

Modeling of the positron sources: Experiment-based benchmarking using SuperKEKB

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High-intensity positron sources are critical for next-generation electron-positron colliders, where positron beam quality and characteristics directly impact the luminosity. Accurate modeling and validated simulation tools for positron sources are essential to optimize their performance. However, modeling a positron source tends to be complex, as it involves multiple interdependent stages, from positron production and capture dynamics to beam transport through the injector linac to the collider ring. In this work, we present a start-to-end simulation tool developed for positron sources modeling. The model was benchmarked against existing simulation tools and validated through experimental measurements conducted at the SuperKEKB positron source. Key operational parameters were systematically scanned to evaluate the simulation model performance, including the primary electron impact position on the target, solenoid field strength around the capture linac, and rf phase settings. The primary figure-of-merit for all validation tests was the positron yield at the end of the SuperKEKB positron capture section. Our model reproduces the measured positron yield (0.603 ± 0.003) under nominal operating conditions, with the simulation result of 0.603 lying well within the 0.5% statistical uncertainty. Furthermore, the simulation results demonstrate a very good agreement with experimental data and other simulation tools, confirming the model's reliability and establishing a framework for future positron source studies.

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I. INTRODUCTION

With the current interest of the High-Energy Physics (HEP) community in precision studies of the Standard Model (SM) and the search for a possible extension beyond the SM, the need for high-luminosity lepton colliders is indispensable. At present, four possible projects are under comprehensive study: the Compact Linear Collider (CLIC) [1], the Future Circular Collider (FCC-ee) [2] at CERN, the International Linear Collider (ILC) [3] in Japan, and the Circular Electron Positron Collider (CEPC) [4] in China. All these linear or circular colliders share the demand for high luminosity, typically on the order of $\sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. Achieving such high luminosities demands intense and low-emittance beams of electrons (e^-) and positrons (e^+). While high-intensity, low-emittance e^- sources are well

established, developing e^+ sources with similar characteristics remains a significant challenge for next-generation colliders.

All e^+ sources in high-energy lepton colliders to date rely on pair production through the interaction of a high-intensity e^- beam with a thick target (several radiation lengths, X_0) made of high-Z materials (e.g., tungsten, tantalum). Despite the high rate of e^+ production at the target, the challenge lies in capturing and transporting these e^+ through the injector while maintaining high transmission to the damping ring (DR). The performance of the e^+ source is typically measured by a key parameter known as the accepted yield, defined as the ratio of the number of e^+ accepted by the DR to the number of primary e^- impinging on the target:

$$\eta = \frac{N_{e^+}}{N_{e^-}}. \quad (1)$$

Maximizing the accepted yield requires a comprehensive start-to-end simulation framework that can optimize e^+ production, capture, and transport efficiency. As part of the FCC-ee injector study, we developed such a model that simulates e^+ production at the target and then tracks the

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resulting e^+ beam through the entire injector up to the DR [5]. Its application to the FCC-ee e^+ source is detailed in [6].

In this work, we present the first experimental validation of a complete start-to-end simulation framework for e^+ source modeling along with benchmarking against the most widely used simulation codes. These studies are performed at the SuperKEKB e^+ source, currently the only high-intensity facility in operation, making it an ideal reference for our study.

This paper is organized as follows: Sec. II provides an overview of the standard layout of the e^+ source, highlighting its challenges, and then detailing the development of our simulation model. In Sec. III, we introduce the e^+ source at SuperKEKB and demonstrate the application of our model to its configuration. Section IV presents the model validation results based on experimental measurements taken at the SuperKEKB e^+ source. Finally, in Sec. V, we summarize our findings and future outlook.

II. e^+ SOURCES CONCEPTUAL DESIGN AND MODELING

e^+ beams can be generated using various techniques depending on the purpose of the experiment and the intensity requirements. In HEP colliders, where high intensity is crucial, e^+ sources almost universally rely on the conventional scheme. In this approach, a high-energy e^- beam is directed onto a high-Z amorphous target, producing bremsstrahlung radiation. These high-energy photons then interact with the target nuclei, leading to the creation of e^-e^+ pairs. In principle, the e^+ production rate is governed primarily by two factors: the power (i.e., beam intensity and the energy of the primary e^-) and the target characteristics (material and thickness). While these parameters determine the e^+ production rate, practical implementation in the collider introduces additional challenges. In particular, the target must withstand a significant thermomechanical load to meet the high-intensity requirements.

As the primary e^- traverses the target, it loses energy through collisional and radiation processes. The radiative losses, namely bremsstrahlung, are carried off by secondary photons, while the collisional losses manifest primarily as ionization, which is the primary source of heating the target. Target heating considerations include both the mean energy deposition (average power) and the instantaneous energy deposition per pulse. The former sets the requirement for the cooling, and the peak value of the latter is known as the peak energy deposition density (PEDD) during a beam pulse. PEDD can create thermal gradients that induce mechanical stresses, potentially leading to target failure if the PEDD exceeds the limit set by the material's tensile strength. The conventional scheme was used for the e^+ source at the SLAC Linear Collider (SLC), where a 33 GeV e^- beam was directed onto a

tungsten-rhenium target with a thickness of six X_0 . The SLC e^+ source holds the record for the highest intensity, achieving an intensity of approximately $6 \times 10^{12} e^+/s$ [7]. Operational experience at SLC has shown that to prevent target damage, the PEDD in a tungsten-rhenium target should not exceed 35 J/g [8]. A similar threshold is considered for pure tungsten targets.

Various design solutions have been proposed to address target heating issues (e.g., thermal stress, material fatigue, etc.). For instance, a moving target spreads successive pulses over a larger surface to reduce cumulative heating and mechanical stress on any single location. At SLC e^+ source, a trolling target was implemented as one such solution [9], while a rotating target is currently under investigation for the e^- -driven e^+ source at ILC [10]. Another design is based on a compound target that incorporates an aligned crystal to exploit channeling radiation and an amorphous converter for e^+ production [11]. Such an approach, known as a hybrid scheme, helps reduce the PEDD by splitting the energy deposition between two targets. The hybrid scheme was previously explored for the CLIC positron source [12,13] and has also been investigated as an alternative for the FCC-ee e^+ source [6].

Following the e^+ production, an immediate capture system is essential since the generated e^+ beam typically experiences a large emittance and a significant energy spread due to multiple scattering. The initial capturing stage employs a matching device (MD) to adapt the beam for further transport. Common MD choices include an adiabatic matching device (AMD) or a quarter wave transformer (QWT) [14]. The MD is primarily used to match the e^+ beam transverse profile to the subsequent sections. The choice of the MD is determined by the operational requirements of the e^+ source. An AMD is preferable when large energy and radial acceptance are required, while a QWT is better suited for cases that demand wide angular acceptance or the selection of specific energy bands.

The subsequent e^+ source stage involves capturing the e^+ beam in radio frequency (rf) buckets of multiple accelerating structures in the longitudinal plane. Due to the large transverse emittance of the e^+ beam, the rf structures are immersed in a strong axial magnetic field (generated by dc solenoids) to focus the e^+ beam transversally. The combination of the MD and the first few accelerating structures is known as the capture section. At the end of the capture section, typically at a few hundred MeV, a chicane with a collimator is used to intercept the secondary e^- . The e^+ are then further accelerated in an e^+ linac to reach the desired energy for the DR.

A typical layout of the e^+ injector is presented in Fig. 1. All these elements of the e^+ injector must be carefully optimized to maximize the accepted yield. Thus, developing a comprehensive start-to-end simulation tool is essential for achieving the ultimate performance of the injector and fulfilling the collider's requirements.

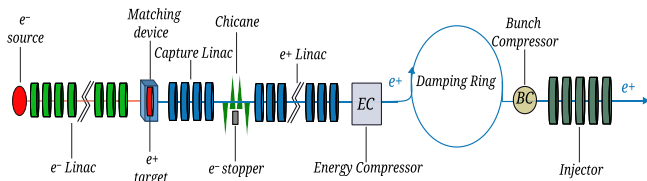


FIG. 1. Schematic layout of different subsystems of the e^+ source basic scheme.

The designing and modeling of e^+ sources are highly intertwined, with each stage of the process relying on specialized tools. For example, the initial modeling of pair production and the deposited energy in the target is typically performed using Monte Carlo (MC) codes such as Geant4 [15–17], FLUKA [18,19], or EGS [20], which simulate particle interactions and radiative processes. Following this, the target thermomechanical aspects are simulated by CST [21] or Ansys [22]. Once the e^+ are produced, beam dynamics codes such as ASTRA [23], ELEGANT [24], MAD-X [25], SAD [26], GPT [27], or RF-Track [28] are employed to simulate their capture, acceleration, and transport through the injector. It is important to note that changes in one part of the design, such as the target geometry, beam optics, or the DR acceptance, often mandate corresponding changes in other parts. Therefore, iterative feedback between these simulation tools is essential.

This paper focuses on the model developed for the FCC-ee e^+ source, emphasizing both the e^+ production stage and the subsequent beam dynamics in the capture linac. Our start-to-end model integrates two main simulation tools. The widely known MC code Geant4 version 11.2.2 utilizes the FTFP_BERT physics list. This physics list offers a consistent description of electromagnetic and hadronic nuclear interactions over a broad energy range. Its accurate modeling of bremsstrahlung and pair production makes it well-suited for simulating e^+ generation in dense, high-Z materials. Subsequently, the RF-Track code version

2.3.2 is employed for the following beam dynamics simulations in the capture section and the e^+ linac. RF-Track enables particle tracking in space and tracking in time. In our model, the equations of motion are integrated using time as the independent variable, solved numerically with the Runge-Kutta method. A convergence study was conducted to balance computational time and numerical accuracy. This analysis identified an integration step of 0.25 mm/c as the optimal choice.

III. EXPERIMENTAL VALIDATION OF THE MODEL USING THE e^+ SOURCE AT SUPERKEKB

The SuperKEKB facility is designed to collide e^- and e^+ at the center-of-mass energies in the regime of B-meson, aiming to search for new physics beyond the SM [29]. The facility comprises an injector linac (LINAC) equipped with e^- and e^+ sources, an e^+ beam DR, a low energy ring (LER) for e^+ and a high energy ring (HER) for e^- , and the Belle II physics detector. The designed beam energies for the two rings, LER and HER, are 4 and 7 GeV, respectively [29]. As the successor to KEKB, which was in operation from 1998 to 2010 and achieved the world-highest peak luminosity of $2.018 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, SuperKEKB is upgraded to reach $8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, $40\times$ KEKB luminosity [30]. At the end of the physics run in 2024, the achieved luminosity was $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [31], 2.5 times higher than the achieved luminosity at the KEKB. One of the primary key factors for achieving such a luminosity is the extensive upgrade and remodeling of the LINAC and the e^+ source.

KEK's LINAC has established a concurrent top-up injection to feed four storage rings. The LINAC is composed of eight sectors (sectors A–C and 1–5) with a bending sector in between (J-arc), as illustrated in Fig. 2. Each sector has eight klystrons, with one klystron driving four 2-m-long accelerating structures. The LINAC supplies an e^+ beam to the LER via e^+ DR, e^- beam to the

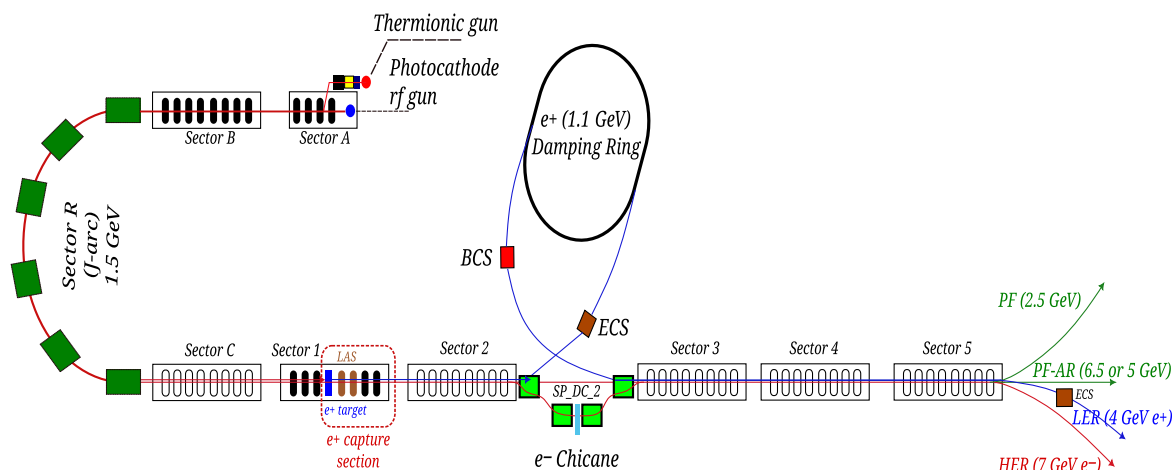


FIG. 2. Schematic layout of the KEK injector LINAC.

HER, and e^- beams to two light sources: Photon Factory Advanced Ring (PF-AR) and Photon Factory storage ring [32]. This simultaneous injection is maintained by utilizing two independent e^- sources operating up to 50 Hz, with each rf pulse delivering two bunches to both the HER and the LER. One source—a dc thermionic gun—supplies the e^- beam for the two light sources and the e^+ target, providing charges of 0.3 and 10 nC, respectively. The other source—a photocathode rf gun—generates a low-emittance e^- beam specifically for the HER. This paper will focus mainly on the e^+ source and the following capture linac located in sector 1 within the LINAC.

A. e^+ source at the SuperKEKB

The e^+ source at SuperKEKB represents the current state-of-the-art and is the world's highest-intensity e^+ source in operation [33]. It employs the conventional scheme, where a primary e^- beam (generated by a thermionic gun with an intensity of 10 nC per bunch) with an energy of 2.9 GeV impinges upon a tungsten target.

The target is a 14-mm-thick ($4 X_0$) cylinder with a 4 mm diameter, and it is housed in a copper holder to ensure efficient cooling and support. Since the LINAC is shared between e^- and e^+ bunches, the e^+ target's center is displaced by 3.5 mm from the beam axis, and a hole with a 2 mm diameter is bored in the copper along the beam axis for e^- beam passage to the HER [34], as shown in Fig. 3.

Upstream of the target, a series of pulsed magnets is positioned to steer the primary e^- beam off axis, directing it to hit the target. Downstream of the target, an MD in the form of a flux concentrator (FC) is installed to increase the e^+ capture efficiency. The FC is a pulsed solenoid magnet made of copper alloy featuring an internal truncated cone shape, with front and rear aperture diameters of 7 and 52 mm, respectively [35]. The total length of the FC is

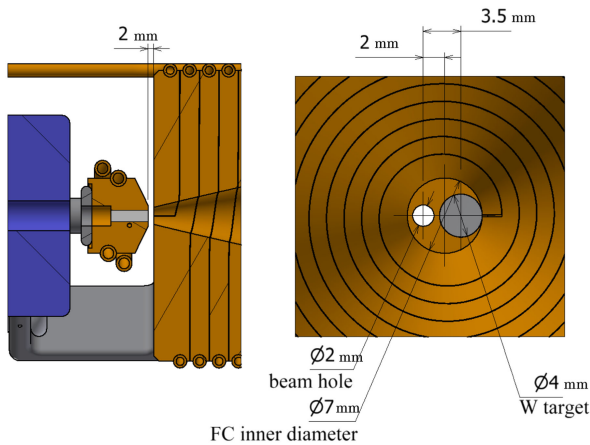


FIG. 3. Schematic layout of the SuperKEKB e^+ source target: side view (left) and downstream view (right), illustrating the target offset position. The beam hole center serves as the reference point.

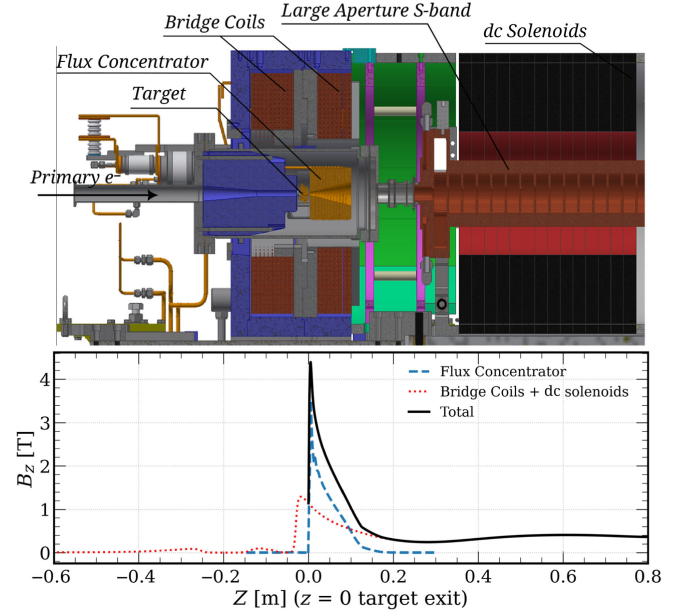


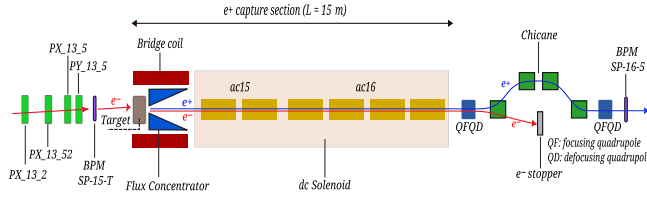
FIG. 4. Cross-sectional view of the SuperKEKB e^+ source target, displaying the flux concentrator, bridge coils, and the dc solenoids with the corresponding longitudinal magnetic field profiles.

100 mm, and its center is positioned at $x = 2$ mm relative to the beam axis to accommodate the target offset. The strong magnetic field inside the FC is excited by a few microseconds pulse with a peak current of 12 kA. As shown in Fig. 4, the longitudinal magnetic field profile rises sharply to a peak value of 3.5 T at the FC entrance, then gradually tapers down to 0.4 T, matching the field of the downstream dc solenoids surrounding the rf structures. dc solenoids, the so-called bridge coils (BCs), have been added to enhance the FC field and improve capture efficiency. The FC has been operating since 2020 without any significant issues. A detailed view of the target area is presented in Fig. 4.

The distance between the FC exit and the rf structures is minimized to 137 mm to preserve the quality of the e^+ beam. The capture linac comprises six large aperture S-band (LAS) traveling wave accelerating structures, whose parameters are listed in Table I.

TABLE I. Parameters of the rf structures in the capture linac.

Parameter	Value	Units
Type	LAS	
Frequency	2.856	GHz
Phase advance	$2\pi/3$	deg
Number of cells	59	
Iris diameter	31.861–29.967	mm
Length	2.064	m
Number of LAS	2 + 4	
Klystron power no-SLED	40	MW
SLED gradient (maximum)	14/10	MV/m

FIG. 5. Schematic layout of the SuperKEKB e^+ source.

Initially, the rf units consisted of a 40 MW klystron and an SLED that fed four LAS [36]. However, to have a flexible setting of the rf gradient in the upstream part of the capture linac, the rf unit KL15 drives only two LAS, while the KL16 rf unit powers the subsequent four structures. At the solenoid channel's exit, located at the end of the last rf structure, several focusing and defocusing quadrupoles are installed to match the beam to the following acceleration sections. Downstream of these quadrupoles, a chicane system is implemented with a peak field of 0.2 T. An e^- stopper is placed at the chicane's center to intercept the secondary e^- . Additional quadrupoles are installed after the chicane to complete the beam matching to the following FODO lattices focusing-based accelerating sections.

Due to the compactness of the capture section and the extremely short time interval between the e^+ and secondary e^- bunches (typically on the order of 100 ps), the use of conventional beam diagnostics within this region is highly constrained. Therefore, in the current setup, only two conventional beam position monitors (BPMs) are employed for beam diagnostics. The first BPM, labeled as SP_15_T, is positioned just before the target and is used for primary e^- beam diagnostics. The second BPM, labeled SP_16_5, is located after the chicane and used for e^+ beam diagnostics. The schematic layout of the SuperKEKB e^+ source is depicted in Fig. 5.

The bunch charge history from the 2024 run measured at different locations along the LINAC is shown in Fig. 6. The primary e^- bunch typically had a charge of 10 nC. The e^+ bunch charge, which was 6 nC after the chicane, gradually decreased to 4 nC at the DR entrance, corresponding to an e^+ yield of 0.4. Beyond the DR and through the remaining part of the LINAC, the e^+ bunch charge stabilized at 3.5 nC.

B. e^+ production and tracking

We applied the model mentioned in the previous section to the SuperKEKB e^+ source. The simulation process consists of the following steps: first, a primary e^- beam is generated based on the parameters listed in Table II. Second, the beam is tracked through the steering magnet in the upstream section of the target using RF-Track. Third, the tracked e^- particles are imported into Geant4, where the e^+ production process is simulated. Finally, the resulting e^+ bunch is extracted and reimported into RF-Track for further beam dynamics studies through the capture section.

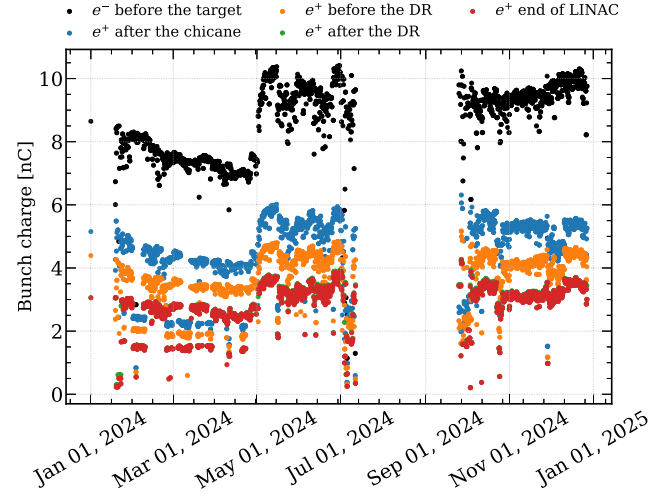


FIG. 6. Bunch charge evolution throughout the e^+ production and acceleration process during the 2024 run. The primary e^- bunch charge before the e^+ target is shown in black. The e^+ bunch charge is plotted at different stages: after the target at the end of the capture section (blue), before injection into the DR (orange), at the DR exit (green), and at the linac exit (red). The gap represents the summer shutdown.

The flexibility of the developed model in Geant4 allows for a precise definition of incoming beam properties, including energy, emittance, energy spread, and time structure. Furthermore, the model considers the full design of the target, including the copper holder, the tungsten target, and the hole for e^- beam passage. According to Geant4 simulation performed based on the parameters listed in Table II, an e^+ yield of $7.6 N_{e^+}/N_{e^-}$ is emerged from the target exit side. As clearly shown in Fig. 7, the e^+ produced has a large transverse momentum spread ($\sigma_{p_x} = 4.33$ MeV/c) and a small lateral size ($\sigma_x = 0.63$ mm). Along the longitudinal direction, the phase space is non-Gaussian and characterized by a momentum spread of $\sigma_{p_z} = 97.1$ MeV/c, with a mean around

TABLE II. SuperKEKB e^+ source operation conditions measured during the experimental campaign.

Parameter	Value	Units
Primary e^- energy	2.9	GeV
Repetition rate	25	Hz
Bunches per rf pulse	2	
Primary e^- bunch charge	10	nC
Beam power	1.45	kW
Beam size σ_x/σ_y	0.45/0.52	mm
Position on the target x/y	2.25/0.2	mm
Estimated power deposited in the target	0.41	kW
PEDD	21	J/g
Estimated gradient (KL15/KL16)	8.13/9.47	MV/m
e^+ charge after the chicane	6	nC
e^+ yield after the chicane	0.6	N_{e^+}/N_{e^-}

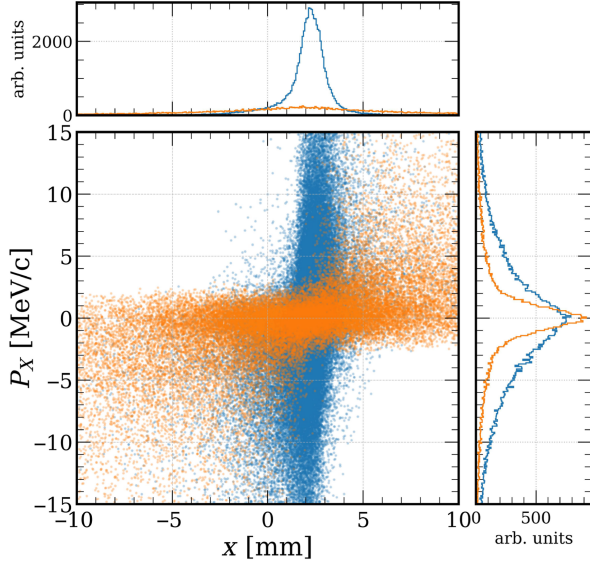


FIG. 7. Transverse phase space of the e^+ at the target exit (blue) and at the exit of the FC (orange).

44.7 MeV/c. These values indicate that e^+ dynamics are strongly influenced by the large transverse emittance and large energy spread.

In addition to the e^+ production, the model assesses the integral energy deposited in the target per incident e^- , which can be scaled according to the primary e^- bunch charge. This parameter helps to estimate the target heating and, therefore, sets the cooling requirements. Also, the model can estimate the PEDD in the target using a specific scoring function in Geant4 (mesh scorer). This function defines a cubic voxel grid, where each voxel records the energy deposited per incident e^- . The voxel dimensions are set to half of the beam size ($\Delta x = \Delta y = \Delta z = \frac{\sigma_x}{2}$) [37]. The development of the electromagnetic shower within the target, along with the corresponding energy density distribution along the beam axis, is presented in Fig. 8. Due to shower development within the target, the maximum energy density was found near the exit face, reaching 21 MeV/mm³ per incident e^- . Based on this value, the estimated PEDD per pulse is 21 J/g.

At the beginning of the capture section, the e^+ bunch passes through the FC, where it experiences a strong axial magnetic field that gradually decreases to match the solenoid field of the capture linac. This tapered magnetic field in the FC influences the beam dynamics in both the transverse and longitudinal planes. In the transverse plane, the gradual field variation induces a phase-space rotation, which reduces the transverse momentum spread to $\sigma_{px} = 1.37$ MeV/c while maintaining an acceptable beam size $\sigma_x = 4.63$ mm (capture linac aperture $2a = 30$ mm), as shown in Fig. 7. In the longitudinal plane, e^+ follow helical trajectories due to the axial magnetic field. The transverse momentum governs the radius of this helical

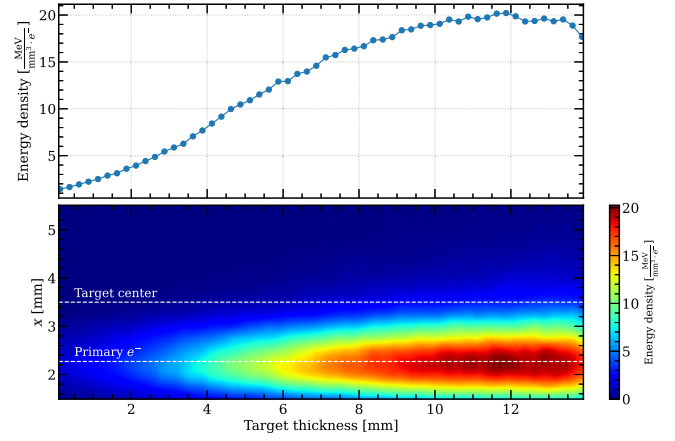


FIG. 8. Energy density along the primary e^- beam axis in the tungsten target, with a maximum value of 21 MeV/mm³ per incident e^- observed near the target exit (top), and electromagnetic shower development within the target (bottom).

motion: e^+ with higher transverse momentum follow wider spirals, while those with lower transverse momentum remain in tighter spirals. This momentum-dependent trajectory variation leads to bunch lengthening as the e^+ bunch exits the FC. As a result, the longitudinal capture efficiency may decrease, since differences in path length spread the bunch longitudinally, making it harder to focus in the capture linac.

In the capture linac, the e^+ are longitudinally captured within rf buckets. The electromagnetic field map is generated using the SuperFish code [38]. It is then imported into RF-Track and interpolated using the cubic interpolation function. This method evaluates the rf field at any given point by performing a cubic interpolation over the nearest 64 mesh points, ensuring a smooth and accurate field representation.

The first LAS structure is chosen to operate in deceleration mode (deceleration rf phase) to enhance bunching efficiency and maximize the number of e^+ confined within a single rf bucket [39]. Accordingly, Fig. 9 shows the e^+ beam dynamics simulation results along the capture section, including the e^+ yield evolution, the mean energy of the survived e^+ , and the magnetic field profile. A significant portion of the e^+ , approximately 70%, is lost between the target exit and the entrance of the first rf structure, due to the apertures. Between the first and second rf structures, a drop in the magnetic field (caused by a gap between the solenoids), combined with the low energy e^+ , results in a small amount of losses at the entrance of the second rf structure. Further losses, approximately 5%, are observed in the chicane, where low-energy e^+ are lost upon striking the edge of the beam pipe at the chicane center. At the end of the capture section, the observed e^+ yield of 0.603 is consistent with the charge history shown in Fig. 6. Furthermore, the initial mean energy of the e^+ , which will eventually reach the end of the capture section, is below

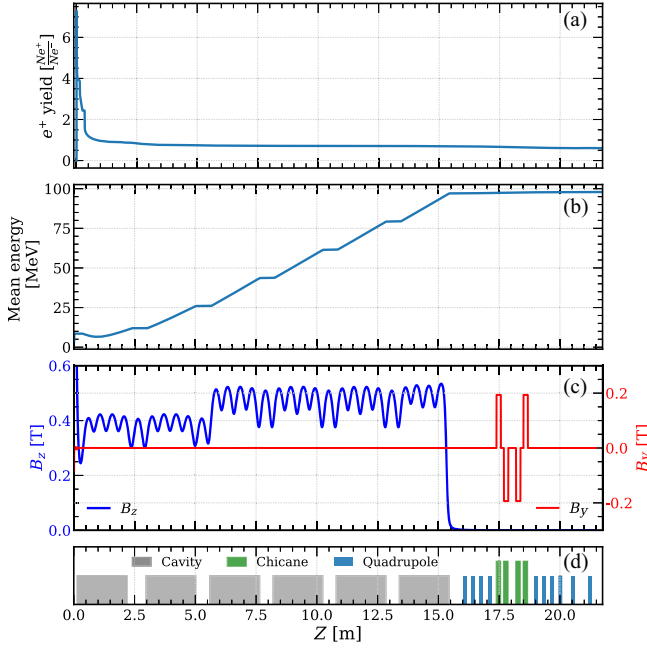


FIG. 9. Simulation results of the SuperKEKB e^+ capture section, illustrating yield evolution (a), mean energy gain (b), magnetic field profiles (c), and schematics of the section's elements (d). At the end of the capture section, an e^+ yield of 0.60 and a mean energy of 100 MeV were found.

10 MeV, mainly determined by the FC acceptance, as shown in Fig. 9(b). Then, in the first rf structure, e^+ are captured in the deceleration mode; due to the phase slippage, they shift to the acceleration phase and continue gaining energy in the second rf structure. When they reach the third rf structure, the phase slippage almost stops, and the acceleration continues steadily until reaching a mean energy of approximately 100 MeV.

IV. BENCHMARKING RESULTS AND DISCUSSION

To assess the reliability of our model, we validated its results with experimental measurements conducted at the SuperKEKB e^+ source and benchmarked it using independent simulation tools. These tools can be categorized into two main approaches. The first approach corresponds to the model used at KEK, where EGS5 is employed for e^+ production, integrated with GPT for particle tracking. For completeness, the second approach utilizes the same Geant4 model presented earlier; however, the tracking is performed using ASTRA instead of RF-Track.

We performed three key measurements to evaluate the accuracy and reliability of the presented model. Corresponding simulations were conducted for each measurement to compare with the experimental data. In each measurement, we scan one parameter while observing two BPMs: SP_15_T to measure the position and charge of the primary e^- , and SP_16_5 to measure the e^+ charge after the



FIG. 10. SuperKEKB e^+ capture section. Photographed in November 2023 during the maintenance day.

chicane (see Fig. 5). The figure of merit (FoM) in all the measurements is the e^+ yield after the chicane

$$\text{FoM} = \frac{Q_{e^+ \text{ at SP_16_5}}}{Q_{e^- \text{ at SP_15_T}}}. \quad (2)$$

Before each scan, we measure the primary e^- transverse size using an $\text{Al}_2\text{O}_3:\text{Cr}$ screen located 1 m upstream of the target. The beam size remained stable throughout the measurement campaign at approximately $\sigma_x = 0.45$ mm and $\sigma_y = 0.52$ mm. The actual SuperKEKB e^+ capture section where the measurements took place is shown in Fig. 10.

A. Field scan of the solenoids in the capture section

The dc solenoids surrounding the accelerating structures in the capture linac are critical in focusing the e^+ beam, as discussed in Sec. II. The magnetic field profile varies along the capture linac, starting at approximately 0.4 T before increasing to 0.5 T, as shown in Fig. 9. This variation arises from historical reasons, as several injector components were repurposed from KEKB. Additionally, the field is not perfectly axisymmetric, causing a transverse kick to the e^+ beam, reducing beam transport efficiency. Four steering magnets were installed around the capture linac to compensate for this effect. In this measurement, the magnetic fields of the BCs, the dc solenoids, and the steering magnets were gradually scanned from 100% to 50% in 10% increments.

The measurement results within the scan range shown in Fig. 11 reveal a linear relationship between the FoM and the magnetic field strength, highlighting the role of the dc solenoids in e^+ capture efficiency. A corresponding simulation was performed and extended to a region without the magnetic field. The simulation results show good agreement with the measurements and confirm that almost no e^+ could reach the end of the capture section without the magnetic field of the dc solenoid channel.

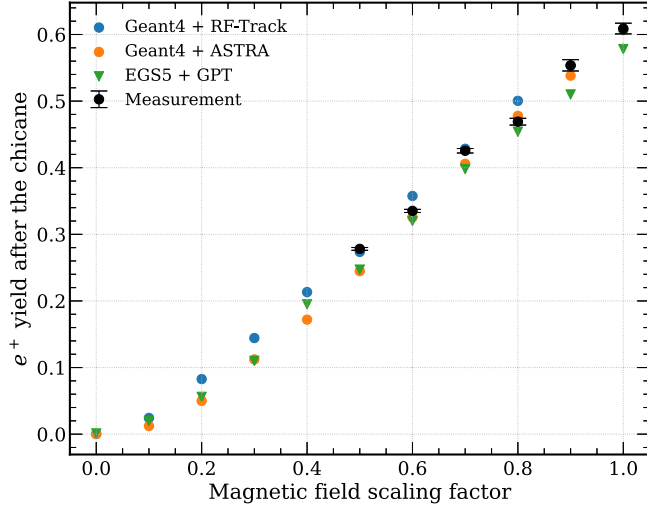


FIG. 11. e^+ yield as a function of the magnetic field of the BCs, dc solenoids, and the steering magnet in the capture linac. Each measurement point was averaged over 50 acquisitions to improve statistical accuracy. Error bars in the figure indicate the resulting standard deviations.

B. Impact position scan of the primary e^- on the target

This measurement involved scanning the primary e^- beam impact position on the target, conducted horizontally and vertically. As described in Sec. III, the target center is positioned 3.5 mm horizontally from the beam axis, and the FC center is located 2 mm horizontally from the beam axis. Two steering magnets are mainly used in the measurement to steer the beam upstream of the target. PX_13_5 magnet for horizontal steering and PY_13_5 magnet for the vertical steering of the primary e^- (see Fig. 5). This scan aimed to evaluate how the primary e^- beam position affects the FoM and investigate the influence of beam alignment on e^+ production.

Before presenting the measurement results, we will compare the two MC codes, Geant4 and EGS5, in simulating the e^+ production after the target. The comparison was performed by moving the primary e^- horizontally across the target, including its copper holder. The results demonstrate excellent agreement between the two simulation tools, as shown in Fig. 12. A similar level of agreement was observed when performing the primary e^- vertical scan on the target.

The measurement and simulation results of the horizontal position scan of the primary e^- on the target are shown in Fig. 13(a). The comparison of the simulations and experimental data manifests a very good agreement. It is important to note that the primary e^- beam is not perpendicular to the target face but arrives at an angle due to the trajectory deviation induced by the steering magnet.

The actual impact position of the e^- beam on the target is 2.25 mm, as determined from the simulated trajectory.

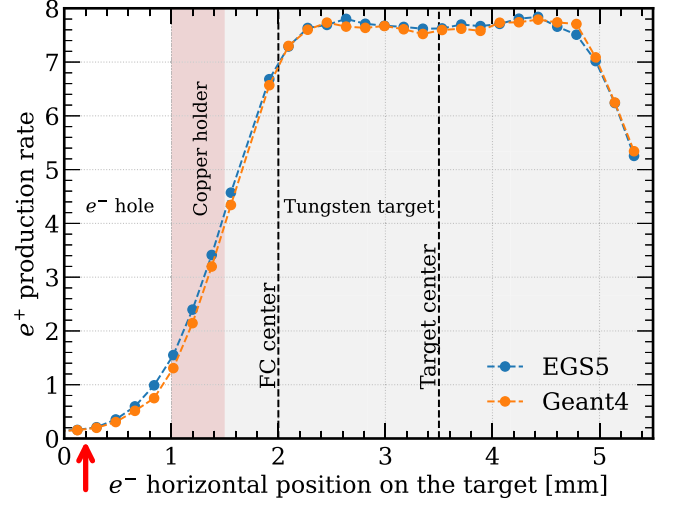


FIG. 12. Simulated e^+ production rate as a function of the primary e^- horizontal impact position. The primary e^- beam is orthogonal to the target, and its direction is indicated by the arrow in the lower left corner. The simulation data points are connected as a guide to the eye and do not represent a fit or model.

Since the SP_15_T BPM is located 1.2 m upstream, it measures a beam position of 1.8 mm under nominal operating conditions, slightly offset due to the beam's angular deviation. When simulated, this effect introduces non-negligible uncertainties in the reconstructed impact position, particularly at large offsets, and consequently results in larger discrepancies between simulation and measurement away from nominal conditions. The e^+ yield profile remains nearly flat for horizontal positions between 1.5 and 2 mm, i.e., in the vicinity of the FC center. This provides a wide horizontal impact position tolerance, almost equal to the beam size. However, a sharp drop in e^+ yield is observed below 1.5 mm, where e^+ originated from the copper holder rather than the target itself.

The next measurement involved a vertical scan of the primary e^- beam impact position on the target using the same method. During the measurement, the e^- beam position was scanned vertically while maintaining the optimal horizontal position at 2.25 mm. The measurement and simulation results of the vertical position scan are presented in Fig. 13(b). The optimal region for maximizing the FoM lies between 0 and 0.5 mm. Outside this range, the FoM decreases sharply, which is consistent with the reasons discussed previously. All simulation tools show good agreement with the measurement data, though EGS5 + GPT tends to underestimate the FoM.

C. RF phase scan of accelerating structures in the capture linac

The final measurement involved scanning the rf phases of the klystron units KL15 and KL16 in the capture linac. In a conventional accelerating linac, the rf phase is typically

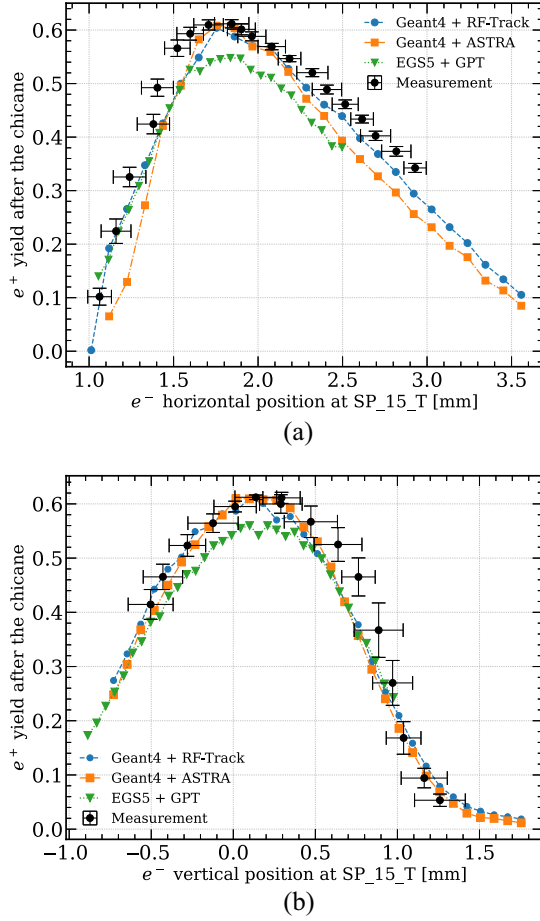


FIG. 13. e^+ yield as a function of the primary e^- beam impact position at the SP_15_T BPM just upstream of the target. (a) Horizontal impact position scan. (b) Vertical impact position scan. Each measurement point was averaged over 50 acquisitions to improve statistical accuracy. However, due to operational conditions on the measurement day, position jitter and charge jitter for the primary e^- beam were observed and reported by the error bars in the figure. The simulation data points are connected as a guide to the eye and do not represent a fit or model.

optimized to maximize energy gain. However, the rf phases are preferred to be in a deceleration mode for e^+ , particularly in the early acceleration stages. This configuration enhances e^+ bunching within a single rf bucket, reducing the energy spread of the e^+ bunch and thereby increasing the number of e^+ accepted by the DR. The operational rf phases were determined relative to the zero-crossing phases, expressed as

$$\phi_{\text{operational}} = \phi_{\text{zero-crossing}} + \phi_{\text{offset}} \quad (3)$$

where the zero-crossing rf phase corresponds to the setting at which the rf field induces neither acceleration nor deceleration of the beam, and ϕ_{offset} is the rf phase offset applied relative to the zero-crossing phase to achieve the desired operating mode (e.g., acceleration or deceleration).

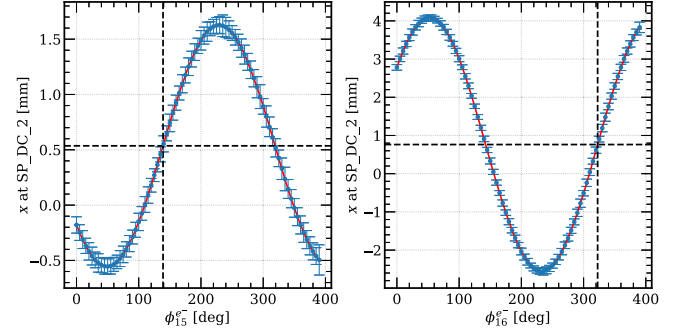


FIG. 14. e^- beam excursion measured in a high-dispersion region as a function of the rf phase for KL15 (left) and KL16 (right). The scan was performed in 5° steps, with each measurement point averaged over 50 acquisitions to improve statistical accuracy. Error bars in the figure indicate the resulting standard deviations. The zero-crossing rf phases were determined by fitting the measured data with a cosinelike function. Dashed lines indicate the identified zero-crossing phases, given by $\phi_{15}^0 = 139.1^\circ$ and $\phi_{16}^0 = 322.5^\circ$.

This method helps in setting a reference point for the comparison between the measurement and simulation.

The measurement began by determining the zero-crossing rf phases. These phases were identified by sending an e^- beam through the e^- hole in the target system (see Fig. 3) and scanning the rf phase of the first klystron unit KL15. The beam position was then recorded using an SP_DC_2 BPM located at the center of a large-dispersion region within the e^- chicane upstream of sector 3 (see Fig. 2). Then, the measured positions were fitted with a cosinelike function to determine the zero-crossing phase. Once this phase was found for KL15, it was fixed, and the same procedure was repeated for KL16. The results of the zero-crossing phase measurements are presented in Fig. 14. This method provided the rf phases for both klystron units $\phi_{15}^0 = 139.1^\circ$ and $\phi_{16}^0 = 322.5^\circ$ where the net energy gain is zero. Note that the zero-crossing rf phases are the same for the e^- and e^+ beams. These two rf phases serve as the reference points for subsequent rf phase scans. Since KL16 powers four LAS structures, it provides a higher energy gain than KL15. As a result, a larger e^- beam excursion was observed, reaching a maximum of 4 mm for KL16, compared to 1.6 mm for KL15, as shown in Fig. 14.

Starting from the zero-crossing rf phases, a two-dimensional rf phase scan was performed with a step of 10° to map the rf phase response and identify the optimal operational point. The measurement data, shown in Fig. 15, are compared with simulation results obtained from our model.

This scan identifies the deceleration rf phase at $\phi_{15,16}^{\text{offset}} = 90^\circ$ corresponding to the operational phases of $\Phi_{15,16}^{\text{operational}} = (229.1^\circ, 52.5^\circ)$, at this setting, the obtained e^+ yield (N_{e^+}/N_{e^-}) from measurement and simulation

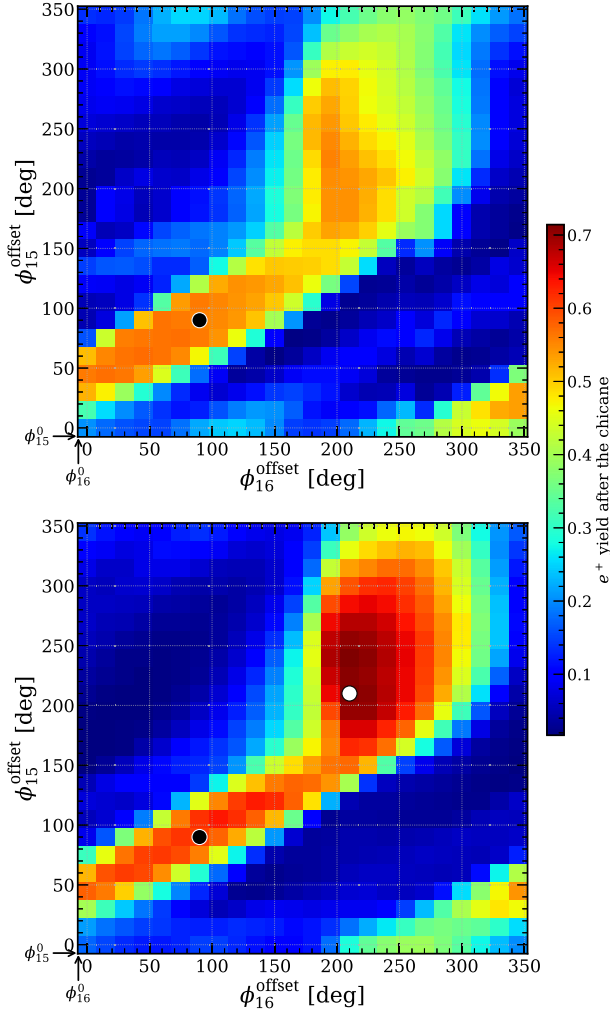


FIG. 15. Two-dimensional rf phase scan of the two klystron units KL15 and KL16 in the capture linac. Measurement data (top), in comparison with simulation results (bottom). Black markers indicate the working phases (deceleration mode) $\Phi_{15,16}^{\text{operational}} = (229.1^\circ, 52.5^\circ)$ at $\phi_{15,16}^{\text{offset}} = 90^\circ$. The white marker denotes the rf phase ($\phi_{15,16}^{\text{offset}} = 210^\circ$) corresponding to the simulated maximum e^+ yield of 0.718.

is 0.587 and 0.605, respectively. Meanwhile, the acceleration rf phase at $\phi_{15,16}^{\text{offset}} = 270^\circ$ corresponding to $\Phi_{15,16}^{\text{operational}} = (49.1^\circ, 232.5^\circ)$ results in an e^+ yield of 0.459 from measurements and 0.599 from simulations. The black markers in Fig. 15 indicate the selected working point corresponding to the deceleration mode. The reason for choosing the deceleration mode is clearly depicted in Fig. 16. At this mode, the energy spread $\frac{\sigma_E}{E}$ within the main rf bucket is 8.63%, allowing a larger fraction of e^+ to fall within the acceptance of the DR. On the other hand, at the rf phase providing the highest e^+ yield (indicated by the white marker on Fig. 15), the energy spread $\frac{\sigma_E}{E}$ increases significantly to 36.74% as shown in Fig. 16. Such a large energy spread will considerably reduce the fraction of e^+

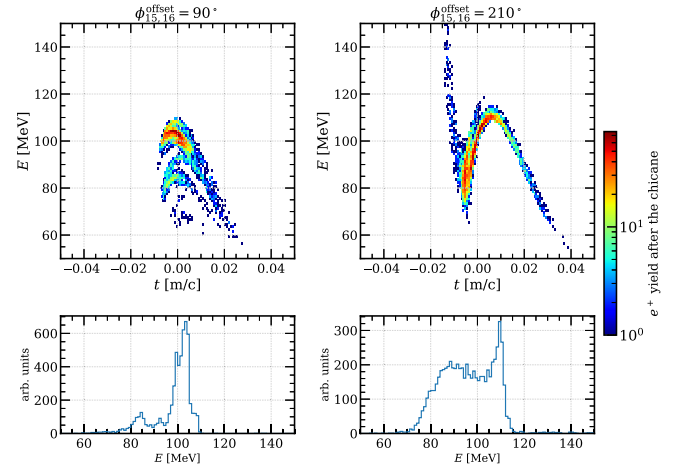


FIG. 16. Longitudinal phase space and energy distribution of the e^+ beam at the end of the capture section, restricted to the main rf bucket. The left panel (top) shows the phase space for the operational rf phase setting $\phi_{15,16}^{\text{offset}} = 90^\circ$ (deceleration mode, marked in black in Fig. 15), with the corresponding energy spectrum (bottom) exhibiting a mean energy of 98.1 MeV and an energy spread ($\frac{\sigma_E}{E}$) of 8.63%. The right panel (top) corresponds to the rf phase that maximizes the e^+ yield, $\phi_{15,16}^{\text{offset}} = 210^\circ$ (white marker in Fig. 15); the associated energy distribution (bottom) shows a comparable mean energy of 97.8 MeV, but with a significantly broader energy spread $\frac{\sigma_E}{E}$ of 36.74%.

captured in the DR, despite the presence of the energy compression system installed upstream of the ring. This underlines the importance of operating the first two rf structures of the capture linac in the deceleration mode.

While this two-dimensional rf phase mapping provides valuable insight into the dependence of e^+ yield on the rf phases, it is not the most practical method for optimizing the capture section during operation and beam tuning studies. As observed in Fig. 15, the maximum e^+ yield is concentrated along the diagonal line, where the two rf phases are nearly equal. This suggests that a one-dimensional rf phase scan, rather than a full two-dimensional scan, is sufficient for practical optimization of the capture linac. The measurement was repeated using a one-dimensional rf phase scan with a finer step size of 5° to refine the optimization process. The simulation results were then compared with the experimental data, as illustrated in Fig. 17.

In the first half of the scan, which corresponds to rf phases near the deceleration mode, there is a very good agreement between the simulation results and the measurements. However, in the second half of the scan, deviations between simulation and measured data become apparent. This discrepancy may be partly due to the idealized layout of the simulation, which does not account for alignment errors or magnetic field asymmetries. In particular, the dc solenoids in the capture linac have an extra dipole component arising from the winding of the

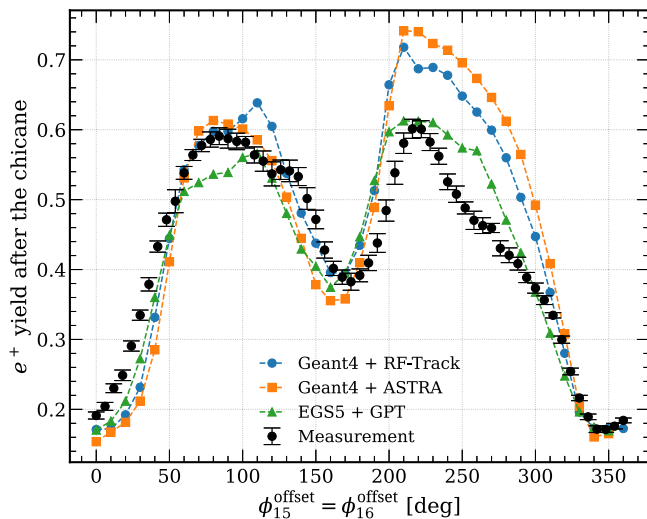


FIG. 17. e^+ yield as a function of the rf phase offset for KL15 and KL16. The scan was performed in 5° steps, with each measurement point averaged over 50 acquisitions to improve statistical accuracy. Error bars in the figure indicate the resulting standard deviations. The simulation data points are connected as a guide to the eye and do not represent a fit or model.

hollow conductor, which is not included in the simulation. Further work is in progress to better understand these differences, and additional experimental and simulation studies are planned.

V. CONCLUSIONS

This paper presented an overview of the high-intensity e^+ sources, addressing the challenges associated with each stage and highlighting the complexity of e^+ source modeling. We have developed and experimentally validated a start-to-end simulation framework that couples Geant4 for particle-matter interactions with RF-Track for 6D beam-dynamics tracking. Applied to SuperKEKB, the model reproduces the operational e^+ yield at the exit of the capture section. The start-to-end simulation predicts an e^+ yield of $0.603N_{e^+}/N_{e^-}$, consistent with the measured value of $0.603N_{e^+}/N_{e^-}$, each with a statistical error of 0.5%. The final experimental accuracy is, in fact, limited by the systematic uncertainty of the BPM charge calibration (typically a few percent), rather than by this statistical error. Accordingly, the small simulation-measurement difference (0.02%) is negligible compared with the overall error budget, demonstrating that the model accurately reproduces the e^+ source performance within the experimental uncertainties. Furthermore, our model has been validated through several measurements conducted at the SuperKEKB e^+ source and compared with two independent models. The first model used at KEK is based on EGS5 + GPT, and the second model integrates Geant4 + ASTRA. The validation encompassed multiple key aspects of the e^+ source, including scanning of the primary e^- impacting

position on the target, the magnetic field of the solenoid in the capture section, and the rf phases in the capture linac. We analyzed the effects of these parameters on the e^+ yield at the end of the capture section, and the benchmarking study demonstrated good agreement with both measurements and the other simulation tools. These findings establish a solid foundation for application in other collider projects, providing a robust framework for designing and optimizing high-intensity e^+ sources.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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