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STUDY OF THE COMBINED EFFECT OF INTRABEAM SCATTERING AND IMPEDANCE IN A LOW-EMITTANCE RING

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Abstract

Intra-beam scattering (IBS) is one of the prominent effects for low-emittance rings resulting in a significant growth of the emittance, energy spread, and bunch length. This effect is partially mitigated by the bunch lengthening caused by the longitudinal impedance. However, a significant bunch lengthening provided by higher-harmonic cavities is needed to keep the emittance low enough for achieving the designed brightness. For low-emittance lattices considered as options for the NSLS-II upgrade, we studied a combined effect of the IBS, impedance, and harmonic cavities using ELEGANT.

INTRODUCTION

Low-emittance rings play a crucial role in providing high-brightness light sources for various scientific applications, including material science, biology, and chemistry. However, the operation of low-emittance rings can be challenging due to intra-beam scattering (IBS). IBS is a phenomenon that causes the emittance, energy spread, and bunch length to increase due to the Coulomb interaction between particles in the beam. Therefore, mitigating the impact of IBS is crucial for maintaining low emittance in high-brightness light sources.

The longitudinal impedance of the vacuum chamber results in an intensity-dependent bunch lengthening, which is helpful to mitigate the impact of IBS at the operational beam current in low-emittance rings. However, for applications with a short zero-current bunch length, such as the case with 5.22 ps rms for NSLS-II upgrade presented lattice, additional bunch lengthening is required to maintain the low emittance necessary for high-brightness light sources. Higher-harmonic cavities (HHCs) can provide this additional lengthening and effectively reduce IBS-related emittance growth.

This study aims to investigate the combined effect of IBS, impedance, and harmonic cavities in low-emittance lattices for the NSLS-II upgrade. As the field of low-emittance light source ring design is currently undergoing a revolution marked by the emergence of various MBA-type lattices that have achieved very low horizontal emittances, X-ray beams are becoming brighter. The hybrid MBA lattice of the ESRF-EBS type has been widely adopted by facilities interested in upgrading their brightness capabilities. In this work, we use a 7BA lattice providing 31 pm emittance as discussed in Ref. [1].

Table 1 shows the beam parameters for the presented study. The effect of the light-generating devices (wigglers sand undulators) on the beam emittance is significant. So for the simulations, we use the upgrade lattice with a full set of IDs increasing the energy loss per turn by about 1 MeV and reducing the horizontal emittance from 31 pm to 11 pm. Assuming that we are coupling-dominated, meaning that the vertical dispersion can be kept sufficiently small, the zero-current vertical emittance is proportional to the horizontal emittance.

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Table 1: NSLS-II-U High-brightness Storage Ring Parameters for Seven-hybrid-bend-achromat Lattice

Parameters	**Symbol**	**Value**	**Unit**
Circumference	C	784.53	m
Beam energy	E	3	GeV
Average current	I_{av}	0.5	A
Momentum compaction	α	5.95	10^{-5}
Natural energy spread	σ_δ	7.88	10^{-4}
RF Voltage	V_{rf}	3.6	MV
Harmonic number	h	1320	
Bunch length w/o HHC	$\sigma_{\tau 0}$	5.22	ps
Bunch length with HHC (optimal)	σ_τ	31	ps
Synchronous tune	ν_s	3.74	10^{-3}
Energy loss per turn	U_0	1352	keV

In the next section, we will discuss the simulation methods and results used to demonstrate the combined effect of intrabeam scattering and impedance in the presence of harmonic cavities.

SIMULATIONS

We use Pelegant [2], a parallel version for ELEGANT tracking simulations, to investigate the impact of a higher harmonic cavity on the bunch length and energy spread. We then examine the combined effect of the cavity with longitudinal impedance, which is modeled using a longitudinal broadband resonator. The resonator's parameters are determined based on prior experience at NSLS-II. Finally, we incorporate IBS into our analysis, considering the combined influence of all three effects on the beam dynamics.

Higher Harmonic Cavity

Low-emittance lattices usually have a small momentum compaction α and short nominal equilibrium bunch lengths resulting in stronger collective effects, which lead to shorter Touschek lifetime and intensity-dependent emittance growth due to IBS. The NSLS-II storage ring upgrade can benefit from the use of a third-harmonic cavity system to improve beam lifetime by increasing the equilibrium bunch length without increasing the energy spread [3].

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To achieve the desired optimal bunch parameters for uniform filling, we utilize an active cavity configuration in ELEGANT using RFCA element. The simulation results in Fig. 1 show the obtained bunch length and energy spread. As can be observed, the bunch length reaches the optimal value of approximately 31 ps, and the spread remains constant after reaching equilibrium, details discussed in Ref. [4].

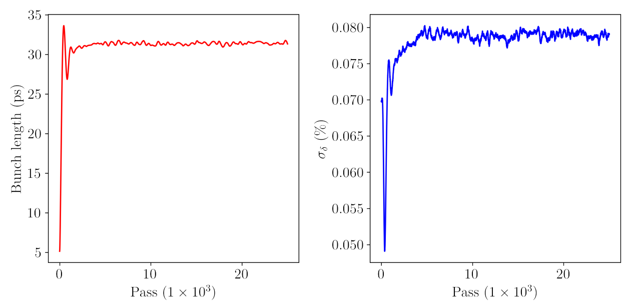

Figure 1: Numerical simulations of the NSLS-II-U lattice with uniform filling active cavity case using ELEGANT.

Longitudinal Impedance

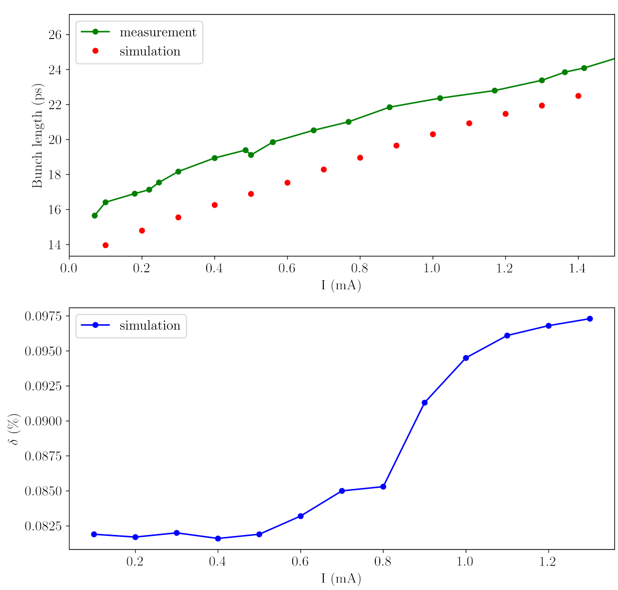

Figure 2: (Top) Comparison of bunch length measurement and elegant simulations and (Bottom) rms energy spread as a function of current per bunch for NSLS-II lattice with 3DW with RF voltage 3.6 MV [5].

Numerical simulations using ELEGANT are being conducted for the NSLS-II lattice, with the three damping wigglers (DW) gaps being closed. In the simulations, a broadband resonator is used as the impedance model, with parameters being adjusted to fit both the measured bunch length and microwave instability threshold discussed in Ref. [5] within approx. 80% agreement. The maximum amplitude of the energy oscillations is determined by examining the last 500 turns of the bunch's time evolution. The top graph in the Fig. 2 compares the measured bunch length with the simulation results, while the bottom graph shows the maximum amplitude energy spread as a function of single bunch current at an RF voltage of 3.6 MV.

We used the resonator model mentioned earlier to simulate the impedance impact on bunch length and energy spread with and without the harmonic cavity for NSLS-II-U lattice. As expected, Fig. 3 shows that the microwave threshold is increased with the higher harmonic cavity.

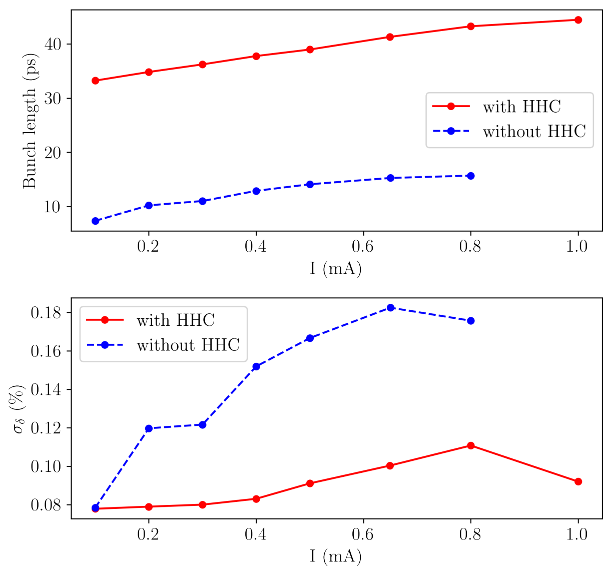

Figure 3: Comparison of impedance induced bunch-lengthening and rms energy spread with and without higher harmonic cavity as a function of current per bunch for NSLS-II-U.

Intrabeam Scattering

Since IBS is a multiple scattering phenomenon that can cause an increase in the beam emittance over time, the equilibrium emittance is determined by various factors. These include synchrotron radiation damping, quantum excitation, and beam optics [6]. These processes interact to balance the competing effects and achieve the minimum achievable beam emittance.

Therefore, utilizing the IBSCATTER element in ELEGANT, along with higher harmonic cavity and broadband resonator impedance models, is an expedient way to proceed.

Figure 4 illustrates the evolution of beam parameters in a low-emittance storage ring due to the combined effects of IBS, impedance, and a higher-harmonic cavity. By comparing the results of IBS with and without impedance-induced bunch lengthening and energy spread, we can assess the impact of impedance on the IBS effect.

Overall, our analysis suggests that impedance-induced bunch lengthening can help to reduce the impact of IBS on the transverse plane. This finding highlights the importance

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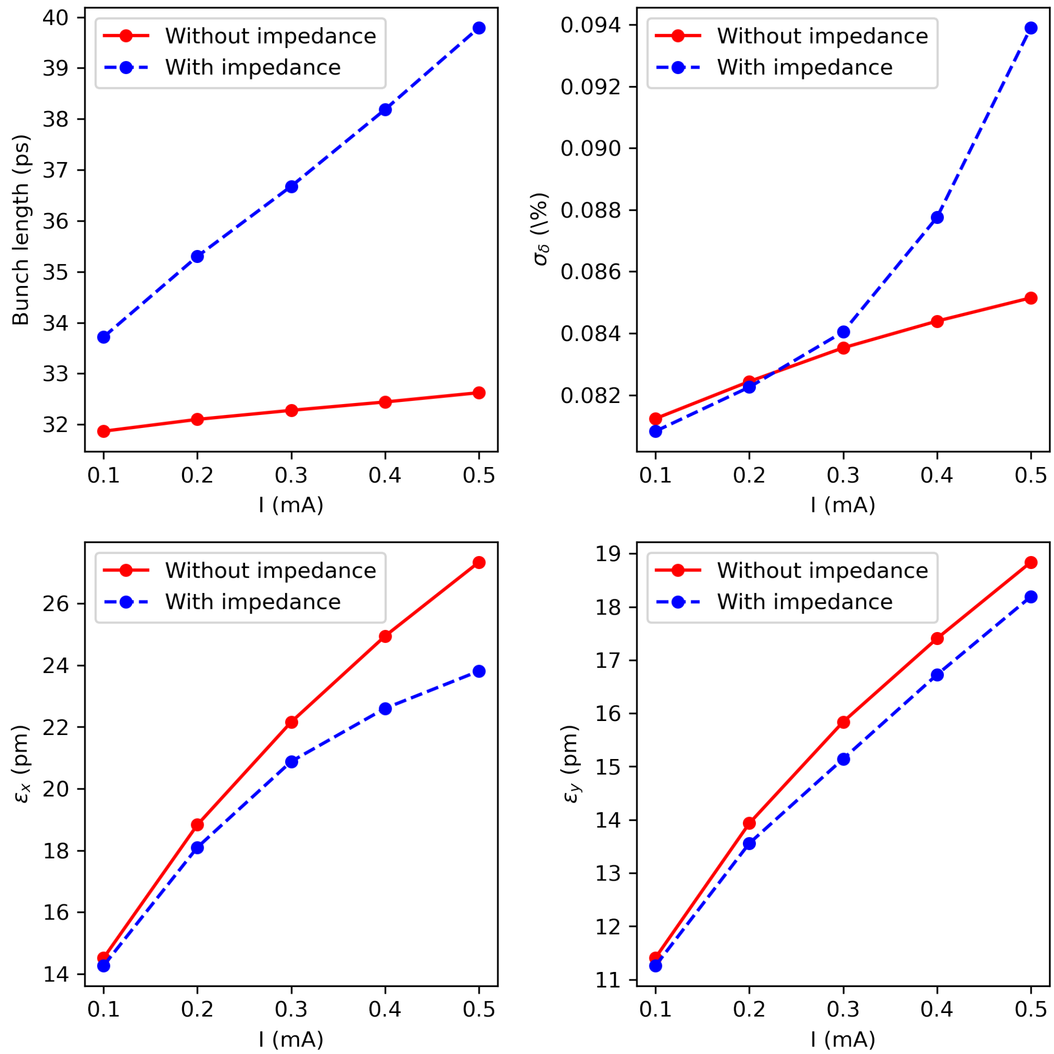

Figure 4: Comparison of IBS induced bunch parameter evolution for different bunch current with and without impedance.

of considering the combined effects of various factors in low-emittance storage rings to optimize beam performance.

CONCLUDING REMARKS

This work emphasizes the importance of considering the combined effects of various factors in low-emittance storage rings to achieve the desired brightness and beam quality for scientific applications using the NSLS-II upgrade lattice candidate. Higher-harmonic cavities provide bunch lengthening, keeping the spread constant and effectively reducing IBS-related emittance growth. Our analysis shows that impedance-induced bunch lengthening can further help reduce the impact of IBS on the transverse plane. In future work, we will compare the tracking results with well-known analytical approaches and implement passive harmonic cavities for different bunch distributions.

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