ANALYSIS OF SLICE ENERGY SPREAD INCREASED BY INTRA-BEAM SCATTERING AT THE SHINE INJECTOR AND LINAC

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Abstract

Intra-beam scattering (IBS) can substantially enhance the slice energy spread of high-brightness electron beams, thereby degrading the performance of free-electron laser (FEL) facilities. This effect is particularly detrimental for advanced operation modes such as self-seeding, which impose stringent requirements on beam longitudinal coherence. Consequently, an accurate evaluation of IBS growth in both the injector and the main linac is essential. SHINE, the first superconducting-linac–based FEL facility in China, has recently completed beam commissioning up to the first bunch compressor (BC1). In this work, we present a theoretical and numerical analysis of IBS-induced slice energy spread growth throughout the SHINE injector and linac. The analytical estimates show good agreement with start-to-end simulations, confirming that IBS leads to 0.5 keV increase in slice energy spread at the injector stage. In the linac section, the accu- mulated IBS-induced energy spread growth before the first bunch compressor (BC1) reaches 1.48 keV. These results highlight the necessity of incorporating IBS considerations into the beam dynamics design and optimization of high-repetition-rate FEL facilities such as SHINE.

INTRODUCTION

X-ray free-electron lasers (XFELs) have become indispensable tools for ultrafast science, enabling studies of matter with unprecedented spatial and temporal resolution [1–3]. The performance of an XFEL critically depends on the quality of the driving electron beam, especially its slice properties, such as slice emittance and slice energy spread (SES). In particular, the SES plays a crucial role in determining the FEL gain process, since it directly affects the Pierce parameter and the longitudinal coherence of the emitted radiation. For advanced FEL operation modes, including self-seeding and external seeding, the requirements on SES are even more stringent. Therefore, understanding and controlling the mechanisms responsible for SES growth is of great importance for modern high-brightness FEL facilities.

Recent experimental studies at facilities such as European XFEL [4], PITF at DESY [5] and SwissFEL [6, 7] have reported measured slice energy spreads significantly larger than the values predicted from conventional injector simulations. These discrepancies were attributed mainly to intra-beam scattering (IBS), which can increase the uncorrelated energy spread during beam transport, particularly in low-energy and high-brightness regimes. Such observations indicate that IBS is an important collective effect that cannot be neglected in superconducting-linac–based XFEL facilities operating with high repetition rates and ultra-high beam brightness.

Shanghai High Repetition Rate XFEL and Extreme Light Facility (SHINE) is the first superconducting-linac–based XFEL facility in China [3]. The facility is designed to deliver high-brightness electron beams for multi-user hard X-ray FEL applications. Due to the relatively long transport distance from the injector to the first accelerating sections, together with the extremely small intrinsic energy spread of the beam, IBS is expected to induce non-negligible SES growth along both the injector and the early linac sections.

In this paper, we present a theoretical and numerical investigation of IBS-induced slice energy spread growth throughout the SHINE injector and linac. The IBS analytical models are first introduced and applied to the SHINE beam parameters. Start-to-end simulations based on RF-Track [8] are then performed to benchmark the theoretical predictions. For the injector section, good agreement is obtained between the analytical calculations and the numerical simulations, showing that IBS leads to an SES increase of approximately 0.5 keV at the injector exit. In the linac section, the accumulated IBS-induced energy spread growth before the first bunch compressor (BC1) reaches 1.48 keV. The results demonstrate that IBS constitutes an important collective effect for SHINE and should be carefully considered in the beam dynamics design and optimization of high-brightness, high-repetition-rate XFEL facilities.

IBS ANALYTICAL MODEL

Intra-beam scattering (IBS) is a multiple small-angle Coulomb scattering process among particles within an electron bunch, which can lead to emittance dilution and energy spread growth during beam transport. For high-brightness electron beams in XFEL facilities, IBS may significantly increase the slice energy spread (SES), especially in low-energy and high-density regions such as the injector and bunch compression sections.

In this work, the IBS analytical model is based on the modified Piwinski formalism developed for low-energy injector and linac applications. Since synchrotron oscillations are negligible in a linear accelerator, the conventional storage-ring treatment can be simplified [9]. For a three-dimensional Gaussian bunch, the SES growth over a transport distance Δs can be expressed as

$$\sigma_\gamma^2 = \sigma_{\gamma,0}^2 + \frac{r_e^2 N_b \Lambda_c}{4\sigma_x \epsilon_n \sigma_z}\Delta s, \tag{1}$$

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where $\sigma_{\gamma,0}$ is the initial slice energy spread, r_e is the classical electron radius, N_b is the number of electrons in the bunch, σ_x is the rms transverse beam size, ϵ_n is the normalized emittance, σ_z is the rms bunch length, and Λ_c is the Coulomb logarithm.

To evaluate the local IBS effect more accurately, slice beam parameters are used instead of projected beam quantities. Since the IBS process in low energy area is dominated by transverse particle collisions, the slice-based treatment is more appropriate for describing the SES evolution [7]. The transverse beam size is represented by the geometric mean of the horizontal and vertical slice beam sizes,$\sigma_{r,s} = \sqrt{\sigma_{x,s}\sigma_{y,s}}$, and the normalized slice emittance is defined as $\epsilon_{N,s} = \sqrt{\epsilon_{x,s}\epsilon_{y,s}}$.

The electron density within the central slice can be related to the peak current through

$$\frac{N_b}{\sigma_z} = \sqrt{2\pi}\frac{q_s}{ce\Delta z_s} = \frac{\sqrt{2\pi}I_p}{ce}, \tag{2}$$

where q_s is the charge contained in the slice, Δz_s is the full slice length, I_p is the peak current, c is the speed of light, and e is the elementary charge. In the present model, the central slice is approximated as a Gaussian beamlet with an rms bunch length $\sigma_{z,s} = \frac{\Delta z_s}{\sqrt{2\pi}}$.

Substituting Eq. (2) into Eq. (1), the SES growth can be rewritten as [7]:

$$\sigma_\gamma^2 = \sigma_{\gamma,0}^2 + \frac{\sqrt{2\pi}r_e^2 I_p \Lambda_c}{4ce\sigma_{r,s}\epsilon_{N,s}}\Delta s. \tag{3}$$

The Coulomb logarithm is evaluated locally for each slice according to

$$\Lambda_c = \ln\left(\frac{\Delta\gamma_{\max}}{\Delta\gamma_{\min}}\right), \tag{4}$$

where the maximum and minimum momentum transfers are given by $\Delta\gamma_{\max} = \gamma^2\sigma_{r',s}$,$\Delta\gamma_{\min} = \frac{r_e}{\sigma_{r,s}\sigma_{r',s}}$ with $\sigma_{r',s}$ representing the rms slice beam divergence and γ the Lorentz factor. Using Eq. (3), the cumulative SES growth induced by IBS can be calculated along the SHINE injector and linac using beam parameters extracted from start-to-end simulations.

IBS ANALYSIS IN THE SHINE INJECTOR

The layout of SHINE injector and linac is illustrated in Fig. 1(a). The injector section shown in Fig. 1(b) employs a VHF photocathode gun to generate low-emittance electron bunches at a repetition rate of 1 MHz with a bunch charge of 100 pC. Downstream of the injector is the main linac, which consists of four accelerating sections (L1–L4) and three bunch compressors (BC1, BC2 and BC3).

Because of the relatively low beam energy and high beam density in the injector region, collective effects such as space charge and intra-beam scattering (IBS) can significantly affect the beam quality, especially the slice energy spread (SES).

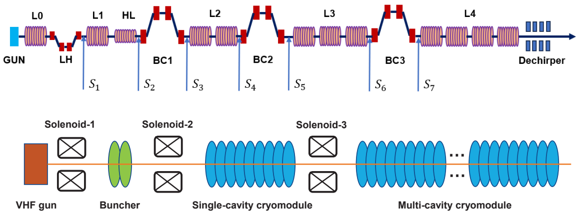

Figure 1: Schematic layout of the SHINE Linac (a) and Injector (b).

To investigate the IBS effect, simulations including only space charge were compared with simulations based on RF-Track [8, 10, 11] including both space charge and IBS effects. Figure 2 shows the longitudinal phase space at the injector exit for the two cases. It can be clearly observed that the inclusion of IBS leads to an additional increase in the beam energy spread, while the overall longitudinal phase-space structure remains nearly unchanged. This indicates that IBS mainly contributes to the growth of the uncorrelated slice energy spread.

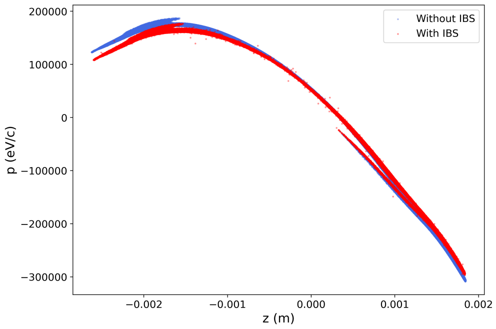

Figure 2: Simulation results with and without IBS effect based on RF-Track at SHINE Injector.

In order to quantitatively evaluate the IBS-induced SES growth, the following analysis procedure was adopted. First, only the central core region of the bunch was selected by applying a longitudinal cut to remove low-density tail particles. Then, the linear energy chirp of the selected particles was removed through polynomial fitting, and the residual RMS energy spread was defined as the slice energy spread. Using this method, the IBS-induced SES growth was evaluated at eight different locations along the injector beamline, corresponding to longitudinal positions of 2.5 m, 5 m, 7.5 m, up to 20 m from the injector entrance.

The theoretical IBS-induced SES growth was then calculated using Eq. (3) with the beam parameters obtained from the simulations. Figure 3 presents the comparison between the theoretical prediction and the RF-Track simulation results. Excellent agreement is achieved throughout the injector beamline, demonstrating the validity of the IBS analytical model for the SHINE injector. At the injector exit, IBS induces an additional slice energy spread growth of approximately 0.5 keV.

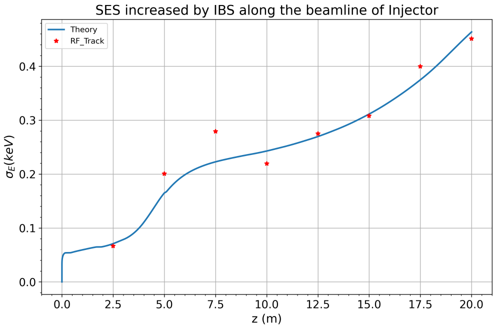

Figure 3: Comparison between the theoretical prediction and the RF-Track simulation results at SHINE Injector.

IBS ANALYSIS IN THE SHINE LINAC

In the SHINE linac, the electron beam is further accelerated and compressed after exiting the injector. Due to the combined effects of high beam brightness, long transport distance, and strong bunch compression, intra-beam scattering (IBS) can continue to induce noticeable slice energy spread (SES) growth along the linac. In this section, both analytical calculations and numerical simulations are performed to investigate the IBS effect in the SHINE linac.

First, the theoretical IBS-induced SES growth without considering the bunch compression effect of the bunch compressors is calculated using the beam parameters along the linac,which is shown in Fig. 4. The IBS-induced SES growth in the linac was also evaluated using start-to-end simulations based on RF-Track. The SES analysis procedure is identical to that described in Section III. Considering the overall beam compression factor of approximately 200 provided by the three chicanes, the initial 1.5 keV level energy spread increase induced by IBS in the early stage of the linac would eventually lead to an SES growth of about 350 keV after full compression. Figure 5 presents the comparison between the analytical predictions and the RF-Track simulation results for the IBS-induced SES growth along the SHINE linac. Overall, good agreement is observed between the theoretical calculations and the numerical simulations in the uncompressed or weakly compressed beam transport sections.

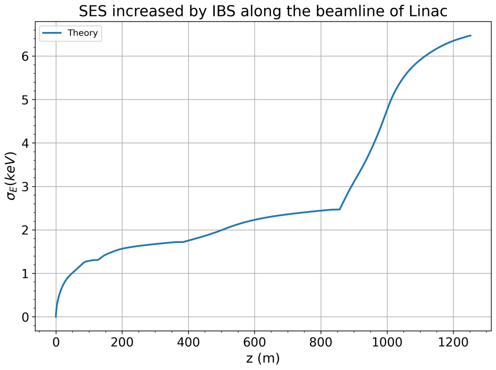

Figure 4: Theoretical increase in slice energy spread caused by IBS ignoring the compression effect of bunch compressors at SHINE Linac.

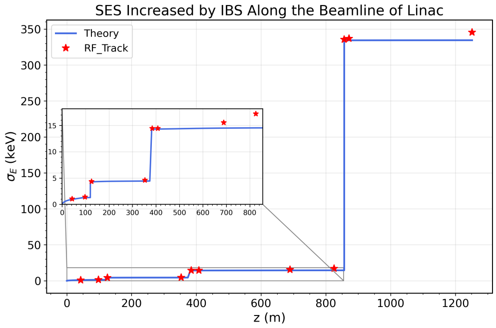

Figure 5: Comparison between the theoretical prediction and the RF-Track simulation results at SHINE Linac.

It should be emphasized that the IBS model used in the initial linac section is based on Eq. (1). However, after strong bunch compression, even the model described by Eq. (3) fails to accurately reproduce the simulation results. Significant deviations are observed between the theoretical predictions and the RF-Track simulations in the strongly compressed beam regime. This indicates that the underlying IBS mechanism for ultra-high-brightness compressed beams is not fully described by existing theoretical models and still requires further investigation.

CONCLUSION

In this work, a systematic theoretical and numerical study of intra-beam scattering (IBS)-induced slice energy spread (SES) growth in the SHINE injector and linac has been presented.For the injector section, the analytical calculations show good agreement with the RF-Track simulation results. IBS induces an additional SES growth of approximately 0.5 keV at the injector exit. In the linac section, IBS continuously accumulates before bunch compression and leads to an energy spread increase of about 1.5 keV before BC1. The results show that conventional IBS theoretical models remain valid in the uncompressed or weakly compressed beam regime. However, after strong bunch compression, even the improved IBS model fails to accurately reproduce the simulation results, indicating that the IBS mechanism in ultra-high-brightness compressed beams still requires further investigation. These results demonstrate that IBS is a non-negligible collective effect in SHINE and should be carefully considered in the beam dynamics optimization and FEL performance evaluation.

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