

Beam-dynamics-informed determination of subharmonic buncher phase and amplitude in the High Energy Photon Source Linac

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(Received 25 February 2025; accepted 20 August 2025; published 17 September 2025)

The High Energy Photon Source (HEPS) Linac is a normal-conducting electron linear accelerator capable of producing high bunch charge beam. Its bunching system includes two subharmonic bunchers (SHBs), one prebuncher, one buncher, and one accelerating structure. The SHB is commonly used in the low-energy section for longitudinal bunching to increase the bunch charge. The phase and voltage of the SHB are crucial for obtaining a high-quality electron beam in Linac. This paper presents a method for calibrating the phase and voltage of the SHB using the time-of-flight technique. Experiments were conducted at the HEPS Linac using two beam position monitors. According to the simulations, we found that bunch length and space charge effect have a significant impact on the results, and we propose corrective measures to address them. To enhance experimental efficiency, we propose a data processing method called the truncated averaging technique that eliminates the need for corrective measures, which has been validated through both simulations and experiments, yielding outstanding results. This paper presents detailed insights into both the simulation and experimental procedures.

DOI: [10.1103/xnb4-kskv](https://doi.org/10.1103/xnb4-kskv)

I. INTRODUCTION

The High Energy Photon Source (HEPS) [1,2] is a fourth-generation synchrotron light source based on a 6 GeV diffraction-limited storage ring [3] that is currently under construction in northern China [4]. The injector consists of a 500-MeV Linac [5,6], a booster [7], and three transfer lines [8]. The Linac is a normal-conducting linear accelerator capable of producing single bunch charge beam exceeding 7 nC. The Linac is composed of three main subsystems including an electron gun [9] for a high-current electron source, a bunching system [10], and the main accelerator. The layout of the HEPS Linac is shown in Fig. 1. In scenarios where the maximum emission current of the electron gun is approximately 10 A, achieving such a high bunch charge requires the bunch length of the beam to be around 1 ns. Consequently, in the bunching system, it is essential to compress the bunch length of the beam from a long pulse down to the order of several picoseconds for further acceleration in the main Linac operating at an rf frequency of 2998.8 MHz. To achieve high transmission

efficiency for high-charge pulses, the bunching system employs two subharmonic bunchers (SHBs). The frequencies of these SHBs are selected as 166.6 and 499.8 MHz, respectively. Positioned immediately after the second SHB is a 2998.8 MHz standing wave prebuncher (PBUN) to provide further bunching while also allowing for the adjustment of the number of bunches. Downstream of the PBUN, a 2998.8 MHz traveling wave buncher and a 2998.8 MHz standard traveling wave accelerating structure are utilized to boost the beam energy with solenoids surrounding these devices for transverse focusing. The bunching system includes two button-type beam position monitors (BPMs) for orbit measurement, one integrated current transformer (ICT) for measuring the bunch charge at the exit of the electron gun. There is another ICT at the exit of the bunching system for bunch charge measurement and an energy analysis station for measuring the energy and energy spread.

For the bunching system of the HEPS Linac, the numerous components and limited observable beam measurement parameters make it quite challenging to achieve the reasonable parameter settings. As the first stage of bunch length compression, the parameter settings of the first SHB (SHB1) are crucial. Therefore, obtaining the phase and voltage settings for the SHB1 is a crucial topic. The design of using SHB for bunch length compression to increase the bunch charge has been applied in several facilities, such as SuperKEKB [11], BEPCII [12], and SSRF [13]. However,

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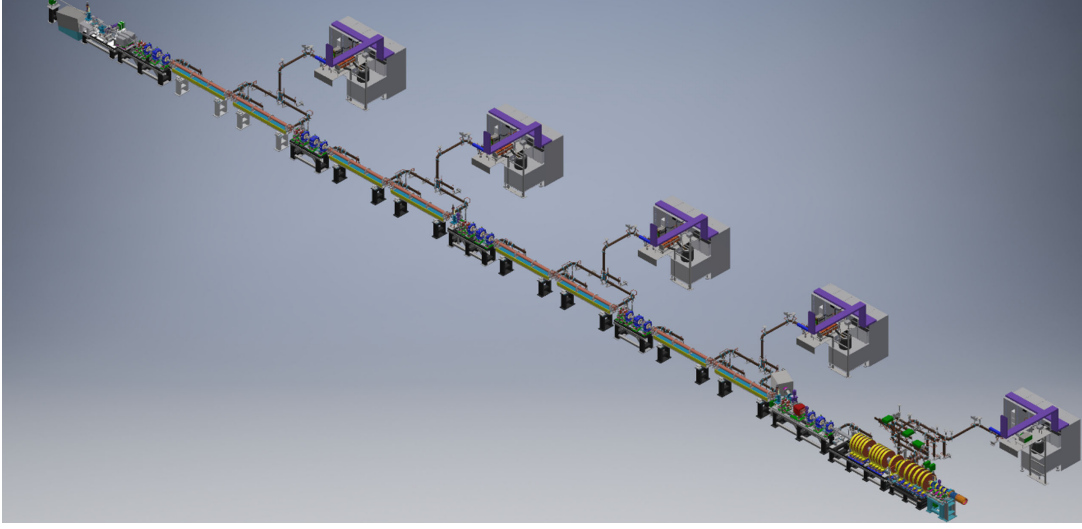


FIG. 1. Layout of the HEPS Linac.

there has been no reported achievement in calibration of the SHB based on electron beam. During the design of the HEPS Linac, a new scheme was adopted. Specifically, a BPM was added behind SHB1, reserving the possibility of calibrating SHB using the time-of-flight (TOF) method. Systematic approaches utilizing TOF measurements to calibrate phase and voltage of the cavity have been used at many facilities [14–20]. Basically, these methods convert the time differences measured by the detectors into beam energy and then compare them with model or simulation results to obtain the cavity phase and cavity voltage. Since it is necessary to convert the time difference into a velocity difference, the cavity must have a significant effect on the particle's velocity during the process of changing phase and voltage. Therefore, this method is primarily applied in hadron accelerators and has not yet been utilized in electron linear accelerators. Usually, the two detectors are placed downstream of the scanned cavity and the most commonly used detectors are BPMs or fast current transformers.

In this paper, we apply the TOF method to calibrate the voltage and phase of the SHB1 at the HEPS Linac and conduct an experiment based on the electron beam. The layout of the SHB calibration system is shown in Fig. 2. Based on the physical design and longitudinal space constraints, SHB1 is positioned between two BPMs, which differs from the traditional layout used for cavity calibration, where the two detectors are located downstream of the cavity. The signals measured by the BPM reflect the overall

effect of the beam. In the TOF measurement, the arrival times of the beam pulses are often determined by their respective centroids (i.e., the mean arrival time of all particles within each bunch). If the beam distribution is asymmetric, the centroid-based timing can be skewed, thereby influencing the accuracy of the TOF results. Based on our research, strong space charge effects and long bunch lengths have been shown to significantly impact the outcomes. We conducted theoretical analyses and simulations to detail these effects on the measurement results and proposed corrective measures. To simplify practical beam experiments, we also proposed a signal processing method called the truncated averaging method, which enables the completion of beam experiments without the need for corrective measures. As an additional benefit, the TOF method can also provide the time offset of the measurement system.

This paper is organized as follows. Section II provides an introduction to the subharmonic buncher. Section III discusses the detailed calibration theory. In Sec. IV, we present a simulation study performed with ASTRA [21] to validate the proposed methods. This section also introduces the global averaging method and truncated averaging method for TOF extraction. Section V presents experimental results at HEPS Linac. Finally, conclusions are drawn in Sec. VI.

II. SUBHARMONIC BUNCHER

The subharmonic cavity compresses the bunch length through velocity modulation. As particles traverse the SHB, particles at different longitudinal positions experience different phases of the electromagnetic field within the cavity, resulting in varying energy gains. When the particle bunch is positioned at a specific phase of the SHB, the particles at the tail of the bunch have higher energy and faster speeds compared to those at the head. Consequently,

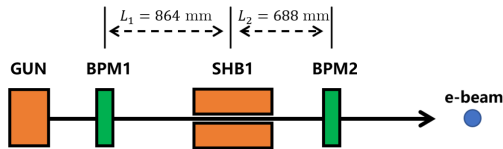


FIG. 2. Layout of the SHB calibration system.

after passing through a drift space, the bunch undergoes compression. As mentioned earlier, the frequency of SHB1 in the HEPS Linac is 166.6 MHz, located between BPM1 and BPM2. The wavelength of the SHB1 is 1.8 m, and the field gap is 40 mm. Consequently, even for an electron energy of 50 keV, the transit time factor exceeds 0.99. Therefore, when calculating the cavity voltage, the influence of the transit time factor can be disregarded. SHB1 is a standing wave single-cell structure cavity, with a simulated R/Q_0 of 171.7. The measured quality factor Q_0 is 8151, resulting in a shunt impedance R_s of 1.4 M Ω . A solid-state power source provides power P_{ps} to SHB1, and the measured power transmission efficiency η of power feed line from the solid-state power source to the input of SHB1 is 90.7%. The standing wave ratio of SHB1 is 1.02. Compared to the power entering the cavity P_{in} , the reflected power P_{rf} is very small and can be ignored; therefore, the cavity voltage can be calculated using the following formula.

$$V = \sqrt{(P_{in} - P_{rf})R_s} = \sqrt{P_{in}R_s} = \sqrt{P_{ps}\eta R_s}. \quad (1)$$

Subsequently, we will introduce the cavity voltage correction method based on electron beam.

III. CALIBRATION THEORY

In the experiment, the relationship between the measured TOF and the cavity phase—known as the phase scan curve—can be established by varying the cavity phase. Subsequently, the phase and voltage of the cavity can be calibrated by fitting the phase scan curve using a theoretical TOF-phase relation. Throughout this paper, the term voltage refers to the effective cavity voltage, which accounts for the transit time factor and cavity geometry. Specifically, the effective voltage is defined as $V_{eff} = E_0 T L_b$, where E_0 is the maximum electric field, T is the transit time factor, and L_b is the cavity length. In this section, a single-particle model is first considered to derive the dependence of TOF on both the cavity phase and the effective voltage. Then, a multiparticle bunch is taken into account to correct the single-particle approximation. The TOF within SHB1 can be a nonlinear function of phase due to velocity changes during acceleration. To simplify the calculation, a kicker model is employed, which approximates the energy gain as an instantaneous change in velocity. Under this model, the TOF through SHB1 is expressed as the sum of two drift times before and after the velocity change.

Figure 3 shows the TOF difference of the reference particle within SHB1 between the kicker model and the exact solution at a cavity voltage of 103 kV—the highest cavity voltage derived from Eq. (1) in the experiment. The TOF for the exact solution was obtained using ASTRA simulation while kicker model TOF was calculated analytically.

A bunch length of 1.5 ns and an energy of 143 keV were used. To conservatively account for the expected energy

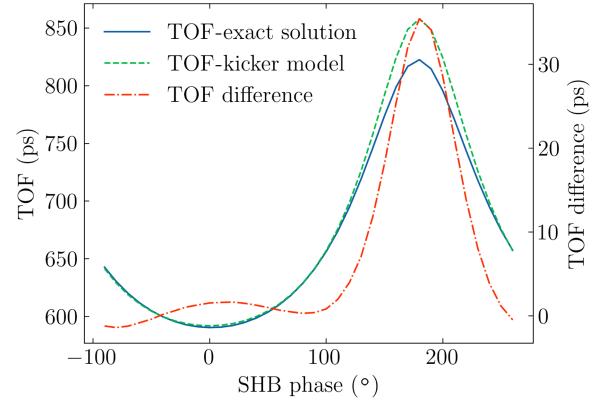


FIG. 3. TOF difference within SHB1 between exact solution obtained using ASTRA simulation and kicker model calculated analytically. The bunch length was set to 1.5 ns with an energy of 143 keV and an energy spread of 2 keV.

spread, a Gaussian distribution with a standard deviation of 2 keV was used in the beam dynamics simulations, based on prior simulation results and potential uncertainties in the experimental conditions. This choice, combined with the longest bunch length and lowest energy observed experimentally, is expected to produce the maximum discrepancy in derived voltages between the exact solution and the kicker model. The maximum TOF difference, approximately 35 ps, occurs at a 180° phase. Figure 4 shows the derived voltages results using the exact solution and the kicker model. It can be observed that the derived voltage difference between the kicker model results and the exact solution is no more than 0.7%, making the kicker model sufficiently accurate for calculating the particle TOF within SHB1.

A. Single-particle model

In the single-particle model, the beam is represented by a single particle whose TOF and energy are calculated by

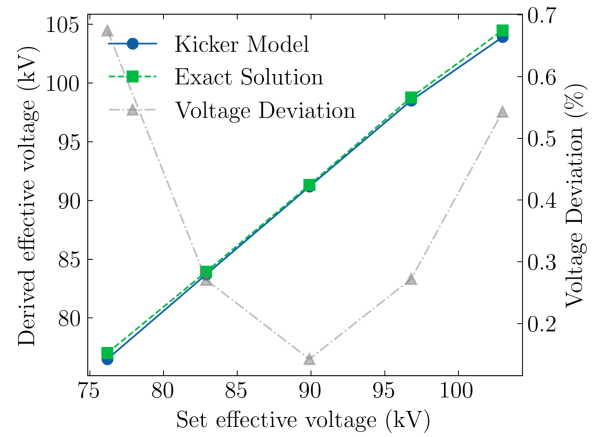


FIG. 4. Derived voltage results using exact solution and kicker model. The bunch length was set to 1.5 ns with an energy of 143 keV and an energy spread of 2 keV.

averaging the TOFs and energies of all particles or a representative subset of them. The energy gain of a single particle inside SHB1 can be expressed as

$$E_2 - E_1 = eE_0TL_b \cos(\phi + \phi_0), \quad (2)$$

where E_0 is the peak electric field voltage of SHB1, T is the transit time factor, L_b is the cavity length, ϕ represents the phase of the low-level radio frequency system, and ϕ_0 denotes the phase offset between this system phase and the actual physics phase. Using the effective cavity voltage V_{eff} , Eq. (2) can be rewritten as

$$E_2 - E_1 = eV_{\text{eff}} \cos(\phi + \phi_0), \quad (3)$$

where effective cavity voltage V_{eff} will be used to represent the voltage of the cavity in this paper.

If we regard particle velocity variation inside SHB1 as a sudden change from v_1 to v_2 , then the TOF from BPM1 to BPM2 can be written as

$$\text{TOF} = \frac{L_1}{v_1} + \frac{L_2}{v_2} + \Delta t, \quad (4)$$

where L_1 is the distance from the center of BPM1 to the field center of SHB1, L_2 is the distance from the field center of

SHB1 to the center of BPM2, v_1 and v_2 are the beam velocity at the upstream and downstream of SHB1, respectively, Δt is the time offset of the measurement system.

By combining Eqs. (3) and (4), we derive the functional relationship of TOF with respect to ϕ , referred to as the single-particle model.

B. Particle-bunch model

Under experimental conditions, only the average TOF and energy of the particle bunch can be obtained, rather than the TOF and energy of each particle. The single-particle model overlooks the longitudinal distribution of the particles, which could influence the mean energy gain and TOF of the particle bunch. Therefore, a particle-bunch model is proposed, taking the longitudinal particle distribution into consideration. Assuming that a reference particle is located at the center of the bunch, the energy gain of an arbitrary particle i can be written as

$$E_{2i} - E_{1i} = eV_{\text{eff}} \cos(\phi + \phi_0 + \Delta\phi_i), \quad (5)$$

where $\Delta\phi_i$ is the phase difference between particle i and the reference particle. The mean energy gain of the particle bunch can be written as the following equation:

$$\begin{aligned} \langle E_{2i} - E_{1i} \rangle &= \frac{1}{N} \sum_{i=1}^N eV_{\text{eff}} \cos(\phi + \phi_0 + \Delta\phi_i) \\ &= eV_{\text{eff}} \left[\left(\frac{1}{N} \sum_{i=1}^N \cos \Delta\phi_i \right) \cos(\phi + \phi_0) - \left(\frac{1}{N} \sum_{i=1}^N \sin \Delta\phi_i \right) \sin(\phi + \phi_0) \right] \\ &= e\kappa V_{\text{eff}} [\cos \Delta\phi \cos(\phi + \phi_0) - \sin \Delta\phi \sin(\phi + \phi_0)] \\ &= e\kappa V_{\text{eff}} \cos(\phi + \phi_0 + \Delta\phi), \end{aligned} \quad (6)$$

where

$$\kappa = \sqrt{\left(\frac{1}{N} \sum_{i=1}^N \sin \Delta\phi_i \right)^2 + \left(\frac{1}{N} \sum_{i=1}^N \cos \Delta\phi_i \right)^2} \quad (7)$$

represents the cavity voltage correction (CVC) coefficient introduced by the longitudinal distribution of the bunch. Since κ will not exceed 1, the average cavity voltage experienced by the entire bunch is lower than that experienced by a single reference particle.

$$\Delta\phi = \arctan \left(\frac{\sum_{i=1}^N \sin \Delta\phi_i}{\sum_{i=1}^N \cos \Delta\phi_i} \right) \quad (8)$$

represents the phase offset introduced by the asymmetric distribution of the beam.

In particle-bunch model, Eqs. (6)–(8) are used to replace Eq. (3) in single-particle model. Equation (4) remains applicable in particle-bunch model, with the modification of replacing TOF of a single particle with the average TOF of the particle bunch. By combining Eqs. (4) and (6)–(8), we derive another functional relationship of TOF with respect to ϕ , referred to as the particle-bunch model. However, replacing single particle TOF with the average TOF of particle bunch in Eq. (4) is not an ideal correction. Using 5000 particles with an initial longitudinal Gaussian distribution and a bunch length of 1 ns, we calculated their TOF and output energy E_2 after SHB1 acceleration using Eqs. (3) and (4) at different SHB1 phases. The effective voltage was set to 76.2 kV. A 149 keV input energy E_1 was assigned to the reference particle, while the beam had a mean input energy $\langle E_1 \rangle$ of 149 keV with a 2 keV energy spread. The SHB1 phase was varied from -180° to 180° in steps of 10° . Figure 5 shows the $\langle \text{TOF} \rangle - \langle E_2 \rangle$ relationship

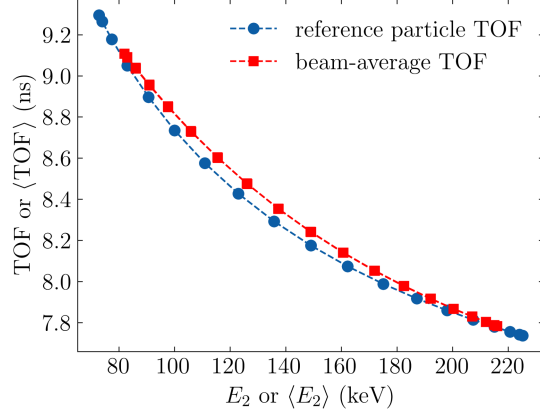


FIG. 5. Comparison between the reference particle TOF and the beam-average TOF as functions of beam energy after SHB1 acceleration. The beam bunch length is 1 ns.

for whole beam and TOF – E_2 relationship for the reference particle in the beam at SHB phases from -180° to 180° , where E_2 and $\langle E_2 \rangle$ denote the kinetic energy of the reference particle and the average kinetic energy of the particle bunch after SHB1 acceleration, respectively. Notably, at the same kinetic energy, the average TOF of the bunch is not equal to the TOF of the reference particle. This phenomenon arises from the longitudinal asymmetry of the beam induced by the electric field of the SHB. Figure 6 shows the TOF distribution at a phase of 0° , extracted from the TOF-energy map in Fig. 5, which spans the full phase range from -180° to 180° under identical conditions. The output energy E_2 of the reference particle is 225 keV while the beam has a mean output energy $\langle E_2 \rangle$ of 216 keV. It can be observed that the longitudinal asymmetry causes a skew in the TOF distribution, leading to the discrepancies between the average TOF of the bunch and the TOF of the reference particle at the same energy. To address this, we introduce the distribution asymmetry correction (DAC), which involves applying a correction factor α to the beam's average TOF to correct for the discrepancy. This correction factor is defined as

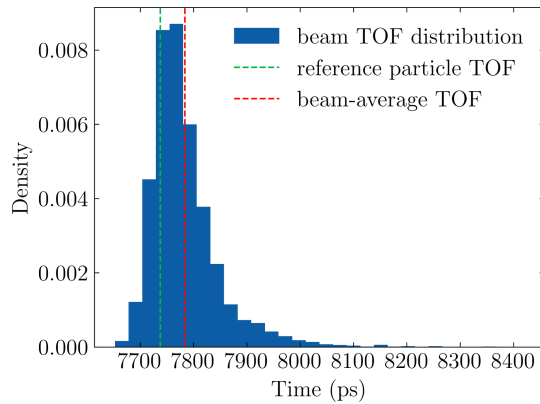


FIG. 6. Discrepancy between reference particle TOF and beam-average TOF due to longitudinal asymmetry.

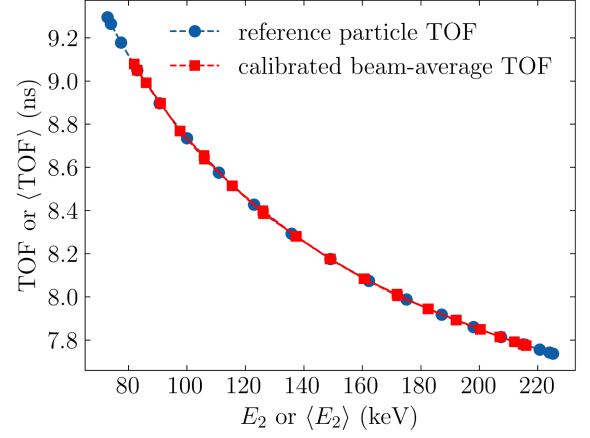


FIG. 7. Comparison between the reference particle TOF and the calibrated beam-average TOF as functions of beam energy after SHB1 acceleration. The beam bunch length is 1 ns.

$\alpha = \text{TOF}/\langle \text{TOF} \rangle$, with the reference particle energy E_2 being the same as the average energy $\langle E_2 \rangle$. This correction adjusts the beam-average TOF to match the reference particle TOF at the same kinetic energy, as shown in Fig. 7. The improvement in derived effective voltage will be discussed in Sec. IV A.

However, it should be noted that utilizing CVC and the DAC requires precise particle longitudinal distribution. As will be discussed in Sec. V, obtaining an accurate particle longitudinal distribution is challenging due to noise interference. We will also demonstrate how to perform fitting analysis using an approximate longitudinal particle position distribution. In the subsequent analysis of simulation and experimental data, both the single-particle model and the particle-bunch model will be used for comparison. For the particle-bunch model, results with and without DAC will also be compared.

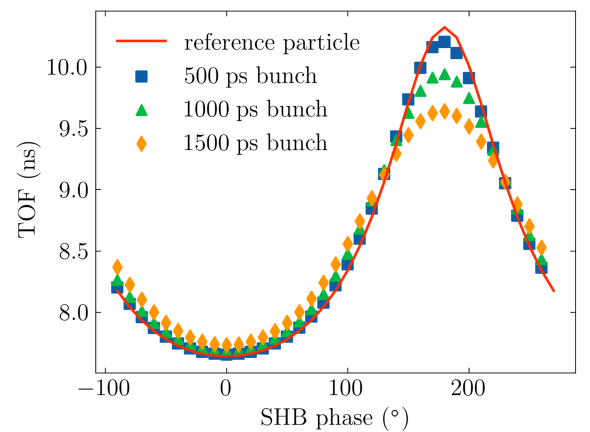


FIG. 8. Simulation phase scan curves with global averaging method. The red line represents the phase scan curve of the reference particle, while the scattered markers indicate the average TOF for all particles obtained from the ASTRA simulations.

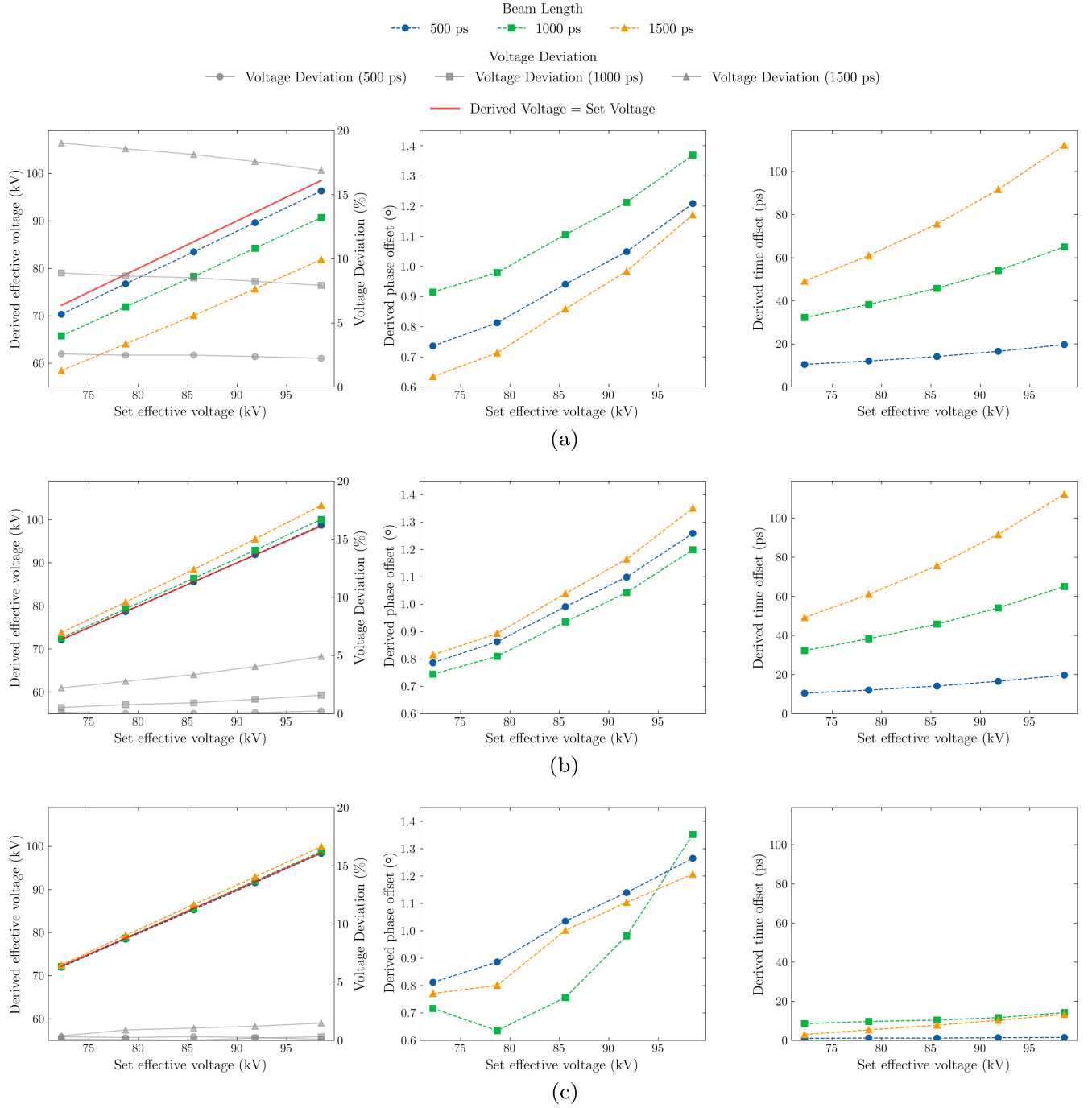


FIG. 9. Simulation curve fitting results. (a) Single-particle model. (b) Particle-bunch model (without DAC). (c) Particle-bunch model (with DAC).

IV. SIMULATION STUDY

A series of beam dynamics simulations were conducted using ASTRA at bunch charge levels of 1.0, 5.0, and 9.0 nC with FWHM bunch length of 500, 1000, and 1500 ps, respectively. The longitudinal particle distribution was set as Gaussian. An initial beam energy of 149 keV was used to match the experimental beam status at the exit of electron gun. The transverse beam intensity was set to be

homogeneous with 20π mm mrad transverse emittance. The effective voltages of SHB were set to range from 70 to 100 kV accordingly. ASTRA simulations were then performed by scanning the SHB phase from -180° to 180° to obtain the particle distribution at different phases, which was then used to construct the phase scan curve. The method used to extract the TOF from the longitudinal particle position distribution data significantly affects the resulting phase scan curve. We will present two TOF extraction methods: the global

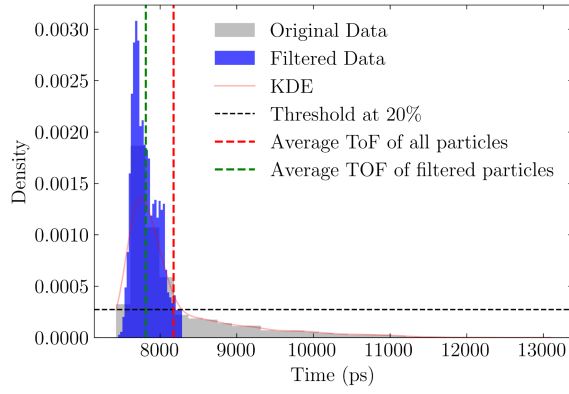


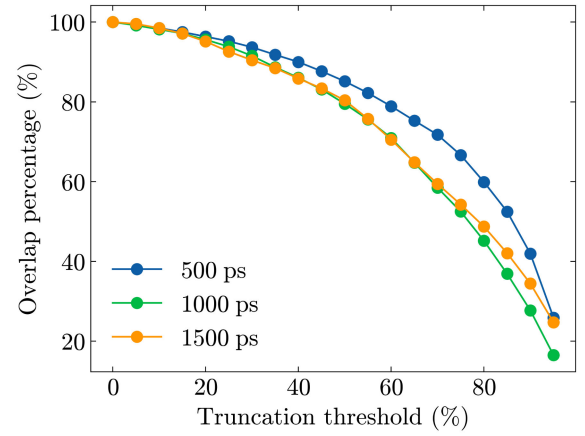
FIG. 10. Distribution of particle positions with 20% voltage threshold.

averaging method and the truncated averaging method. The phase scan curves derived from these methods will be analyzed using different correction techniques to derive the cavity voltage and phase results.

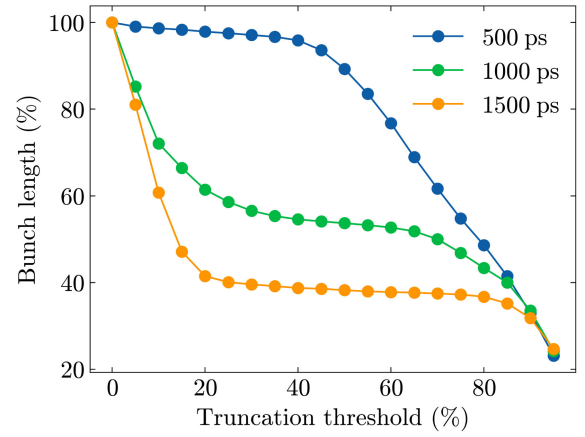
A. Global averaging method

The global averaging method calculates the TOF of the particle bunch by averaging the TOFs of all particles. The phase scan curve obtained using the global averaging method is shown in Fig. 8, together with the TOF of the reference particle for comparison. At a bunch length of 500 ps, the averaged beam TOF exhibits reasonable agreement with the reference particle TOF. However, as the bunch length increases, the discrepancy between the two becomes more pronounced, underscoring the need for implementing CVC and DAC.

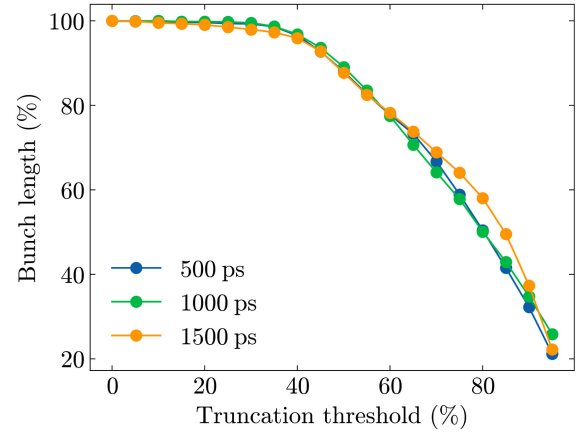
The single-particle model, the particle-bunch model without DAC, and the particle-bunch model with DAC were sequentially employed for data analysis. The derived effective voltage, time offset of the measurement system, and phase offset as a function of the set effective voltage of SHB are shown in Fig. 9. Ideally, the derived effective voltage should match the set effective voltage precisely, irrespective of the bunch length. Additionally, the derived phase offset and time offset are expected to be zero, since no actual measurement system exists in the simulation. It can be observed that the derived effective voltage deviates greatly from the set effective voltage at long bunch lengths in Fig. 9(a) while the deviation becomes smaller in Fig. 9(b). This large deviation in the effective voltage derived by the single-particle model is primarily attributed to the inaccuracy of its energy calculation function Eq. (2). With the improvement of energy calculation function Eq. (6), the deviation becomes smaller. With the addition of the DAC, the deviation is further reduced, as shown in Fig. 9(c). The derived phase offset error remains within 2° in all three cases, with minimal differences observed between the cases. The derived time offset exhibits greater deviation at longer bunch lengths for both the single-particle model and the particle-bunch model



(a)



(b)



(c)

FIG. 11. Effect of truncation threshold on beam characteristics. (a) Overlap percentage as a function of truncation threshold under SHB phase 180° . The overlap is defined as the fraction of particles remaining at BPM2 that are also included in the truncated set at BPM1. (b) Bunch length at the BPM2 position as a function of truncation threshold under SHB phase 180° . (c) Bunch length at the BPM2 position as a function of truncation threshold under SHB phase 0° .

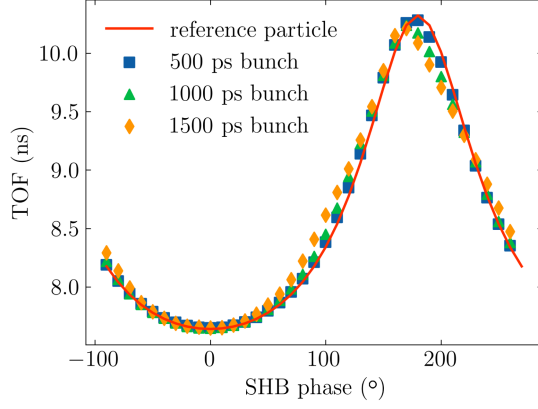


FIG. 12. Simulation phase scan curves with truncated averaging method. The red line represents the phase scan curve of the reference particle, while the scattered markers indicate the average TOF for filtered particles obtained from the ASTRA simulations.

without DAC. Upon incorporating the DAC for the particle-bunch model, the error is significantly reduced.

B. Truncated averaging method

In the previous analysis of the simulated data, the TOF of particle bunch was calculated by averaging the TOFs of all particles in simulation. Although good results were achieved after the correction, considering that the correction involves a certain level of complexity, we propose a technique to simplify the measurement process, which is the truncated averaging method. Meanwhile, in actual experiments, the method can eliminate the impact of noise. Consequently, we also tested this approach in the simulation. As shown in Fig. 10, kernel density estimation (KDE) was applied to the particle distribution at the BPM2 position under an SHB phase of -180° to calculate the density curve. After

identifying the peak density, 20% of the peak value was calculated as a threshold, and data below this threshold were discarded. The TOF of the particle bunch was calculated as the average TOF of the remaining particles, i.e., the portion highlighted in blue.

To justify the use of the 20% threshold, we first evaluated how much of the core beam is retained after truncation. As shown in Fig. 11(a), we define the overlap percentage as the fraction of particles remaining at BPM2 that are also present in the truncated particle set at BPM1. At a 20% threshold, the overlap remains as high as 95%, indicating that the truncation primarily removes low-density tails while preserving the central particle distribution. We then examined how the SHB phase affects the relationship between bunch length and TOF. As shown in Fig. 8, at 180° , the TOF varies significantly between long and short bunches, whereas at 0° , the TOF remains relatively stable regardless of bunch length. This means that, under 180° , the TOF is more sensitive to the bunch profile and can be distorted by the presence of long tails, making truncation especially beneficial in this case. This effect is further illustrated in Figs. 11(b) and 11(c), which show how different truncation thresholds affect the bunch length at BPM2 under 180° and 0° , respectively. At 180° , a 20% threshold significantly reduces the bunch length for initially long bunches while maintaining it for short ones. At 0° , the bunch length remains nearly unchanged across all initial lengths. Taken together, these results show that a 20% truncation threshold effectively suppresses low-density noise, improves TOF consistency in phase-sensitive scenarios, and retains the core structure of the beam with minimal loss. Therefore, 20% emerges as a well balanced and practically robust choice for both simulation and experimental implementation.

The phase scan curve obtained using this truncation method in simulation is shown in Fig. 12, alongside the reference particle's phase scan curve. The results demonstrate

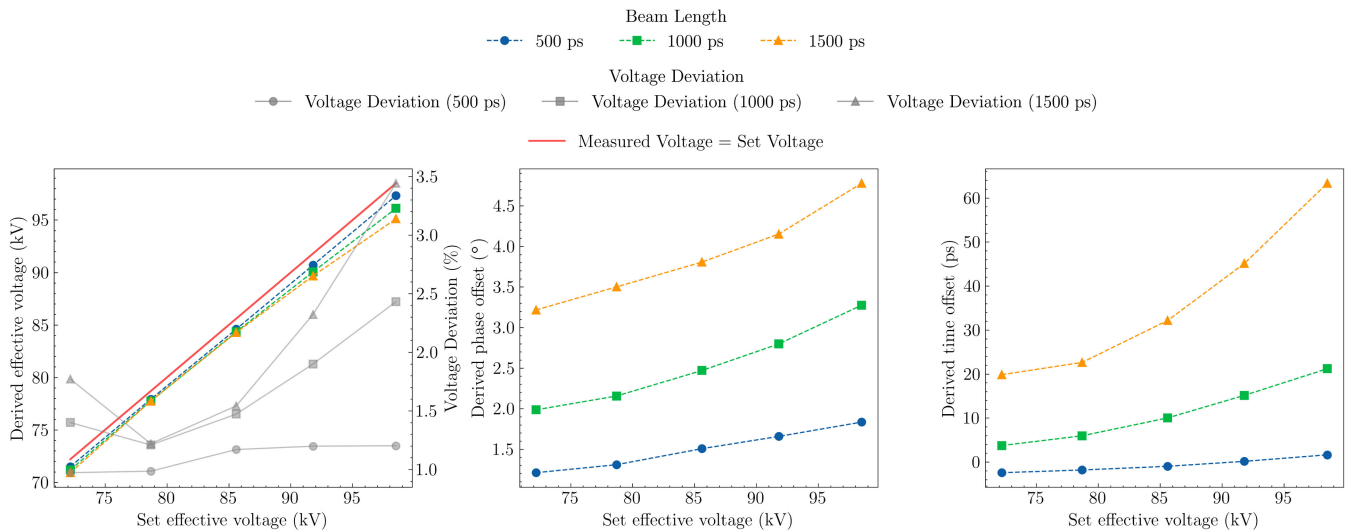


FIG. 13. Simulation results using the single-particle model with truncated averaging method.

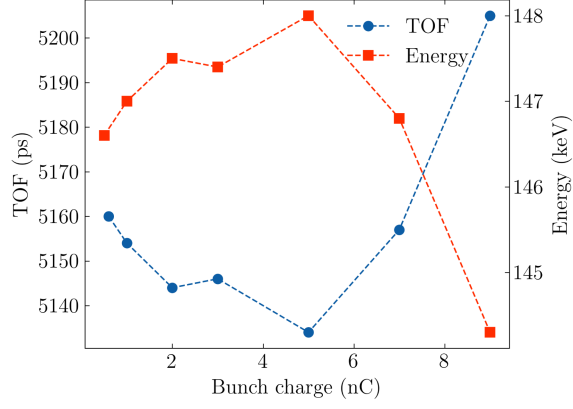


FIG. 14. TOF at different bunch charges with SHB turned off.

that the phase scan curves obtained using the truncated averaging method exhibit good agreement with the reference particle's across a broad range of bunch lengths, rather than only at short bunch lengths.

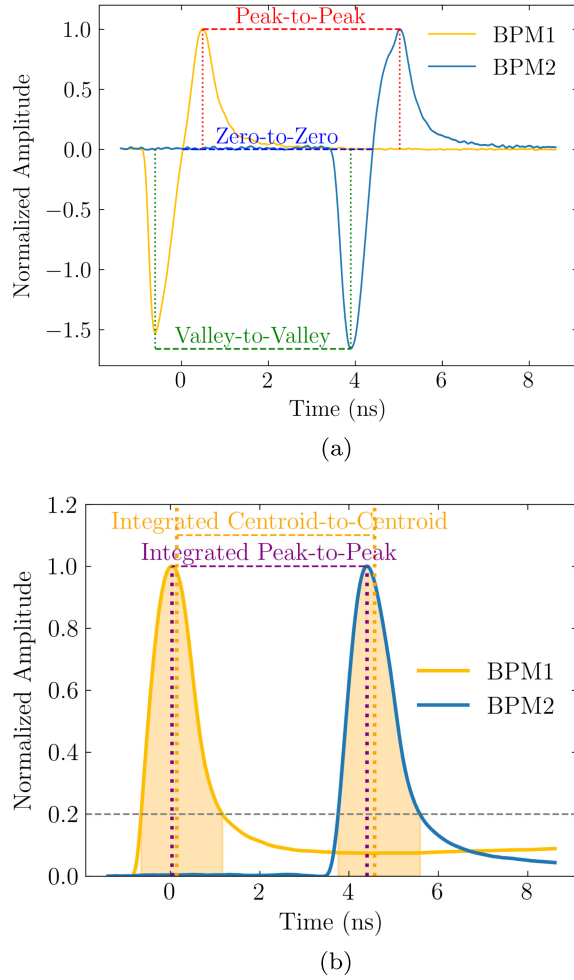


FIG. 15. Comparison of various TOF extraction methods. (a) Signals from BPM1 and BPM2. (b) Integrated signals from BPM1 and BPM2.

Since the phase scan curve remains consistent with that of the reference particle across various bunch lengths, there is no need to introduce corrections from the particle-bunch model. The single-particle model can be directly applied for fitting, and the derived results are illustrated in Fig. 13. Compared to the results derived using the particle-bunch model in Fig. 9, the fitting accuracy is lower when using the single-particle model combined with the truncated averaging method. This outcome is anticipated, as truncating 20% of the initial and final particle distributions does not guarantee that the same subset of particles is retained. However, the single-particle model combined with the truncated averaging method is more straightforward. Given the difficulty of obtaining perfectly accurate particle position distributions in actual experiments, this method holds greater practical significance.

V. EXPERIMENT RESULTS AND DISCUSSION

In HEPS Linac, the energy of the electron beam at the exit of electron gun is designed to be 149 keV, with a bunch length of approximately 1 ns [5], which is about 1/6 of the

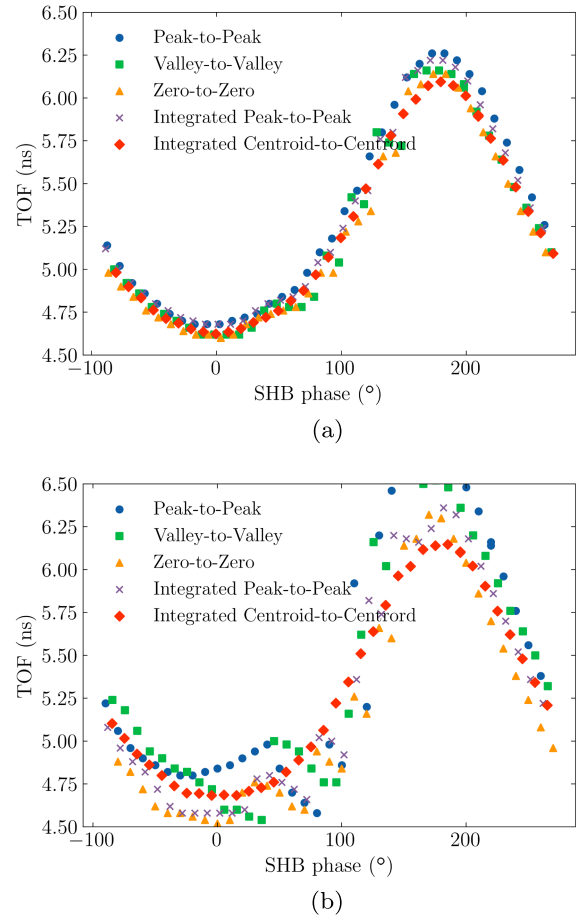


FIG. 16. Comparison of phase scan curves obtained using different TOF extraction methods. (a) 0.6 nC bunch charge. (b) 9.0 nC bunch charge.

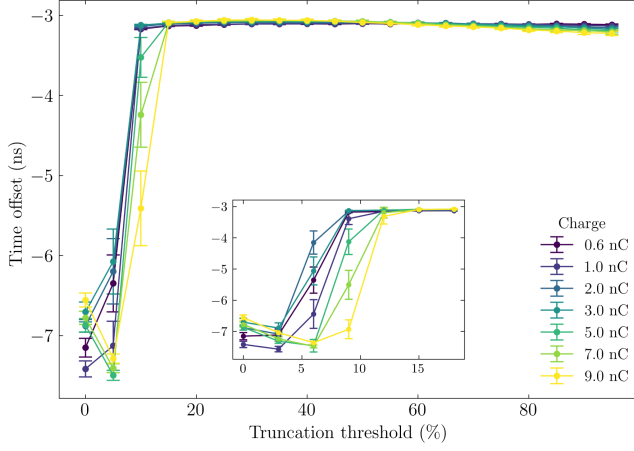


FIG. 17. Time offset as a function of truncation threshold.

rf period of SHB1. In the experiment, data were collected at seven charge levels from 0.6 to 9.0 nC. The amount of charge was changed by adjusting the pulser voltage and bias voltage of the electron gun. At each charge level, SHB1 power was varied from 4.0 to 8.0 kW in 1 kW increments, and data were collected at each power setting. At each SHB1 power level, SHB1 phase was varied from -180° to 180° in 10° increments to obtain the phase scan curve.

Due to the space charge effect, beam energy is expected to decrease at higher bunch charge levels, resulting in an increased TOF. Consequently, it is essential to calibrate the beam energy at different charge levels to account for the influence of the space charge effect. This calibration was performed by calculating the beam energy using the TOF method with SHB1 turned off, as shown in Fig. 14.

In this experiment, signals from BPM1 and BPM2 were acquired using an oscilloscope for the extraction of TOF data. A representative waveform obtained from the oscilloscope is presented in Fig. 15(a). Multiple approaches were

employed to extract the TOF data and derive the phase scan curve, including the use of peak, valley, and zero-crossing points of the waveform to determine the TOF. These methods are also depicted in the figure. In addition to extracting the TOF directly from the raw oscilloscope waveform, TOF can also be obtained by integrating the oscilloscope signals to generate an approximate particle position distribution curve. The TOF can then be extracted from this distribution curve using key features such as the centroid or peak position, as shown in Fig. 15(b). When calculating the centroid position, data below 20% of the peak value were excluded to minimize noise interference, and the centroid was determined using voltage as the weighting factor. The phase scan curves obtained using the aforementioned methods are presented in Figs. 16(a) and 16(b). It can be observed that, at low bunch charges, all methods yield the expected phase scan curve. However, at higher bunch charges, only the phase scan curve obtained using the integrated centroid-to-centroid method retains a well-defined shape, while the curves from other methods appear distorted. Therefore, the integrated centroid-to-centroid method was chosen for processing the experimental data. Since the portion of the particle distribution below 20% of the peak value was truncated to mitigate noise, as discussed in Sec. IV B, the single-particle model was selected for the curve fitting procedure. The time offset obtained with truncated averaging method as a function of the truncation threshold is shown in Fig. 17. As observed from the figure, the time offset derived from the fitting, along with its corresponding error bars, exhibits significant variation when the truncation threshold is below 20%. However, beyond a truncation threshold of 20%, these fluctuations become minimal. Therefore, the truncation threshold was ultimately set to 20%.

The curve fitting results derived using single-particle model with truncated averaging method are shown in Fig. 18. An effective voltage curve calculated using the forward power and shunt impedance as defined in Eq. (1) is

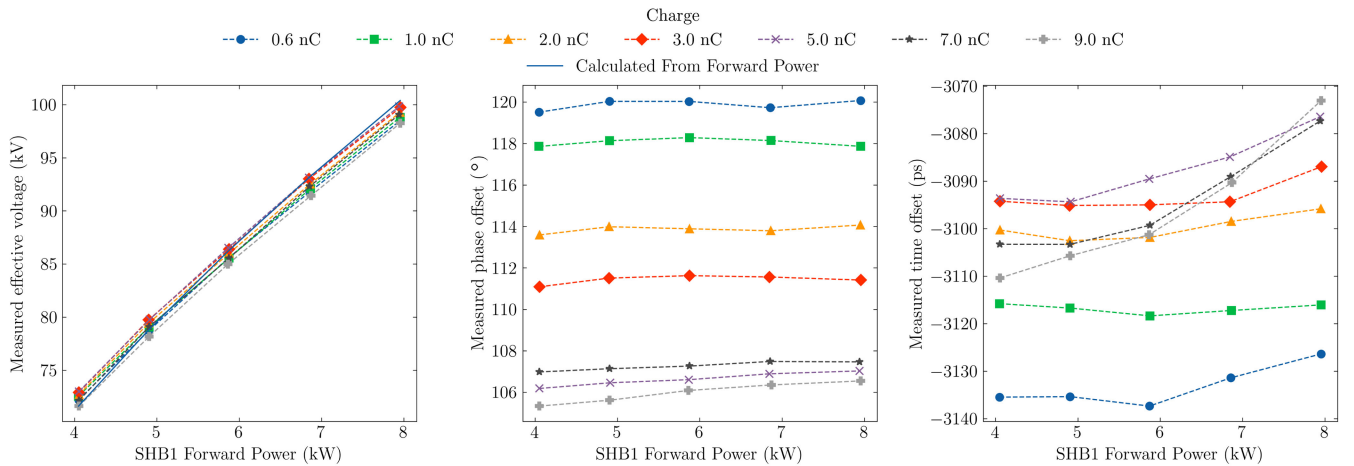


FIG. 18. Experimental results using the single-particle model with truncated averaging method.

also plotted in the figure. It can be observed that the fitted effective voltage agrees well with the effective voltage calculated from the forward power and shunt impedance. The difference in the derived effective voltage between low and high bunch charges is relatively small. The variation in derived phase offset at different charge levels directly indicates changes in beam energy, which result from the space charge effect. The calibration results of the cavity voltage, phase, and time offset mentioned above significantly contribute to the actual beam commissioning.

VI. CONCLUSION

This paper presents an experimental method for calibrating the phase and voltage of the SHB using two BPMs. For data analysis, both the single-particle model and the particle-bunch model were proposed, with two approaches employed for TOF extraction: the global averaging method and the truncated averaging method. Additionally, a beam dynamics simulation study was conducted using ASTRA.

The results revealed that the single-particle model exhibited inaccuracies, particularly at longer bunch lengths when extracting TOF using the global averaging method. In contrast, the particle-bunch model, combined with the global averaging method, achieved high accuracy over a wide range of bunch lengths, although it relied on the particle position distributions, which are challenging to obtain.

When utilizing the truncated averaging method, the single-particle model yielded results comparable to those obtained with the corrected particle-bunch model. Moreover, the combination of the truncated averaging method with the single-particle model proved to be both simpler and more practically significant.

The design of the HEPS Linac, incorporating one BPM placed before and another after the SHB1, offers valuable insights and serves as a reference for similar system designs.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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