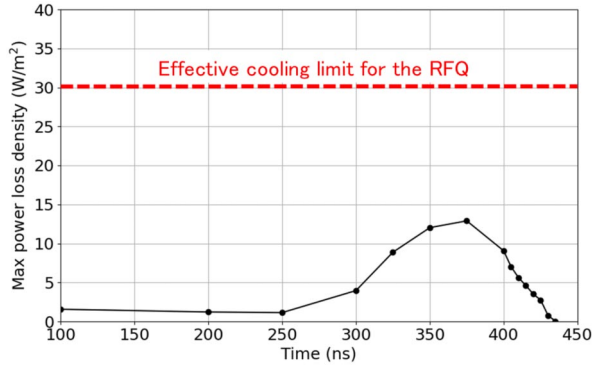


FIG. 32. Maximum power loss density in the RFQ as a function of the time.

between 300 and 410 ns. All the beam losses remain below 2.16 MeV, the maximum power density is half of the cooling limited efficiency at 375 ns after chopper is on, Fig. 32. These losses do not pose a problem for the operation of the RFQ.

Figure 33 presents the beam current, emittance and Twiss parameters at the end of the RFQ. After 300 ns, the emittances and mismatches exceeded the main linac tolerances. As consequence of that, the losses at the main linac

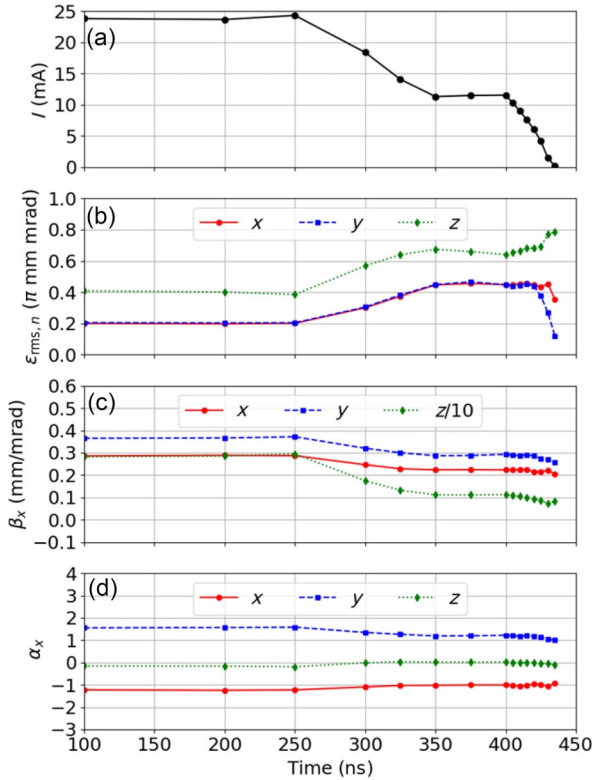


FIG. 33. Beam transient parameters at the end of the RFQ due to turning on the chopper. In the β graph (c), similar as in Fig. 23(c), the amplitude in the z -plane was scaled down by a factor of 10 to match the scale of the transverse plane. Current (a), normalized rms emittance (b), rms size (c), β -Twiss (d), and α -Twiss (e).

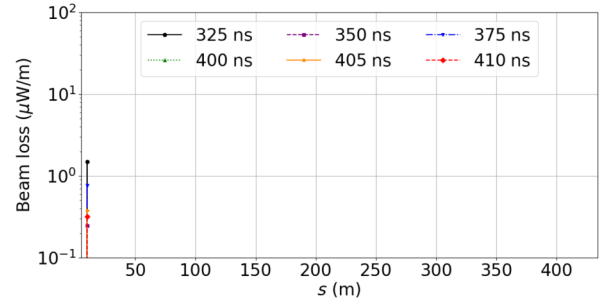


FIG. 34. Beam transient losses along the linac and the beam transport due to turning on the chopper. The beam losses were recorded from 325 up to 410 ns.

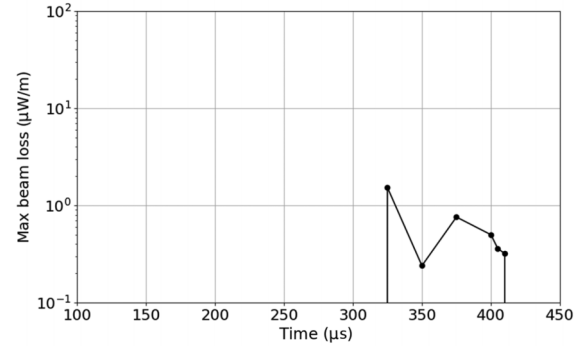


FIG. 35. Maximum local loss as a function of time when the chopper is on.

were recorded from 325 up to 410 ns, see Figs. 34 and 35. The losses were computed considering the beam conditions remain almost the same in the time interval of 5 ns, similar approach as the SCC buildup section. The losses were the order of $\mu\text{W/m}$ and were located at the entrance of the second HWR-cryomodule and the maximum peak is about $2 \mu\text{W/m}$. The start of beam loss coincided with the time when the beam presents transverse emittance and mismatch that exceed the tolerances of the main linac. Furthermore, the final simulations showed greater mismatch and emittance than the initial ones, yet did not record any losses. This indicates that the beam must maintain a certain current intensity, i.e., SC, for the “free energy” resulting from the mismatch to instigate an instability, which supports the conclusion of the previous section.

Figure 36 presents the beam envelopes for the 100, 325, and 435 ns. The 325-ns case is very similar to the 100-ns one, with slightly higher beam envelopes. On the contrary, the 435-ns case shows smaller beam envelopes, but with some oscillations.

It should be noted that, even considering slower voltage rise and fall times of 150 ns (10 times longer), the predicted beam losses will result in similar peak losses over a slightly longer timeframe. This will not affect the beam loss budget. Furthermore, the beam tail will remain

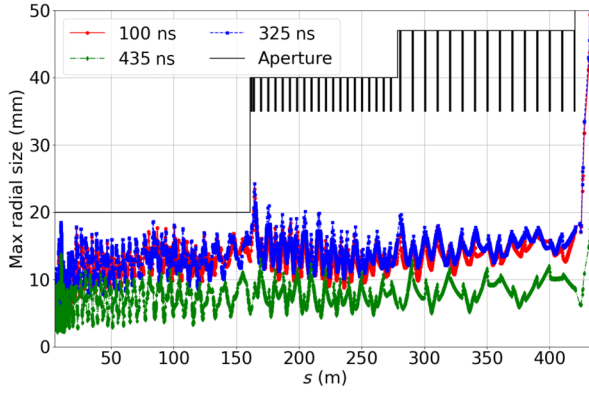


FIG. 36. Beam transient losses along the linac and the beam transport due to turning on the chopper.

short enough (less than 1 μs) to monitor the reactor's subcriticality.

C. Chopper off

A certain degree of SCC has remained between the ion source and the first solenoid of the LEBT, which results in a lower emittance growth regarding the SCC buildup at the same initial time as is seen comparing Figs. 18(b) and 37(b) for the first 40 μs .

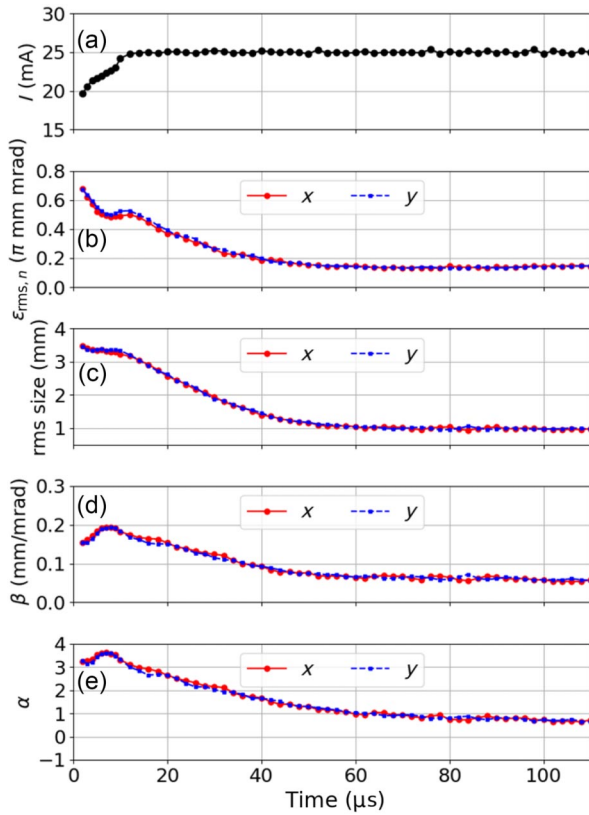


FIG. 37. Beam transient parameters at the end of the LEBT produced by turning off the chopper. Current (a), normalized rms emittance (b), rms size (c), β -Twiss (d), and α -Twiss (e).

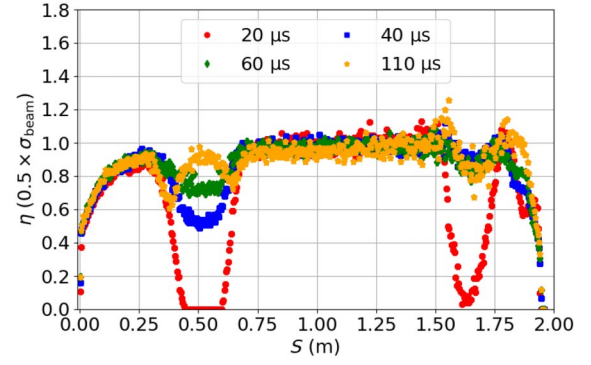


FIG. 38. SCC degree for the beam center after the chopper was turned off.

Similarly, the η values presented on Fig. 38 agree with the SCC buildup case, Fig. 19. However, the 20 μs case has a higher value than SCC buildup due to the remaining SCC at the first part of the LEBT. Furthermore, the lower values within the solenoids are due to the location of the positive ions, H_2^+ and Kr^+ , whose distribution was virtually unaffected by the chopper kick.

The performance in the RFQ, Figs. 39–41, and the main linac, Figs. 42–44, is basically the same as the SCC

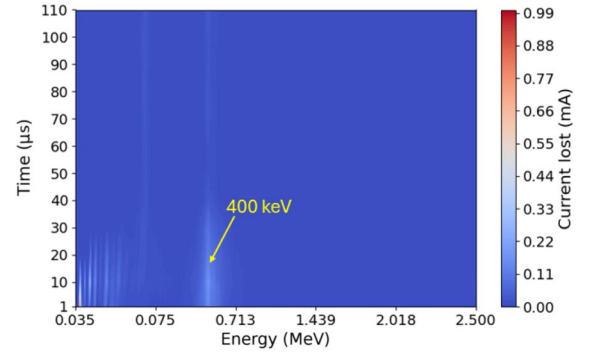


FIG. 39. Current losses distribution as a function of the energy in RFQ and time produced by turning off the chopper.

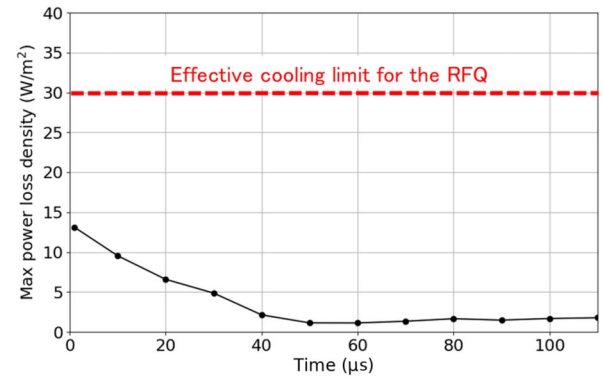


FIG. 40. Maximum power loss density in the RFQ as a function of the time.

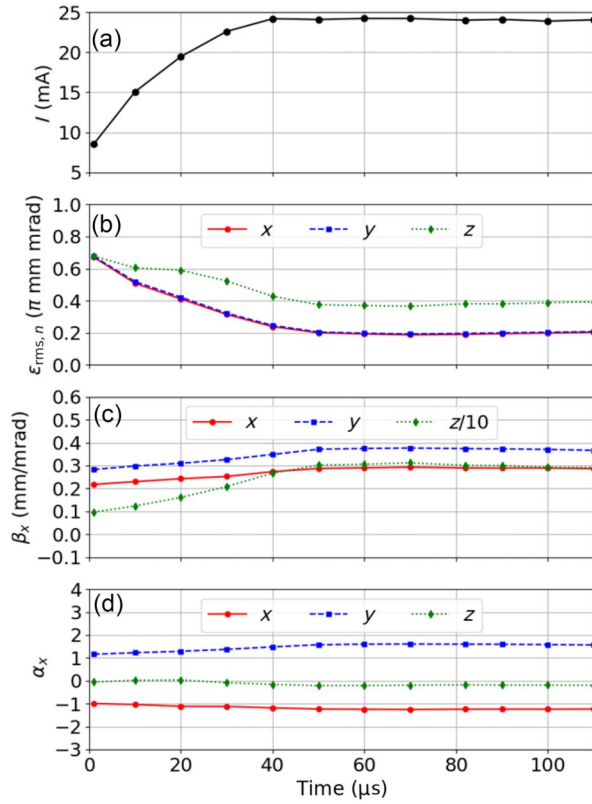


FIG. 41. Beam transient parameters at the end of the RFQ produced by turning off the chopper. Similar to Figs. 23(c) and 33(c), in the β graph (c) the amplitude in the z -plane was scaled down by a factor of 10 to match the scale of the transverse plane. Current (a), normalized rms emittance (b), rms size (c), β -Twiss (d), and α -Twiss (e).

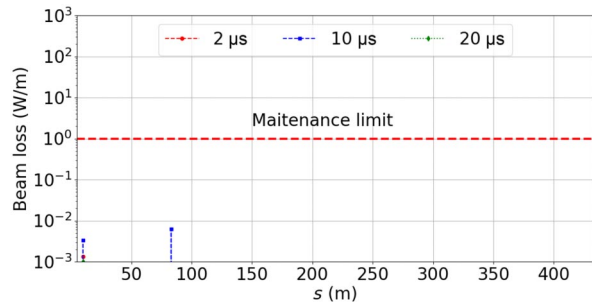


FIG. 42. Beam transient losses along the linac and the beam transport produced by turning off the chopper. Losses are confined to the first 10 μs; nevertheless, they are below the maintenance limit.

buildup, excepting the first 40 μs. As we discussed above, the emittance growth was less than SCC buildup, which resulted in a reduction in the beam losses at the downstream part: RFQ (Figs. 39 and 40) and main linac (Figs. 42 and 43).

The maximum local beam loss in the RFQ was 14 W/cm^2 , with all transient beam losses remaining below 2.16 MeV. Beam losses in the main linac were confined to

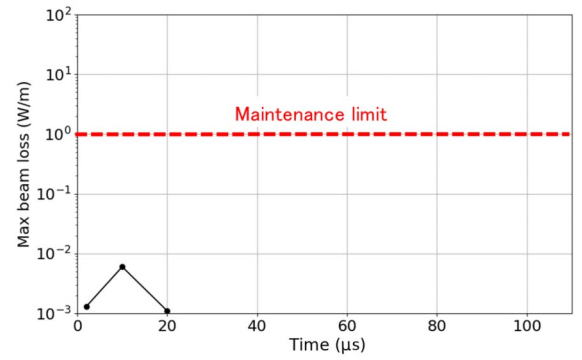


FIG. 43. Maximum local loss as a function of time when the chopper is off.

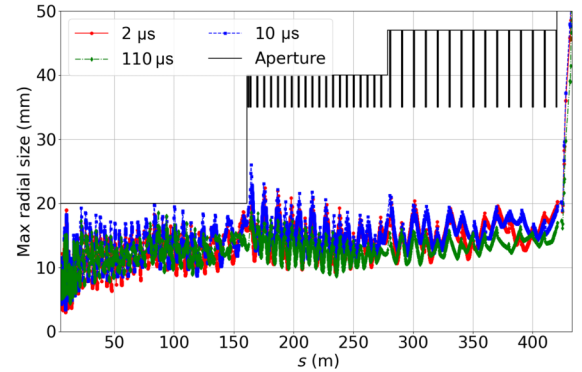


FIG. 44. Beam transient losses along the linac and the beam transport produced by turning off the chopper.

the first 20 μs and the first 100 m (at beam locations similar to those in other cases), with a peak value below 10^{-2} W/m . Furthermore, the highest beam loss coincides with conditions where the 60% nominal current, transverse mismatch ($\approx 25\%$), and emittance ($\approx 100\%$) exceed the tolerance limits of the main linac.

V. CONCLUSIONS

Beam transients are no steady-state beam conditions that can significantly jeopardize the operation of a particle accelerator. Although magnetostatic LEBTs generate beam transients due to SCC, they constitute the predominant design for high-intensity linacs because they can handle higher currents than electrostatic ones. Moreover, magnetostatic LEBTs are preferred for high-availability accelerators, like ADS, as they are less prone to beam trips.

This study is the first to report the effect of beam transients throughout the entire linac by simulating the formation of SCC and its interaction with the chopper in the LEBT section, followed by the tracking of the beam to the reactor. In addition, this work simultaneously simulates the interaction with two residual gases and combines the effects of primary beam ionization, electron-induced

ionization, primary beam charge exchange, and secondary electron emission from the surface.

In this analysis, high-mass parasitic ions (H_2^+ and H_3^+) originating from the ion source were omitted. Initial studies have shown that their inclusion in the simulation has a limited impact on the SCC but increases simulation complexity and computation time. Moreover, these ions are lost in the cone collimator and the first section of the RFQ, without affecting the beam loss budget.

Our findings revealed that, contrary to widespread belief, the worst-case scenario does not occur at zero SCC. The most detrimental cases occur just after zero SCC, or before reaching that point during the chopper's operation. At this stage, the beam accumulates enough SCC that the resulting beam parameters are sufficient to be transmitted through the RFQ with a significant current (i.e., SC) to convert the free energy of the mismatch to harmful instabilities that cause losses in the downstream sections. The majority of the nonoptimal beam was intercepted by the cone collimator and the initial section of the RFQ at low energy avoiding activation and cooling issues. The beam losses in the superconducting section were estimated to be below 1 W/m and limited to the first 100 m. While the tracking simulations using 10^7 macro-particles yield zero lost particles near the end of the linac—implying a statistical loss bound—directly resolving a loss level strictly below 1 W/m in this 30-MW regime would require approximately 3×10^7 particles. Therefore, at the last part of the linac, the conclusion of < 1 W/m losses is a projection supported by the substantial aperture-to-envelope clearance (about two to one), rather than a directly resolved statistical loss convergence.

Additionally, the chopper produces beam tails of 190 ns for monitoring the neutron population in the reactor, which is a requirement for ADS operation.

The results show that beam transients caused by SCC will lead to acceptable levels of beam losses for the JAEA-ADS linac.

ACKNOWLEDGMENTS

The author Bruce would like to thank Tomonobu Itagaki, Kai Masuda, and Nicolas Chauvin, for their valuable help with the WARP code. Antonio Caruso for his help of the chopper discussion. This research was conducted with the supercomputer HPE SGI8600 in the Japan Atomic Energy Agency. This work was supported by JSPS KAKENHI Grant No. JP24H00235.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

APPENDIX SENSITIVITY ANALYSIS

In Subsec. III B, two equations were introduced to quantify the degree of SCC (η) and the compensation time (τ^*). We calculated the normalized sensitivity coefficient to evaluate the percentage change in the model output in response to variations in the input variables. Given a function $f(x_1, \dots, x_n)$, the sensitivity of f with respect to the variable x_i is given by [75]:

$$S(x_i) = \frac{\partial f}{\partial x_i} \frac{x_i}{f}, \quad (\text{A1})$$

which input variables have the greatest impact on η and τ^* , η values are computed using the following formula:

$$\eta(\sigma_{\text{beam}}) = \frac{\#e^-(\sigma_{\text{beam}}, s, t)}{\#H^+(\sigma_{\text{beam}}, s, t) + \#A^+(\sigma_{\text{beam}}, s, t)}, \quad (\text{A2})$$

where $\sigma_{\text{beam}}(s, t)$ indicates the transverse size of the beam for a certain position (s) and time (t), e^- stands for electrons, H^+ for protons, and A^+ for the positive ion produced, e.g., Kr^+ .

In this case, the variable is σ_{beam} and the normalized sensitivity coefficients were computed as

$$S(\sigma_{\text{beam}}) = \frac{\Delta \eta}{\eta} \frac{\sigma_{\text{beam}}}{\Delta \sigma_{\text{beam}}}. \quad (\text{A3})$$

Figure 45 shows the $S(\sigma_{\text{beam}})$ for different values of σ_{beam} along the LEBT. The model presented average sensitivity values of 0.016, 0.009, 0.007, and 0.004 for 0.5 , 0.9 , 1.1 , and $1.5 \times \sigma_{\text{beam}}$, respectively. Although these sensitivity values are relatively low; we observe some significant peaks near the ends of the solenoids, where electrons are concentrated at higher densities. The largest values were less than 0.3 for the case of $0.5 \times \sigma_{\text{beam}}$; here, a 50% variation at the input resulted in a 30% change at the output in the solenoid's end regions.

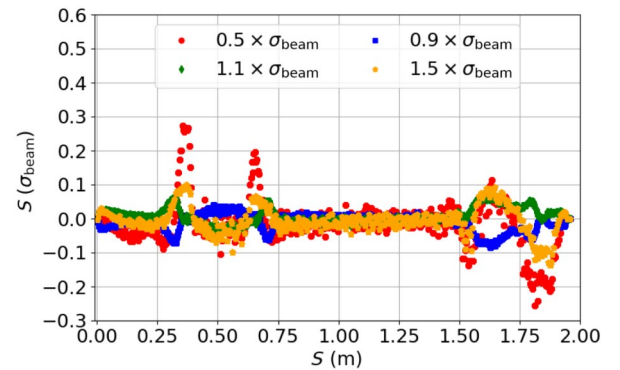


FIG. 45. Normalized sensitivity studies for η .

τ^* is estimated by

$$\frac{1}{\tau^*} = \sum_{p=b}^n \sum_{i=1}^n \frac{P \sigma_i v_p}{k_B T}, \quad (\text{A4})$$

where the index p represents different types of particles: the primary beam b and the neutralizing particles n , the index i refers to the cross section of the injected gases, k_B denotes the Boltzmann constant, T is the temperature of the residual gas, and P represents the pressure.

Using Eqs. (A4) and (A1), we found that for the normalized sensitivity coefficient for the pressure and the velocities of the protons and electrons. Velocities were selected because the residual gas cross section values depend on the beam energy, which is related to the velocity.

For the pressure, we found that:

$$S(P) = \frac{\partial \frac{1}{\tau^*}}{\partial P} \frac{P}{\frac{1}{\tau^*}} = 1. \quad (\text{A5})$$

For the velocities,

$$\begin{aligned} S(v_p) &= \frac{\partial \frac{1}{\tau^*}}{\partial v_p} \frac{v_p}{\frac{1}{\tau^*}}, \\ &= \sum_{i=1}^n \frac{P}{k_B T} \left(\frac{\partial \sigma_i}{\partial v_p} v_p + \sigma_i \right) \frac{v_p}{\sum_{p=b}^n \sum_{i=1}^n \frac{P \sigma_i v_p}{k_B T}}, \end{aligned} \quad (\text{A6})$$

where p represents the primary beam (protons) or the neutralization particles (electrons), $\frac{\partial \sigma_i}{\partial v_p}$ is computed using numerical derivation from the cross section data [40–42].

The normalized sensitivity coefficient was calculated for each input variable and evaluated within the range of 0.5–1.5 times its reference value, considering the parameters listed in Table III. Figure 46 shows that pressure has the greatest impact on the model, about twice the v_{proton} . The values of $S(v_{\text{proton}})$ and $S(v_{\text{electron}})$ are lower because

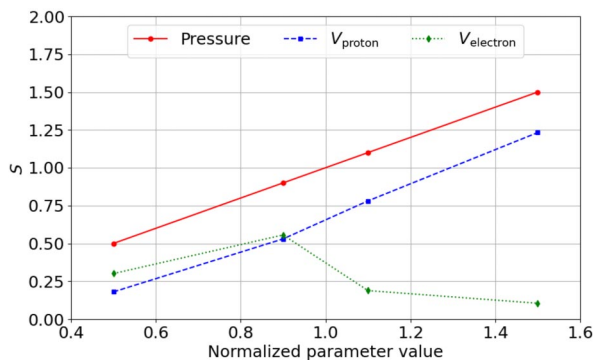


FIG. 46. Normalized sensitivity studies for τ^* .

Eq. (A6) indicates that derivative term includes only the summation corresponding to the particle variable (i.e., proton or electron), results in values less than one.

Another relevant aspect is that the residual gas cross section exhibits a curved response as a function of velocity (or beam energy), reaching a maximum at a specific energy level [40]. In the case of the proton, the cross section shows increasing behavior within the energy range considered; however, the peak occurs at lower velocities (energies), which is why a decrease is observed as velocity increases.

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