POSSIBLE UPGRADING OF THE SLS RF SYSTEM FOR IMPROVING THE BEAM LIFETIME

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Abstract

The RF system which was adopted for the SLS (Swiss Light Source) initial phase [1] is based on the choice of conventional, already well-proven equipment. The use of superconducting (sc) cavities has been ruled out as a starting solution. However, for improving the beam lifetime in the storage ring (SR) when operating at very high brightness, the initial normal conducting (nc) system could be further complemented with idle (only-beam-driven) sc cavities. Within that scheme, two different approaches have been investigated: either doubling the fundamental RF voltage using one 500 MHz sc cavity, or lengthening the bunches with one (possibly two) third harmonic sc cavity(ies) [2,3]. These upgrading options are discussed here.

1 INTRODUCTION

The RF system which was adopted for the SLS starting phase is described in more details in [1]. For the SR, it consists of four 500 MHz plants, each comprising a nc single cell cavity of the ELETTRA type, powered with a 180 kW CW klystron amplifier via a WR1800 waveguide line. The main characteristics of this system as well as the basic parameters of the SR are listed in Table 1.

Circumference, L [m]	288.
Revolution frequency, f_o [MHz]	1.04
Energy, E [GeV]	2.4
Radiation loss / turn, ΔU [MeV]	0.6
Beam current, I_b [A]	0.4
Beam power loss, P_b [kW]	240.
Momentum compaction, α	7. E-4
Momentum spread, σ_p [%]	0.09
Longitudinal damping time τ_s [ms]	4.5
Transverse damping time, $\tau_{x,y}$ [ms]	9.
RF frequency, f_{RF} [MHz]	499.652
Harmonic number, $h = f_{RF} / f_o$	480
Total RF voltage, V_{RF} [MV]	2.4
Number of cavities, n_{cav}	4
Cavity shunt impedance, R_s [MΩ] [[MΩ	3.4
Cavity quality factor, Q_o	40000
Cavity wall dissipation, P_d [kW]	60.
Cavity input power P_t [kW]	120.
Number of klystron amplifiers, n_k	4
Max. klystron power, P_k [kW]	180.
Synchronous phase, ϕ_s [degree]	14.5
RF acceptance, ε_{RF} [%]	± 3.5
Bunch length, σ_s [mm]	4.
Synchrotron frequency, f_s [kHz]	7.5

Table 1: Main SR and RF parameters

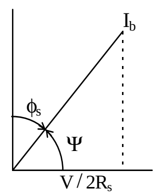
In order to further improve the beam lifetime - which is dominated by Touschek scattering - in the SR when operating at very high brightness, the RF system described before could be upgraded following two different approaches: either increasing the energy acceptance by doubling the 500 MHz voltage or lengthening the bunches using a 3rd harmonic system. Both schemes would be advantageously realized in complementing the initial nc system with idle (only-beam-diven) sc cavities.

2 THE HYBRID “POWERED NC AND IDLE SC” RF SYSTEM

The basic idea is to separate the functions of the two RF systems in order to optimize their respective performance: the nc system supplies the power for restoring the losses per turn; the beam-driven sc system only contributes to the potential well [4].

2.1 Beam induced voltage in an idle cavity

The power lost by the beam passing through an idle cavity is: $P_b = V\, I_b \cos\psi = - V\, I_b \sin\phi_s = V^2 / (2\, R_s)$; $V = 2\, R_s\, I_b \cos\psi$, is the cavity voltage induced by the beam, ψ is the cavity tuning angle defined as : $\mathrm{tg}\,\psi = 2\, Q_o\, \delta f / f_r$ where $\delta f = h\, f_o - f_r$ is the cavity frequency detuning; $\phi_s = \psi - \pi / 2$ is the synchronous phase.



If the cavity is detuned sufficiently far from resonance ($\delta f >> f_r / Q_o$), one gets:

$$\psi \approx \pi / 2,\ \phi_s \approx 0,\ P_b \approx 0 \text{ and } V \approx I_b\, (R/Q)\, f_r / \delta f.$$

A sc cavity with its very high Q_o is the ideal component for making use of the induced voltage while keeping the beam energy losses at negligible level: assuming a typical R/Q value of 50 Ω and the SLS nominal beam current (I_b = 0.4 A), one finds that 2.6 MV are induced when the cavity is detuned by about 4 kHz at 500 MHz. This amount of detuning which corresponds to several thousands of the cavity bandwidth well fulfills the required condition, $\delta f >> f_r / Q_o$ and it remains much smaller than the revolution frequency. The induced voltage could be easily maintained even at extremely low current by controlling the detuning, still within the previous limits. The beam power deposited into the sc cavity, equal to the wall dissipation (~ 50 W), is negligible as compared to the radiation losses.

During the injection, the RF voltage in the sc cavity builds up with the current and the induced transients always remain quite tolerable. Note that, during the injection, the detuning of the sc cavity is a “free” parameter that can be set "at will". In the storage regime the RF voltage of the sc cavity is controllable in closed loop via its frequency tuning system.

All the above considerations remain valid for a higher harmonic cavity.

2.2 Increase of the energy acceptance using a 500 MHz idle sc cavity

If one combines the previously described 500 MHz nc system with an idle sc cavity of same frequency and voltage ($V_{sc} = V_{nc} = 2.6$ MV), one gets for the overall RF voltage an amplitude of 5.2 MV and a synchronous phase, ϕ_s of 6.5°. As compared to the initial situation with only the nc system, this corresponds to an enhancement factor of 1.6 in terms of *RF energy acceptance* (from 3.7 % up to 5.8 %). Concurrently, since the sc cavity is detuned such as to produce additional focusing, the bunches are shortened by a factor of 1.4. Taking into account both effects, the Touschek life time could theoretically be improved by a factor of about 3. With the introduction of mini-gap undulators, the actual efficiency of this method could finally be limited below the previous expectation by the *lattice energy acceptance*; computer simulations are in progress to estimate its effective value [3].

On the other hand, for the operation modes where the lifetime is less critical, the sc cavity would permit to save a significant amount of the power dissipated in the nc cavities by operating them at reduced voltage and larger synchronous phase.

Concerning the Robinson's criterions for the stability of synchrotron oscillations, the presence of the idle sc cavity is beneficial since it reinforces the oscillation damping strength while keeping the instability current threshold unchanged [2,4].

2.3 Lengthening of the bunches using a 3rd harmonic idle sc cavity

An alternative method of improving the beam lifetime consists in producing longer bunches with less density. Again, this could be advantageously realized using a hybrid system as described before but with a higher harmonic cavity detuned in the other direction (de-focusing case). Figure 1 shows the RF voltages (nc, sc and nc+sc) versus phase, as well as the corresponding computed RF buckets and bunch profiles, in the SLS case with a 3rd harmonic (1.5 GHz) idle sc cavity. The beam induced voltage of about 0.8 MV, required to have a quasi zero slope over the phase domain covered by the bunch, is obtained with a detuning of 36 kHz (for $R/Q \approx 50\ \Omega$ and $I_b = 0.4$ A, as before). One finds that the bunches are lengthened by a factor of about 4 ($\sigma_z \approx 4.\sigma_{zo} \approx 15$ mm) while the energy acceptance is nearly unaffected as compared to the single nc system. Consequently, the Touschek lifetime should be also improved by a factor of about 4. Note that, with the introduction of mini-gap undulators, the actual lifetime begins to be affected by gas scattering effects [3].

Concerning the Robinson stability, the condition is more delicate than in the focusing case since the harmonic sc cavity is now detuned such that it contributes to anti-damping. The computation of the oscillation growth (or damping) rates [2] showed that the stability condition is largely fulfilled with full stored beam current since the sc cavity is then detuned far from the first satellites of the synchrotron frequency. If one wants to maintain the same voltage at reduced beam current, instabilities could theoretically occur (~ 100 mA) when exciting a satellite of the synchrotron frequency exactly in resonance. On the other hand, this is easily avoidable: changing the frequency of the sc cavity - which naturally has an extremely narrow bandwidth - by a fraction of a kHz should be sufficient to re-establish stable conditions without affecting too much the operating parameters.

Using two cavities instead of a single one (see next section) should permit to extend the operating beam current range down to a few tens of mA.

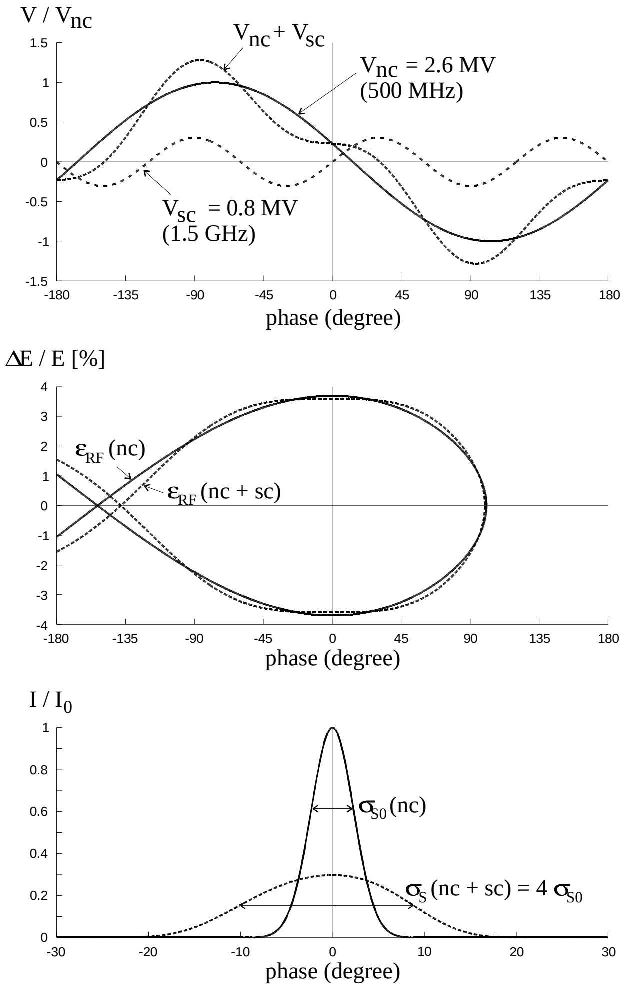


Figure. 1 : Normalized RF voltages (nc, sc, nc+sc) vs phase, RF buckets and bunch profiles (nc, nc+sc) for $V_{nc} = 2.6$ MV, $V_{sc} = 0.8$ MV and $f_{sc} = 3.f_{nc} = 1.5$ GHz.

3 DISCUSSION OF THE UPGRADING ALTERNATIVES

The previous results indicate that, in order to improve the beam lifetime of the SLS, the bunch lengthening technique is more efficient than increasing the fundamental RF voltage. With the former solution, an enhancement of the beam Touschek lifetime by about a factor 4 is anticipated. Moreover, one can expect a significant amount of Laudau damping - due to the nonlinearity of the RF waveform - which should help in fighting the coupled bunch instabilities. Another benefit is that the resulting decrease in peak current should raise the threshold for single bunch instabilities. Note also that the harmonic cavity could easily be detuned in the other direction, shortening the bunches by a factor of about 1.5, if wished.

Different possible versions of harmonic systems were considered and compared. This is summarized in Table 2 which shows typical operating parameters for an idle sc system using one or two cavities and for a nc alternative.

	idle sc system		idle nc system
f_r [GHz]	1.5		1.5
n_{cav}	**1**	**2**	**10**
$R_s * n_{cav}$ [Ω]	10 E9	40 E9	10 E6
Q_o	2 E8	4 E8	1.5 E4
V [MV]	0.85	0.85	0.85
E [MV/m]	8.5	4.25	0.85
P_d [W]	**40**	**10**	**36 000 ***
I_b [A]	0.4	0.4	0.4
ϕ_s [degree]	~ 0	~ 0	6
δf [kHz]	**35.5**	**71**	**470**
ε_{RF} [%]	± 3.65		± 3.45
σ_z [mm]	15		15
f_s [kHz]	2.2		2.2

Table 2 : nc and sc versions of a 3rd harmonic idle RF system for bunch lengthening (*power to be restored by the 500 MHz system: $\Delta\phi_s \approx 2°$).

Although the required level of performance is fully compatible with the use of a single sc cavity, adding a second one presents significant advantages:

- lower accelerating gradient and cryogenic losses for the same total voltage;
- higher voltage capability;
- extension of the operating beam current range down to lower values (doubled detuning for the same voltage and current);
- possibility of applying the two-cavity HOM damping technique developed for SOLEIL (at 350 MHz) [5].

The SOLEIL design consists of a pair of sc cavities with the HOM damped by means of coaxial couplers, located on the tube in between the two cavities. Following this approach, the space requirement and investment cost should remain quite comparable with equivalent systems based on a single cavity [6].

Idle harmonic nc cavities are being operated (or planned) in other laboratories [7,8]. For our purpose, this solution would require about ten cavities in order to keep at a reasonable level (~ 40 kW) the power to be restored by the main RF system and ensure the stability within a range 100 mA < I_b < 400 mA [2]. Moreover, making this system "invisible for the beam" would require an unpractical amount of detuning.

All the above considerations led us to favor the idle sc version based on the SOLEIL two-cavity design, "scaled down to 1.5 GHz".

4 CONCLUSIONS

In order to further improve the beam lifetime in the SLS SR when operating at very high brightness, two approaches have been considered: either increasing the energy acceptance by doubling the 500 MHz voltage or lengthening the bunches using a 3rd harmonic system. Both schemes could be advantageously realized by complementing the initial nc system with idle (only-beam-driven) sc cavities. Such a *hybrid "powered nc and idle sc" system* appeared to be particularly flexible and easy to control; moreover, the difficulties related to the transmission of large power through the sc cavities with the associated technological and operational problems are naturally eliminated.

Computer simulations indicated that the bunch lengthening option would be more efficient, improving the beam Touschek lifetime by a factor of about four. This is the approach presently investigated and amongst the possible variants of such a system, the favored one is an idle sc version based on the SOLEIL two-cavity design, "scaled down to 1.5 GHz". This solution is well suited to provide the necessary damping of the parasitic HOM impedances and moreover should lead to a quite good compromise in terms of reliability, flexibility, space requirement as well as investment and operational costs.

5 REFERENCES

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