STUDY OF MICROWAVE INSTABILITY FOR SLS-2*

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Abstract

An ultra-low emittance electron storage ring is under development for the Upgrade of Swiss Light Source (SLS-2). An antechamber scheme consisting of round beam channel with 10 mm inner radius is considered to accommodate the required strong quadrupole and sextupole magnets, achieve the ultra-high vacuum, and absorb the undesired synchrotron radiation. However, the small size of vacuum chamber increases the susceptibility of the beam to the impedance induced collective instabilities. We will present the preliminary study of the microwave instability for SLS-2 storage ring considering the longitudinal Resistive-Wall (RW) impedance due to three different options for the beam chamber. The microwave instability thresholds are calculated under the conditions of two possible RF frequencies (100 MHz and 500 MHz) and three different materials (aluminum, copper, and stainless steel). The influences of third-harmonic cavities are also studied.

INTRODUCTION

SLS-2 would replace the existing storage ring by a new ultra-low emittance ring, which is under development based on the concepts of Multi-Bend Achromats (MBA), Longitudinal Gradient Bends (LGB) and Anti-Bends (AB) [1–3]. The development of SLS-2 aims to reduce the equilibrium horizontal emittance of the beam from about 5.5 nm to about 100 - 150 pm, while keeping the beam energy the same (2.4 GeV), maintaining the same total current (400 mA), fitting the new storage ring into the same tunnel, and reusing the injector (electron gun, LINAC, and booster) of the storage ring.

As other ultra-low emittance rings, the SLS-2 storage ring employs very strong quadrupole and sextupole magnets, for the purpose of reducing the emittance, correcting the chromaticity, and enlarging the dynamic aperture. To accommodate the required strong magnets, the vacuum chambers have to be very small, which is a big challenge for the design of the vacuum system. Using fully Non-Evaporable Getter (NEG) coated round chambers like the MAXIV [4] 3-GeV ring is one possible solution to achieve strong enough magnetic fields and ultra-high vacuum simultaneously. However, NEG coating will probably increase the Resistive-Wall (RW) impedance of the chambers because of its low electrical conductivity. Moreover, the possible damage of NEG due to the synchrotron radiation is another drawback. A preliminary solution for SLS-2 is to use the antechamber scheme without NEG coating in the round beam channel, which means the beam can see round chambers made of metal while the synchrotron radiation absorbtion and vacuum pumping are taken care in the antechamber. At the moment, aluminum, copper, and stainless steel are the three candidates for the SLS-2 chambers. The inner radius of the beam channel is 10 mm in the preliminary design. One important purpose of the studies presented in this paper is to verify the validity of such a small vacuum chamber.

Besides the material of vacuum chambers, the RF frequency hasn't been decided either. We currently have two candidates for the primary RF frequency. One is 500 MHz used in SLS. The other is 100 MHz used in the MAXIV [4] 3-GeV ring. Third-order harmonic cavities are considered in both cases to help stabilize the beam.

In the rest of this paper, the influences of the material of vacuum chambers, the primary RF frequencies and the harmonic cavities will be discussed. The study of microwave instability for the SLS-2 storage ring (lattice db02l) with the consideration of the longitudinal RW impedance will also be presented.

RF PARAMETERS

RF parameters should be chosen carefully because of their strong influences on the threshold of microwave instability. Generally speaking, using lower RF frequency can generate longer bunch, corresponding to lower intensity at the same bunch charges. From this point of view, the lower RF frequency is preferred. However, in order to achieve the same total current, using higher RF frequency requires lower single-bunch charges because of the larger harmonic number. We therefore need to calculate the microwave instability thresholds at different frequencies, and compare the threshold current with the required single-bunch current at each frequency.

500 MHz and 100 MHz are the candidates for the primary RF frequency of SLS-2 based on the experiences of SLS and MAXIV, respectively. The total peak RF voltages at both frequencies are chosen to provide the energy acceptance of $\pm 5\%$, which is considered large enough since the equilibrium momentum spread of a bunch determined by synchrotron radiation is about 0.103% in the lattice db02l (without IDs). The corresponding total peak RF voltages are $V_{\mathrm{pk1-100\ MHz}} = 0.811$ [MV] and $V_{\mathrm{pk1-500\ MHz}} = 1.43$ [MV] at 100 MHz and 500 MHz, respectively. If 500 MHz is chosen for SLS-2, the threshold of the single-bunch current should be higher than 4 mA in the same normal operation mode of SLS [5] in order to achieve 400 mA total current. However, the threshold of the single-bunch current should be higher than 4.2 mA if we choose 100 MHz as the primary RF frequency and fill in all the buckets uniformly.

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The third harmonic cavities are considered to operate in the bunch lengthening mode for the purpose of increasing the microwave instability threshold. In the preliminary study, the harmonic cavities are set to provide the ideally flat RF potential under the assumption that both peak voltages and RF phases of the harmonic cavities are variables. The resulting bunch distributions at 0.016 mA in the cases with and without harmonic cavities are shown in Fig. 1, where no bunch distortion appears because of the low bunch current.

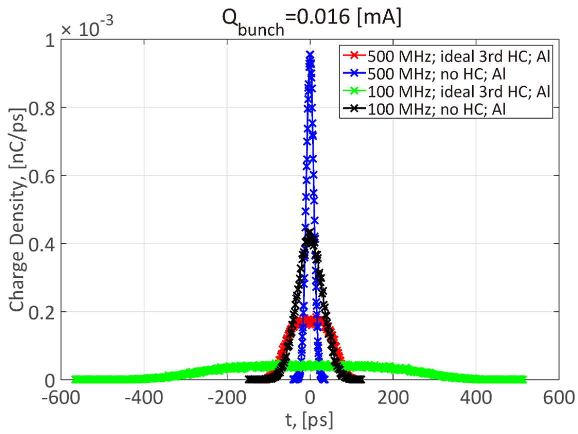

Figure 1: Longitudinal equilibrium bunch distribution for different RF parameters. The RMS bunch lengths are $\sigma_{\tau-500\text{ MHz}-\text{noHC}} = 9.1$ [ps], $\sigma_{\tau-500\text{ MHz}-\text{idealHC}} = 41.7$ [ps], $\sigma_{\tau-100\text{ MHz}-\text{noHC}} = 30.6$ [ps], $\sigma_{\tau-100\text{ MHz}-\text{idealHC}} = 176.5$ [ps].

LONGITUDINAL RW WAKE FUNCTIONS AND WAKE POTENTIALS

As mentioned above, the electron bunches will propagate in a round channel with 10 mm inner radius in the SLS-2 storage ring. Therefore, the short-range RW wake function can be calculated by the Eq. (12) in the reference [6] under the assumption that the electrical conductivity of the materials are constant. The calculated results using SLS-2 parameters are shown in Fig. 2. The DC electrical conductivity of the used materials [7] are $\sigma_{\text{aluminum}} = 3.50 \times 10^7$ [S/m], $\sigma_{\text{copper}} = 5.96 \times 10^7$ [S/m], and $\sigma_{\text{stainless steel}} = 1.45 \times 10^6$ [S/m], respectively.

The longitudinal loss factor k gives the information of the energy loss per turn due to the impedance. k can be calculated from the wake potential, which is the convolution between the longitudinal bunch distribution and the point-charge wake function (shown in Fig. 2). The convolution can be calculated directly by discretizing both the longitudinal bunch distribution and the point-charge wake function using the same bin sizes. We use a 1-nC Gaussian bunch with the RMS length $\sigma_z = 2.6 \times 10^{-3}$ [m] and the round copper chamber with 10 mm inner radius as an example to test the convergence of the direct computation. The loss factors are also calculated using the *mbtrack* [8,9] and `elegant` [10]

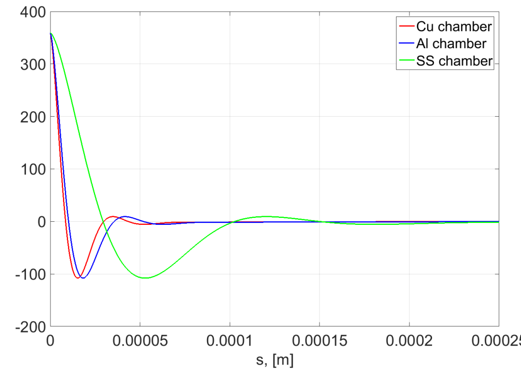

Figure 2: Longitudinal short-Range RW wake function of round chamber (10 mm inner radius) which are made of three different materials (copper (red); aluminum (blue); stainless steel (green)).

at different bin sizes for comparison. The results are plotted in Fig. 3.

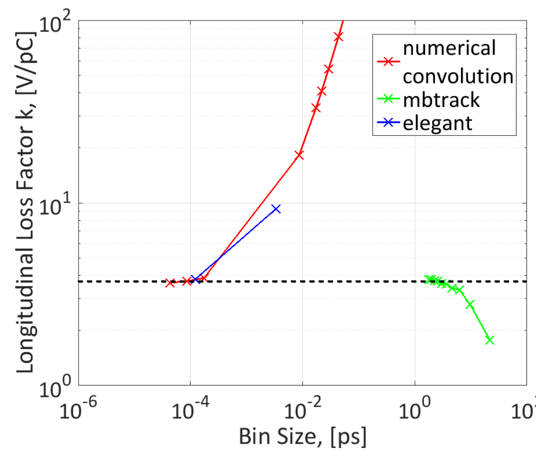

Figure 3: Longitudinal loss factor calculated by the numerical convolution, *mbtrack*, and `elegant`. The dashed line indicates 3.72 V/pC.

We find that the longitudinal loss factor converges too slowly to compute directly. Similarly, tiny bin size is needed if we calculate the k value by importing the point-charge wake function directly into `elegant`. However, the results converge much faster in *mbtrack*. Instead of requesting the point-charge wake function imported, *mbtrack* provides a module to calculate the wake function, which is based on the same method described above (Eq. (12) in the reference [6]). Furthermore, in order to make sure that the reconstruction of the wake potential converges fast, *mbtrack* doesn't sample the wake function driven by point charge directly. Instead, it takes the average value in the first bin as the wake function in the first bin and samples the values of the point-charge wake function in the middles of the rest bins [11].

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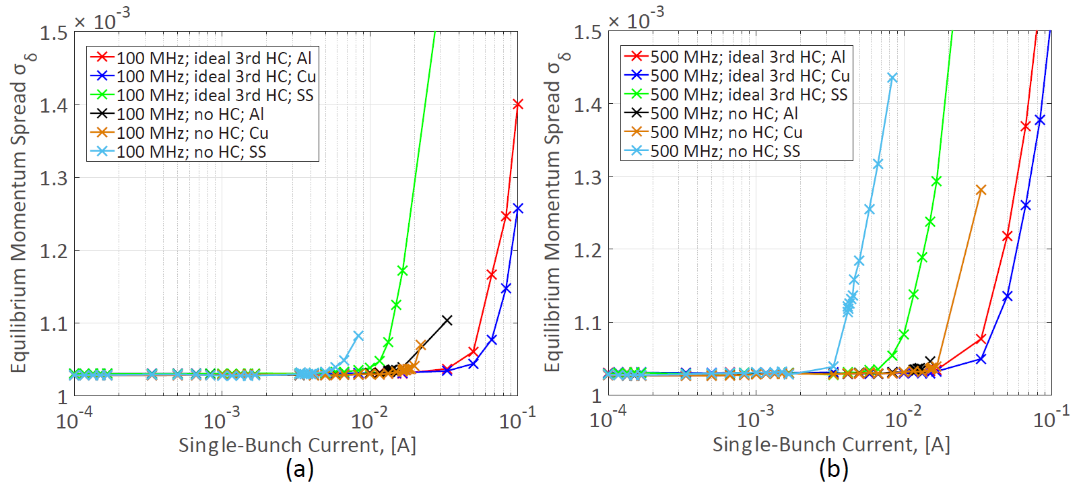

Figure 4: RMS momentum spread at different RF parameters and Single-bunch currents. (a) shows the results in 100 MHz cases, while (b) represent the 500 MHz cases.

MICROWAVE INSTABILITY

Microwave instability is a longitudinal single-bunch instability, which can induce violent bunch lengthening and momentum spread broadening above threshold. Therefore, it's important to find out the threshold of microwave instability and make sure to operate a ring below the threshold, for the purpose of avoiding the reduction of beam quality.

We run simulations to estimate the microwave instability thresholds by the multi-particle tracking code *mbtrack*, because the above mentioned analysis has shown that *mbtrack* converges pretty well at relatively large bin sizes. Therefore, we believe that the reasonably good estimations can be made by *mbtrack* in reasonable computing time.

The longitudinal RW wake function of the 10 mm round chamber is the only impedance source included at the moment. The simulation results are collected in Fig. 4. It's shown in the figure that the momentum spread keeps constant at low single-bunch current, and increase rapidly when above the threshold.

The microwave instability threshold in different cases are listed in the Table 1. We define the bunch starting to be unstable, when the momentum spread is higher than 1.01 times of the zero-current value. The simulations show that the threshold of microwave instability is higher when existing the third harmonic cavity operated in the ideal bunch lengthening mode. Under the same RF parameters, better conductor corresponds to higher threshold current because of its smaller longitudinal RW impedance. However, the comparison between the cases without harmonic cavity at different RF frequencies shows that using lower RF frequency doesn't necessarily result in remarkable increase of the threshold current.

Table 1: Threshold by *mbtrack* Simulation

RF Systems	Materials	Threshold
100 MHz, no HC	Copper	19.8 mA
100 MHz, no HC	Aluminum	16.9 mA
100 MHz, no HC	Stainless Steel	5.92 mA
100 MHz + ideal 3rd HC	Copper	42.8 mA
100 MHz + ideal 3rd HC	Aluminum	35.2 mA
100 MHz + ideal 3rd HC	Stainless Steel	10.3 mA
500 MHz, no HC	Copper	16.7 mA
500 MHz, no HC	Aluminum	14.0 mA
500 MHz, no HC	Stainless Steel	3.35 mA
500 MHz + ideal 3rd HC	Copper	22.8 mA
500 MHz + ideal 3rd HC	Aluminum	18.3 mA
500 MHz + ideal 3rd HC	Stainless Steel	7.08 mA

CONCLUSION & OUTLOOK

We present our studies of the microwave instability considering the longitudinal resistive-wall impedances of the round chambers made by different materials. The calculated thresholds using stainless steel chamber (no harmonic cavity), which are significantly lower than the cases using copper and aluminum chamber, don't show large enough margin comparing to the required single-bunch current (4 mA). However, the longitudinal RW impedance does not seem to be a limiting factor if copper chamber or aluminum chamber with 10 mm inner radius is used in SLS-2.

The cases with harmonic cavities under the ideal bunch lengthening conditions are also studied. The remarkable increases of the thresholds are always observed when using harmonic cavities in the 100 MHz RF cases. However, in the 500 MHz RF cases, the increases of thresholds due to the harmonic cavities are not as significant.

To find out the threshold in the real ring, we will include the impedance of more components (e.g., BPMs) in the calculations.

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