ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPGW107

OVERVIEW OF COLLECTIVE EFFECTS IN SLS 2.0

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Abstract

At the end of 2017, the conceptual design for an upgrade of the Swiss Light Source (SLS) was finished, promising a 40 fold smaller emittance and a corresponding increase of the spectral brightness from the current value. From the point of view of collective effects, the main changes in the new design are a reduced chamber size, fully coated with NEG, and operation at small and negative momentum compaction with low synchrotron frequency. We give an overview of the latest results for the ring. Most critical is the threshold for the longitudinal single bunch instability. Taking into account the combined effect of wake impedances and CSR, we have to rely on bunch stretching by a higher harmonic system to achieve stable operation at nominal current.

INTRODUCTION

The Swiss Light Source (SLS) started user operation in 2001 and has been operating in top-up mode since then, delivering about 5000 hours of user time per year into 18 user beamlines with excellent availability. Taking advantage of new advanced optics concepts, we intend to upgrade it towards a diffraction limited light source (SLS 2.0 [1]). To obtain the required improvement in emittance of at least 40, a novel type of lattice using longitudinal gradient bends and reverse bends was developed (see also Table 1). It will fit the existing infrastructure with minimum changes, but some modifications in the shielding walls and shifts of the source points of several beamlines may be required, since the old design with a three fold symmetry and three different types of straights could be replaced by a strictly regular layout with twelve fold symmetry.

Comparing the upgraded machine layout with the current one, the major points with respect to collective effects will be the following: For resistive wake fields, we'll have a reduced diameter (20 mm) of the beam pipe fabricated from copper with a thin, 500 nm NEG (Non Evaporable Getter) coating for better pumping and desorption. RF voltage is lower, so we can work with three instead of four ELETTRA type cavities [2]. To reduce transient beam loading effects, we will use only one cell of the existing third harmonic system [3] to provide Landau damping. Momentum compaction and synchrotron frequency will be reduced. Transversely, shorter damping times help with the impedance thresholds, while we have the reverse situation in the longitudinal plane.

As of now, design work on the ring optics is still on going and may result in changes with subsequent effects on the machine threshold. As a consequence, the vacuum system as well as most of the components as tapers, BPMs etc are not finalized. In the following, we are using a more generic model of the accelerator assuming a round beam pipe, which includes all components as well as the same types of insertion devices currently installed in the SLS.

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Table 1: Main Parameters of SLS 2.0 and SLS

	SLS 2.0	SLS
Circumference [m]	290.4	288.0
Energy [GeV]	2.4	2.4
Current [mA]	400	400
Momentum compaction	$-1.33 \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$
RF frequency [MHz]	499.6	499.6
Nom. RF voltage [kV]	1420	2080
Harmonic number	484	480
Filling pattern gap	10%	19%
Damping time $\tau_{x,y,E}$ [ms]	4.9/8.4/6.5	8.6/8.6/4.3

Longitudinal single bunch effects seem to be the most critical part of the machine, so currently, most of the work has been concentrated on that. In the following, we discuss the impedance contributions from wake fields and CSR effects and describe how to arrive at thresholds simulations with a realistic model for Landau damping including transient effects. Furthermore we show very preliminary results for transverse effects.

LONGITUDINAL MACHINE IMPEDANCE

The vacuum system is still under design, so we are currently working with generic geometries to estimate the contribution to the total impedance budget of the storage ring. It includes resistive wakes from beam pipe (20 mm diameter, length 248.4 m, homogeneously coated with 500 nm Ti-Zr-V NEG) and insertion devices (14 m chamber with 4 mm height, 28 m with 6 mm height), 150 BPMs, cavities (main RF and higher harmonic) as well as generic tapers transitioning between chamber and insertion devices. The full impedance spectrum is shown in Fig. 1.

Wakes were only calculated for a length corresponding to the size of the RF bucket, so the resonance frequencies of the main and harmonic cavities are smeared out and not visible in Fig. 1, while circumferential resonances inside the BPMs still show up near 8 GHz.

CSR Effects

Sufficiently strong coherent synchrotron radiation in the bends results in radiated electromagnetic fields overtaking the bunch. Particles in the tail act on those in the head, which can lead to self modulation in the bunch intensity and instability. While this has not been observed at the SLS, the situation at SLS 2.0 is quite different due to the very low and negative momentum compaction factor. Analytically,

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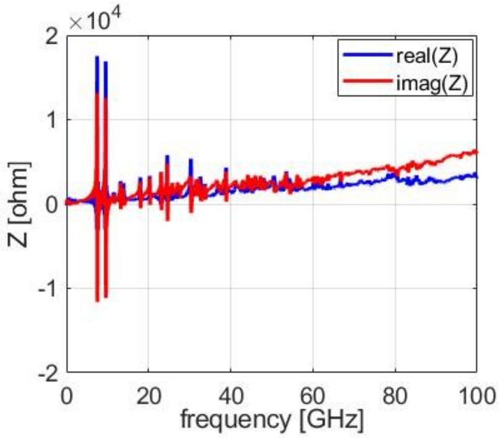

Figure 1: Full longitudinal broad band impedance spectrum (up to 100 GHz) for SLS 2.0.

the threshold is mainly determined by the peak field of the magnets, up to 6 T for the super bends corresponding to a bending radius of 1.33 m, and the shielding by the vacuum chamber wall [4]. The analytical estimate has been derived only for positive momentum compaction, but as shown in [5], it can be applied also for negative α for sufficiently long bunches. Assuming operation with the harmonic RF system and long bunches with a nominal rms length of 40 ps, CSR effects alone give us a threshold current of 5.6 mA. Without harmonic system, the bunch length is 9 ps with a theoretical threshold of 1.1 mA.

To include CSR into the tracking, we used the following approach: If we approximate the vacuum chamber by a pair of infinitely large parallel plates and look only into the steady state (excluding transients occurring when the beam enters or leaves the bends) CSR effects can be modeled analytically by an equivalent impedance [4]. The global contribution in SLS 2.0 is obtained by adding up the contribution of each magnet slice. This analytical approach for the CSR calculation is provided also by an optics element in ELEGANT [6].

LONGITUDINAL SINGLE BUNCH EFFECTS

Landau Cavities

The two cell third harmonic cavity has a strong beneficial effect on the bunch length and in turn on the stability thresholds of the machine. With the typical fill pattern including an ion clearing gap, transient effects in both the harmonic cavity and the main RF reduce this. Less cavities means less transients, our baseline assumes operating with three main RF cavities and using only one cell of the third harmonic cavity (3HC). Compared to current operating condition in the SLS, this requires to increases the operating voltage in the 3HC from 327 kV/cell to 430 kV/cell, which is still within the nominal parameter range of the device. Minimizing the size of the ion clearing gap further reduces the transients. Calculations by A. Wrulich [7] indicate, that already a gap size of 10 bucket is sufficient for ion clearing. Having some random fluctuations in the bunch charges as they happen anyway in Top Up operations may allow even smaller gaps, less transient effects in the RF and so higher thresholds. Currently, we apply a safety margin of two and use a gap size of 20 as a reference value.

Tracking Simulation Results

The tracking codes ELEGANT [6] and Mbtrack [8] are used to calculate the threshold of the single bunch longitudinal microwave instabilities of SLS 2.0 using the impedance specified above. The most sensitive parameter to detect the threshold is the rms energy spread δE/E. The threshold is defined as the bunch charge where the single bunch energy spread grew by more than 1% with respect to the natural energy spread. The simulation were done in several steps: A single bunch simulation without harmonic cavity gives us a pessimistic value for the threshold. Including an ideal harmonic system without transients an optimistic one and including the transients due to the fill pattern gap a realistic feeling, where we are between the pessimistic and optimistic side.

The code ELEGANT is used for the first step without harmonic cavity. Up to eight million macro particles were tracked over 50000 turns (roughly seven times the damping time) to ensure the convergence of the results. The computed charge threshold from the single bunch ELEGANT simulations without harmonic cavity is $Q_{sb,th.}$ = 0.75 nC (360 mA total current), with a corresponding loss factor equal to 32.0 V/pC. For comparison, the nominal single bunch charge with uniform filling would be 0.8 nC (400 mA). It is clear, that the accelerator definitely requires operation with a well functioning harmonic cavity.

Including an ideal harmonic cavity stretching all bunches in the train the same way results gives us the second, optimistic, value for the threshold. Both ELEGANT and Mbtrack simulations were performed and both codes give the same single bunch threshold $I_{sb,thr.}$ = 2.68 mA, a factor 3.25 larger than the nominal $I_{sb,nom.}$ = 0.83 mA. (The loss factor calculated for the ELEGANT multibunch simulation at the nominal current is 2.76 V/pC).

In our experience, the code Mbtrack is particularly well suited to model a whole bunch train with gaps, even allowing all kinds of distribution of charge per bunch. In order to use constant settings for the RF detuning parameters for all runs, we kept the total beam current at 400 mA while letting the bunch charge vary only in three reference bunches, the first, middle and last one in the train. As described above, we used only three RF cavities and only one cell of the 3HC module (the second cell is detuned and contributes only to the broad band impedance). With the gap size of 20 buckets, the current safety margin over the nominal current with the previously mentioned provisional impedance budget corresponds to a factor 2.25. Table 2 summarizes the thresholds found for the different filling pattern studied.

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Table 2: Thresholds Currents versus Filling Patterns

	$I_{sb,thr.}$ [mA]	$I_{sb,thr.}$ / $I_{sb,nom.}$
Uniform filling	2.68	3.23
10 empty buckets	2.5	2.98
20 empty buckets	1.92	2.25
48 empty buckets	1.82	1.98

OTHER INSTABILITIES

Transverse Single Bunch Effects

In the SLS, the transverse mode coupling instability (TMCI) is controlled by running at non zero chromaticity. For the upgrade, the picture is similar, as can be seen in Fig. 2, which shows calculated thresholds obtained via turn-by-turn 6D tracking using ELEGANT [6]. Thresholds were determined following the approach in [9]: no radiation damping is included in the tracking, and the growth rate from tracking is compared to the radiation damping rate determined by the lattice. To start, we used only a basic model including resistive losses in the beam pipe, comparing the uncoated copper tube to a coated one with 500 nm NEG (excluding the insertion devices) [10]. Without harmonic cavity, the threshold is rather insensitive to the chromaticity. It is only with the deformation of the potential well by the harmonic cavity, that it can be controlled.

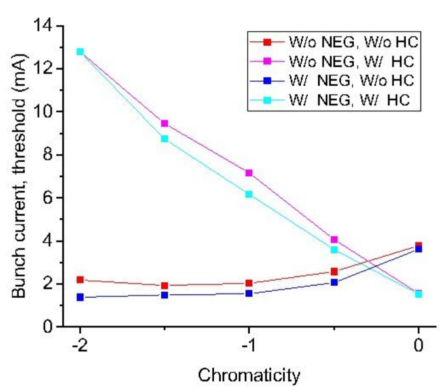

Figure 2: Thresholds for the transverse instability in the vertical plane assuming only contributions from resistive wall effects. Shown are cases with/without NEG coating and with/without ideal third harmonic cavity.

Another set of simulations, which included radiation damping, showed clearly transverse mode coupling instability when the harmonic cavity was turned on. This was also the case when the chromaticity was set to zero without harmonic cavity. However, clear mode coupling was not observed with chromaticity at, e.g., -1.5. Going to values below -2 increased the threshold again.

As mentioned, the transverse impedance model is not yet complete. Also, we assume an ideal harmonic cavity without transient beam loading, so that it is too early to make quantitative predictions. Nonetheless we can say already now that, as in the longitudinal single bunch case, we need to rely on operation with a harmonic cavity and with a fill pattern using a small gap to ensure stability.

The situation may still change since at the current stage of the project, components like vacuum chamber transitions are not yet fully defined. In comparison to the situation in SLS, we should profit from the lower average beta functions in the optics of SLS 2.0, which gives higher thresholds.

Coupled Bunch Instabilities

The situation for coupled bunch instabilities is expected to be similar to SLS, probably we will be somewhat more dependent on the feedback system. Bunch by bunch feedback systems in both transverse and longitudinal planes are part of the machine design to ensure stable operation.

CURRENT STATE

As a rule of thumb, we assume to require a margin of safety of two between predicted and required threshold currents. With the current baseline parameters, this is reached and the accelerator is expected to run stable at nominal current. Without a final design of the vacuum system, it is based on a somewhat generic model of the accelerator including all components, where still changes and optimizations are expected.

The thickness of the NEG coating affecting the resistive wake is an important issue [11]. We are currently trying to go even thinner than the nominal value of 500 nm. On the other hand, the chamber geometry is rather complex, bent longitudinally with antechamber and possibly tapering at the location of the super bends, so the coating homogeneity can be expected to vary quite a bit, something we have to take into account for the impedance.

A second important parameter for the threshold is the size of the gap in the fill pattern, since it affects transient beam loading in the RF system and so the effectiveness of the harmonic cavity. A gap size of 10 buckets may be already sufficient for ion clearing. Having some random fluctuations in the bunch charges as they happen anyway in Top Up operations may allow even smaller gaps, smaller transients and so higher thresholds.

To better estimate the required margin of safety between theoretical calculated thresholds, we are currently working on an experimental validation using the existing SLS, setting up an impedance model of the accelerator as it is now, which will be used to calculate thresholds, subsequently to be validated with beam at the accelerator. As part of the fine tuning we are also currently investigating an alternative lattice for SLS 2.0, which would have a beam pipe aperture between 17 and 18 mm.

ACKNOWLEDGEMENTS

For the application of the ELEGANT and Mbtrack codes to our simulations, we benefited strongly from advice and support of F. Cullinan (MAX IV), R. Nagaoka (Soleil), M. Venturini (ALS) and H. Xu (IHEP). For our work on CSR effects, we profited a lot from discussions with K. Bane,

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C. Mayes (SLAC) and D. Zhou (KEK), who also cross validated our model with their own codes with respect to transient CSR effects in regions of varying magnetic field.

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