Study on Single-Bunch Instability of the Shenzhen Industrial Light Source

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Abstract

The Shenzhen Industrial Light Source (SILF), as a fourth-generation light source, is designed with a vacuum chamber radius of 12 mm and numerous insertion devices with gaps as low as 4 mm, which significantly increases the total ring impedance. Due to the designs of ultra-low transverse emittance and small momentum compaction factor, beam collective effects become one of the main factors limiting machine performance. Therefore, SILF plans to adopt third-harmonic superconducting cavities (3HC) to lengthen the bunch length, suppress instabilities, and increase the beam current threshold. Based on the SILF storage ring magnetic lattice structure and impedance model, this paper investigates single-bunch instabilities to analyze the differences with and without harmonic cavities, and compares the effectiveness of active and passive harmonic cavities. The results show that third-harmonic cavities can substantially increase the single-bunch charge threshold, which is beneficial for achieving various operation modes; the difference in single-bunch charge thresholds between active and passive superconducting harmonic cavities is relatively small; under the present impedance conditions, the single-bunch charge threshold meets the 300 mA design requirement.

Full Text

Preamble

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Study on Single Bunch Instability of Shenzhen Industrial Light Source

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Abstract

[**Background**] The Shenzhen Innovation Light Source Facility (SILF) is a fourth-generation light source currently under construction in Shenzhen, China. The storage ring has a circumference of approximately 700 m, an average beam current of 300 mA, and a natural emittance of about 90 pm · rad. To accommodate high-field-gradient magnets and small-gap insertion devices, SILF employs a narrow-aperture vacuum chamber with a radius of 12 mm and insertion device gaps as low as 4 mm, resulting in very high beam-coupling impedance. Combined with its low natural emittance and low momentum compaction factor, SILF is intrinsically more sensitive to impedance-driven collective effects.

[**Purpose**] To suppress beam instabilities and increase the threshold current, a third harmonic cavity (3HC) is under consideration. Based on single-bunch instabilities, this paper focuses on the impact of the 3HC and compares the effectiveness of active versus passive implementations.

[**Methods**] The broadband impedance was represented by resistive-wall and geometric components, modeled and analyzed using ECHO and CST respectively. Instabilities were evaluated through macro-particle simulations using ELEGANT. Three scenarios were analyzed: no 3HC, active 3HC, and passive 3HC. The first two scenarios used single-bunch simulations with optimum voltage and phase configurations at zero current. The last scenario employed multi-bunch simulations with uniform spacing and 5–20% filling rate to maintain low current (approximately 30–60 mA). This was accomplished in two steps: first, the passive 3HC was detuned to achieve the desired bunch-lengthening factor (~4); second, impedance was included with the same detuning.

[**Results**] The results show that both 3HC configurations can greatly suppress microwave instabilities and remarkably increase the TMCI threshold with positive chromaticity. When chromaticity is +3, the threshold reaches 2.5 nC and 2.4 nC for active and passive 3HC respectively. Without 3HC, the threshold remains at 1.0 nC when chromaticity exceeds +1. The single-bunch charge thresholds satisfy the 300 mA requirement in all cases.

[**Conclusions**] The 3HC is necessary for varied operation modes in SILF. The efficiency difference between active and passive 3HC is nearly negligible with respect to the single-bunch threshold.

Keywords: Ultra-low emittance storage ring; Impedance; Single bunch instability; High order harmonic cavity

Classification: TL99

Diffraction-limited storage rings represent an important direction for fourth-generation synchrotron light sources, featuring lower beam emittance (0.01–0.3 nm · rad), higher brightness, and improved transverse coherence compared to third-generation sources. To achieve low emittance, diffraction-limited storage rings require strong focusing magnets, which severely constrain vacuum chamber dimensions, and employ numerous small-gap insertion devices, leading to significantly increased ring impedance. The reduced transverse emittance and smaller momentum compaction factor make the beam more sensitive to collective effects. To achieve better beam quality, diffraction-limited storage rings typically use high-order harmonic cavities in conjunction with fundamental RF cavities for bunch lengthening. For example, the Beijing High Energy Photon Source (HEPS) uses an active third harmonic cavity, while the Hefei Advanced Light Source (HALF) uses a passive third harmonic cavity, both stretching the bunch length by approximately 6 times to suppress collective effects by reducing electron density and achieve better beam quality and machine performance. The SILF storage ring adopts a Hybrid-7BA magnetic lattice with a natural emittance of about 90 pm · rad and straight sections approximately 6 m long. Consequently, SILF will utilize superconducting RF cavities, but the final choice between active and passive third harmonic superconducting cavities remains under study—precisely the focus of this work.

Based on the design schemes of various system components, we first established models and performed impedance calculations for each component using the numerical simulation programs ECHO and CST. We then used the ELEGANT program to simulate bunch lengthening, microwave instability, and transverse instability under three conditions: without harmonic cavity, with active harmonic cavity, and with passive harmonic cavity. By analyzing the differences in single-bunch charge thresholds under these scenarios, we evaluated whether the current design can meet the 300 mA operational requirement and support multiple filling patterns.

1 SILF Storage Ring

The SILF storage ring is designed with a Hybrid-7BA magnetic lattice, with a circumference of approximately 700 m, beam energy of 3 GeV, total current of 300 mA, and natural emittance of about 90 pm · rad. The key parameters are summarized in Table 1 , including the effects of insertion devices.

Table 1 Key parameters of the SILF storage ring

Parameters	Values	Units
Beam energy	3 GeV	GeV
Beam current	300 mA	mA
Natural emittance	~90.0	pm · rad
Tunes (Qx/Qy)	68.26/24.22	
Natural chromaticity (x/y)	-114.86/-79.76	
Damping time (x/y/s)	34.97/43.74/25.01	ms
Momentum compaction	6.6$\times10^{-5}$	
Fundamental RF frequency	500 MHz	MHz
3rd RF frequency	1500 MHz	MHz

Parameters	Values	Units
Energy loss per turn	1.0 MeV	MeV
Energy spread	1.0	‰
Natural RMS bunch length	2.5	mm
Fundamental RF voltage	3.5 MV	MV

1.1 Full Ring Impedance

Any non-ideal materials, discontinuities, or irregularities in the storage ring structure can generate impedance. The electromagnetic fields excited by the beam act back on the beam itself, potentially causing beam quality degradation, instabilities, and component heating when the electron density is high. Storage ring impedance is divided into resistive-wall impedance and geometric impedance. Based on the design schemes of key components from each system, we performed individual modeling and impedance calculations for all elements, including the fundamental RF cavity, harmonic cavity, flanges, welds, bellows, vacuum pumps, BPMs, injection kickers, insertion devices, and various transition sections.

The main vacuum chamber in SILF has a radius of 12 mm and uses copper chambers with 1 m thick NEG coating on the inner surface. In-vacuum insertion devices have gaps of 4–8 mm, also using copper chambers with NEG coating; in-air insertion devices have gaps of 2–3 mm, using copper foil shielding. Resistive-wall impedance was calculated in the frequency domain using the ECHO 1D program. Impedance for axisymmetric and complex geometric structures was calculated in the time domain using ECHO 2D and CST respectively, with an excitation beam of 1.5 mm RMS bunch length, corresponding to a cutoff frequency of approximately 70 GHz.

The full ring longitudinal impedance and normalized transverse impedance spectra are shown in Figure 1 [Figure 1: see original paper]. Peaks in the longitudinal impedance are produced by bellows, BPMs, and the RF system. Peaks in the transverse impedance are produced by BPMs and bellows, while the low-frequency portion is dominated by resistive-wall impedance and numerous BPMs. Full ring impedance analysis indicates that the total longitudinal broadband impedance is approximately 110 mΩ, the total parasitic power loss is about 176 V/pC, and the total transverse power loss factor is approximately 37 kV/(pC · m).

2 Single Bunch Instability

Single bunch instabilities include bunch lengthening effects, microwave instability, and transverse mode-coupling instability (TMCI), all of which are associated with broadband impedance. Studies at other light sources such as HEPS, MAX IV, DIAMOND-II, and ALS-U have demonstrated that combining fundamental and higher-harmonic cavities can stretch bunch length and significantly suppress single bunch instabilities, both increasing thresholds and reducing the rate of energy spread growth above threshold. SILF plans to use a third harmonic superconducting cavity for bunch lengthening, but the choice between active and passive implementations remains under investigation—one of the key tasks of this work. All calculations in this section were performed using the ELEGANT program.

For the fundamental and active third harmonic cavity cases, simulations used 10^5 macro-particles to model a single bunch, tracking for 100,000 turns (more than 5 damping times). For the passive third harmonic cavity, the R/Q value was 90 and Q_0 was 2$\times10^{8}.Forthefundamentalandpassiveharmoniccavitycases,theringwasuniformlyfilledwithbunchesat5\{$ macro-particles, tracking for 200,000 turns (more than 10 damping times) to account for the establishment of equilibrium electromagnetic fields in the passive harmonic cavity.

2.1 Third Harmonic Cavity and Bunch Lengthening

The parameters for the fundamental and active/passive harmonic cavities were set according to ideal bunch lengthening conditions. Active and passive harmonic cavities were implemented in ELEGANT using RFCA and RFMODE elements respectively. For the passive harmonic cavity case in this section, the single-bunch charge was 0.6 nC with 10% bunch filling rate, and the cavity detuning frequency was 5.14 kHz. The bunch distributions under no/active/passive harmonic cavity conditions are shown in Figure 2 [Figure 2: see original paper]. Under "zero" current conditions without longitudinal impedance, the bunch achieves ideal stretching. The normalized bunch distributions are shown in the left panel of Figure 2, with RMS bunch lengths of 2.5 / 11.9 / 12.0 mm and normalized peak electron densities of 5.0×10^{10} / 8.7×10^{9} / 1.1×10^{10} s^{-1} respectively. Both active and passive harmonic cavities can stretch the bunch length by more than 4 times. Without harmonic cavity and with active harmonic cavity, the bunch distribution is symmetric, while the passive harmonic cavity produces a distribution peaked toward the tail.

With longitudinal impedance included, the bunch distributions are shown in the right panel of Figure 2. Compared to the zero-current case, the bunch distribution loses symmetry and the stretching deteriorates. Without harmonic cavity and with active harmonic cavity, the bunch peak shifts toward the head, while the passive harmonic cavity case remains peaked toward the tail. The RMS bunch lengths decrease to 2.2 / 10.6 / 11.1 mm for the three cases respectively. The normalized peak densities increase significantly to 9.5×10^{10} / 1.3×10^{10} / 1.5×10^{10} s^{-1}, representing increases of 90%, 50%, and 35% respectively.

2.2 Microwave Instability

Microwave instability is an important single bunch instability in storage rings, caused by longitudinal impedance. It leads to bunch length variation and energy spread increase without causing particle loss. The variation of bunch length and energy spread with single-bunch charge under no/active/passive harmonic cavity conditions is shown in Figure 3 [Figure 3: see original paper]. Without harmonic cavity, bunch length first decreases then increases with charge, and energy spread remains at 1.00‰ up to 1.30 nC, after which instability occurs and energy spread increases rapidly. With active harmonic cavity, bunch stretching occurs and bunch length follows a similar trend, with energy spread remaining at 1.00‰ up to 1.10 nC. Beyond this threshold, instability occurs but energy spread increases much more slowly than without harmonic cavity. For the passive harmonic cavity case, the detuning frequency was first adjusted to achieve bunch lengthening comparable to the ideal active harmonic cavity case at zero current (see "Passive 3HC, w/o ZL" in Figure 3 left panel). Longitudinal impedance was then added, altering the bunch stretching (see "Passive 3HC, w/ ZL"). With passive harmonic cavity, energy spread remains at 1.00‰ up to 0.90 nC, then instability occurs. Between 0.90–2.0 nC, energy spread increases faster than in the active harmonic cavity case, but above 2.0 nC the increase rate becomes similar. Considering the 300 mA operational requirement, single-bunch charge is about 0.60 nC in uniform filling mode and about 0.75 nC at 80% filling rate. Therefore, the microwave instability thresholds in all three cases meet the requirements.

2.3 Transverse Single Bunch Instability

Transverse single bunch instability typically limits the single-bunch charge in storage rings. When single-bunch charge increases to the instability threshold, transverse emittance grows rapidly and may lead to particle loss. In calculating transverse single bunch instability, both longitudinal and normalized transverse impedances were included, and positive chromaticity was used to increase the threshold. Since vertical impedance is larger than horizontal, only vertical instability was considered.

The transverse single bunch instability results for SILF are shown in Figure 4 [Figure 4: see original paper]. (1) The top left panel shows the effect of chromaticity adjustment on the single-bunch instability threshold for the three cases. Without harmonic cavity, increasing chromaticity from 0 to +1 raises the threshold from 0.37 nC to 1.0 nC, with no further increase at higher chromaticity. At zero chromaticity, adding active or passive harmonic cavity increases bunch length but reduces the threshold to about 0.14 nC due to decreased longitudinal oscillation frequency. With increased chromaticity, both active and passive harmonic cavities can further increase the threshold because the harmonic cavity provides Landau damping and chromaticity correction disperses the transverse oscillation frequency until reaching the instability limit. At +3 chromaticity, the thresholds are 2.50 nC and 2.40 nC for active and passive harmonic cavities respectively, meeting not only the 300 mA design requirement but also supporting various bunch filling patterns. (2) The top right panel shows mode analysis without harmonic cavity at zero chromaticity, clearly indicating a threshold of 0.37 nC. (3) The bottom left panel shows mode analysis with active harmonic cavity at +1 chromaticity, indicating a threshold of 0.80 nC. (4) The bottom right panel shows mode analysis with passive harmonic cavity at +1 chromaticity, indicating a threshold of 0.75 nC.

Conclusion

Based on SILF's magnetic lattice and vacuum system design, we performed modeling and impedance calculations for major storage ring components, obtaining the full ring coupling impedance. Using this impedance model, we investigated single-bunch instabilities for three cases: without harmonic cavity, with active harmonic cavity, and with passive harmonic cavity. The results demonstrate that the presence or absence of harmonic cavity significantly affects the single-bunch charge threshold, while the difference between active and passive implementations has minimal impact. Longitudinal single-bunch instability does not limit the single-bunch current threshold, but affects beam quality beyond the threshold. Transverse single-bunch instability limits the single-bunch charge and requires positive chromaticity for suppression to meet the 300 mA operational requirement. Under current impedance conditions with +3 chromaticity and harmonic cavity, the single-bunch threshold exceeds 2.4 nC, satisfying design requirements. If future operation modes demand higher single-bunch charge, optimization of certain components such as BPMs and bellows will be necessary.

Author Contributions

Ji Ruimin performed the simulations, drafted and revised the manuscript; Liu Guimin designed the research, provided theoretical guidance, and reviewed the manuscript; Lin Chuntao participated in some calculations and manuscript revision; He Tao contributed to content revision; Xu Xiaolin provided technical support for simulation software and servers.

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Note: Figure translations are in progress. See original paper for figures.