Study on Single-Bunch Instabilities in 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 ring impedance. Owing to the design of ultra-low transverse emittance and small momentum compaction factor, beam collective effects constitute one of the main factors limiting machine performance. Therefore, SILF proposes to employ third-harmonic superconducting cavities (3HC) to stretch the bunch length, suppress instabilities, and enhance the beam current threshold. Based on the magnetic lattice and impedance model of the SILF storage ring, this study investigates the differences with and without harmonic cavities through single-bunch instability analysis, and compares the effectiveness of active versus passive harmonic cavities. The results demonstrate that third-harmonic cavities can substantially increase the single-bunch charge threshold, facilitating the realization of multiple operation modes; the corresponding single-bunch charge thresholds for active and passive superconducting harmonic cavities exhibit minor differences, with values of 2.5 and 2.4 nC, respectively, at a chromaticity of +3; the single-bunch charge threshold under present impedance conditions meets the 300 mA design requirement.

Full Text

Single Bunch Instability Analysis Based on SILF Design

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Abstract

[Background]: This study analyzes single bunch thresholds for the Shenzhen Innovation Light Source Facility (SILF), which features high beam-coupling

impedance, low natural emittance, and a low momentum compaction factor.
[Purpose]: To suppress beam instabilities, a third harmonic cavity (3HC) is under consideration. This study investigates the impact of 3HC and compares the effects of active versus passive 3HC configurations on single-bunch instabilities.
[Methods]: Broadband impedance was represented by resistive-wall effects, while geometric contributions were 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 employed single bunch simulations with optimum voltage and phase configurations at zero current. For the passive 3HC scenario, multi-bunch simulations with uniform gaps and 5-20% filling rate were used to maintain low current levels (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]: Results show that both 3HC configurations can greatly suppress microwave instabilities and significantly increase the transverse mode coupling instability (TMCI) threshold with positive chromaticity. When chromaticity is +3, the thresholds are 2.5 nC and 2.4 nC for active and passive 3HC respectively. Without 3HC, the threshold remains at 1.0 nC when chromaticity is greater than +1. The single bunch charge thresholds satisfy the 300 mA requirement for all cases.
[Conclusions]: 3HC is essential for SILF when single bunch charge requirements exceed 1 nC. The difference between active and passive 3HC is negligible, particularly when chromaticity is less than or equal to +3.

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

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 [1]. Compared to third-generation sources, diffraction-limited storage rings require strong focusing magnets to achieve low emittance, which severely restricts vacuum chamber dimensions and incorporates numerous small-gap insertion devices, leading to significantly increased ring impedance. The reduced transverse emittance and smaller momentum compaction factor make the beam more susceptible to collective effects [2,3]. To achieve better beam quality, diffraction-limited storage rings typically employ high-order harmonic cavities in conjunction with fundamental RF cavities for bunch lengthening. For example, the High Energy Photon Source (HEPS) uses an active third harmonic cavity [3], while the Hefei Advanced Light Facility (HALF) uses a passive third harmonic cavity [4], both stretching bunch length by approximately 6 times to suppress collective effects through reduced electron density, thereby achieving better beam quality and machine performance. The SILF storage ring [5] adopts a Hybrid-7BA magnet lattice structure with natural emittance of approximately 90 pm · rad and straight section length of about 6 m. Therefore, SILF will utilize superconducting RF cavities, but the final choice between active and passive third harmonic superconducting cavities remains under study. This paper evaluates their impact and differences from the perspective of single bunch instability.

Based on design specifications for various system components, we first established models and performed ring impedance calculations using numerical simulation programs ECHO [6] and CST [7]. Using ELEGANT [8,9], we then calculated bunch lengthening, microwave instability, and transverse instability under three modes: no harmonic cavity, active harmonic cavity, and passive harmonic cavity (hereinafter referred to as Mode A, Mode B, and Mode C respectively). We analyzed differences in single bunch charge thresholds among these modes to assess whether the current design can meet the 300 mA requirement and support various operational modes.

1 SILF Storage Ring

The SILF storage ring employs a Hybrid-7BA magnet lattice structure with circumference of approximately 700 m, beam energy of 3 GeV, total beam current of 300 mA, and natural emittance of approximately 90 pm·rad. Key parameters of the SILF storage ring are listed in Table 1 , including the effects of insertion devices.

1.1 Ring Impedance

Impedance arises from non-ideal materials and non-smooth, discontinuous structures in storage rings. Affected by impedance, electromagnetic fields excited by the beam act on itself, potentially causing beam quality degradation, instabilities, and component heating under high electron density conditions [1-3]. Storage ring impedance comprises resistive-wall impedance and geometric impedance [10-12]. This study performed individual component modeling and impedance calculations based on design specifications for key components, including fundamental cavities, harmonic cavities, flanges, welds, bellows, vacuum pumps, BPMs, injection magnets, insertion devices, and various transition sections.

The SILF storage ring main vacuum chamber radius is 12 mm, using copper chambers with 1 m NEG film coating on the inner wall. Vacuum-outside insertion devices have 4-8 mm gaps, also using copper chambers with NEG film coating. Vacuum-inside insertion devices have 2-3 mm gaps, using copper film 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 a Gaussian bunch of 1.5 mm RMS length as the excitation beam, corresponding to a cutoff frequency of approximately 70 GHz.

The total ring longitudinal impedance and normalized transverse impedance spectrum are shown in Figure 1 [Figure 1: see original paper]. Peaks in longitudinal impedance originate from bellows, BPMs, and RF systems. Peaks in transverse impedance originate from BPMs and bellows, with low-frequency contributions primarily from resistive-wall effects and numerous BPMs. Ring impedance analysis indicates total longitudinal broadband impedance of approximately 110 mΩ, total parasitic power loss of about 176 V/pC, and total transverse power loss factor of 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 related to broadband impedance [1-3]. Studies at other light sources such as HEPS [2,12], MAX IV [13], DIAMOND-II [14], and ALS-U [15] have demonstrated that combining fundamental and high-order harmonic cavities can stretch bunch length, significantly suppressing single bunch instabilities by increasing thresholds and reducing the rate of energy spread increase above instability thresholds. SILF plans to use a third-order superconducting harmonic cavity for bunch lengthening, but the choice between active and passive operation remains under investigation and constitutes one of the tasks of this work. Calculations in this section were performed using the ELEGANT program.

Modes A and B used 10^5 macro-particles to simulate a single bunch, tracking for 100,000 turns (>5 damping times). The passive third harmonic cavity has R/Q value of 90 and Q_0 of 2\$×10$^{\{8\}.ModeCsimulationsuniformlyfilled5}${4}\$ macro-particles per bunch and tracking for 200,000 turns (>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

RF cavity parameters were set according to ideal bunch stretching conditions. Active and passive harmonic cavities were simulated in ELEGANT using RFCA and RFMODE models respectively [14-16]. In this section, single bunch charge was 0.6 nC for all three modes. In Mode C, bunch filling rate was 10% and harmonic cavity detuning frequency was 5.14 kHz. Under "zero" current conditions without longitudinal impedance, bunches achieved ideal stretching. Normalized bunch distributions for Modes A, B, and C are shown in the left panels of Figure 2 [Figure 2: see original paper], with RMS bunch lengths of 2.5/11.9/12.0 mm respectively, and normalized peak electron densities of 5.0\$×10$^{\{10\}/8.7×10}${9}/1.1×10^{10}\$ s^{-1}. Both active and passive harmonic cavities stretch bunch length by more than 4 times. Bunch distributions are symmetric in Modes A and B, while Mode C shows peak 偏向尾部.

With longitudinal impedance included, bunch distributions are shown in the right panels of Figure 2. Compared to zero-current conditions, bunch distributions lose symmetry and stretching degrades. In Modes A and B, bunch peaks 偏向头部, while Mode C maintains peak 偏向尾部. RMS bunch lengths decrease to 2.2/10.6/11.1 mm for Modes A, B, and C respectively. Normalized peak bunch densities increase significantly to 9.5\$$\times 10^{\{10\}/1.3\times 10}$\{10\}/1.5×10^\{10\}\$ s^{-1}, representing increases of 90%/50%/35% respectively.

2.2 Microwave Instability

Microwave instability is an important single bunch instability in storage rings, caused by longitudinal impedance, leading to bunch length variations and energy spread increases without particle loss. Bunch length and energy spread variations with single bunch charge for the three modes are shown in the left and right panels of Figure 3 [Figure 3: see original paper] respectively. In Mode A, bunch length first decreases then increases with charge, with energy spread maintained at 1.00‰ up to 1.30 nC, after which instability occurs and bunch oscillations begin with rapid energy spread increase. Mode B with active harmonic cavity shows bunch stretching effects, with bunch length similarly decreasing then increasing; energy spread remains at 1.00‰ up to 1.10 nC, after which instability occurs but with much slower energy spread increase than Mode A. For Mode C, detuning frequency was first adjusted to achieve bunch stretching comparable to Mode B's ideal stretching under zero current (see Mode C, w/o ZL in left panel); then longitudinal impedance was added, altering bunch stretching (see Mode C, w/ ZL in left panel). Energy spread remains at 1.00‰ up to 0.90 nC, after which 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 approximately 0.60 nC in uniform filling mode and about 0.75 nC at 80% filling rate. Therefore, microwave instability thresholds satisfy requirements in all three modes.

2.3 Transverse Single Bunch Instability

Transverse single bunch instability typically limits single bunch charge in storage rings. As single bunch charge increases to instability thresholds, transverse emittance grows rapidly, potentially causing particle loss. Calculations included longitudinal impedance and normalized transverse impedance, with positive chromaticity used to increase transverse single bunch instability thresholds. Since vertical impedance exceeds horizontal impedance, only vertical instability was considered.

SILF transverse single bunch instability results are shown in Figure 4 [Figure 4: see original paper]. (1) Upper left panel shows chromaticity adjustment effects on single bunch instability thresholds across three modes. In Mode A, adjusting chromaticity from 0 to +1 increases the threshold from 0.37 nC to 1.0 nC, with no further increase at higher chromaticity. With zero chromaticity, Modes B and C show increased bunch length but reduced thresholds (~0.14 nC) due to decreased longitudinal oscillation frequency. With increased chromaticity, both Modes B and C show continued threshold improvement. This occurs because harmonic cavities introduce Landau damping, and chromaticity correction disperses transverse oscillation frequencies until reaching instability thresholds. At chromaticity +3, thresholds reach 2.50 nC and 2.40 nC for active and passive 3HC respectively, satisfying not only the 300 mA design requirement but also supporting various bunch filling patterns. (2) Upper right panel shows mode analysis for Mode A at zero chromaticity, clearly indicating a threshold of 0.37 nC. (3) Lower left panel shows mode analysis for Mode B at chromaticity +1, indicating a threshold of 0.80 nC. (4) Lower right panel shows mode analysis for Mode C at chromaticity +1, indicating a threshold of 0.75 nC.

Conclusion

Based on SILF magnet lattice and vacuum system designs, we modeled and calculated major storage ring components to obtain the total ring coupling impedance. Using this impedance model, we investigated single bunch instabilities under three modes: no harmonic cavity, active harmonic cavity, and passive harmonic cavity. Results show that harmonic cavity presence significantly affects single bunch charge thresholds, while active versus passive harmonic cavity operation has minimal impact. Longitudinal single bunch instability does not limit single bunch current thresholds but affects beam quality above threshold. Transverse single bunch instability limits single bunch charge and requires positive chromaticity for suppression to meet 300 mA operational requirements. Under current impedance conditions with chromaticity +3 and harmonic cavities, single bunch threshold charge exceeds 2.4 nC, satisfying design requirements. If operational modes demand higher single bunch charge, optimization of certain components such as BPMs and bellows will be necessary.

Author Contributions: JI Ruimin performed simulations and drafted/revised the manuscript; LIU Guimin designed the study, provided theoretical guidance, and reviewed the manuscript; LIN Chuntao participated in calculations and manuscript revision; HE Tao contributed to content revision; XU Xiaolin provided technical support for software and servers.

References:

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