SLS OPERATIONAL PERFORMANCE WITH THIRD HARMONIC SUPERCONDUCTING SYSTEM

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Abstract

Within the framework of the S3HC project, two identical cryomodules, one for Swiss Light Source (SLS) and one for ELETTRA, were developed at CEA Saclay. Each cryomodule contains a third harmonic superconducting RF system consisting of two passive 1500 MHz Nb/Cu single-cell cavities. At the SLS the commissioning of the cavity in the bunch lengthening mode took successfully place end of September 2002 and that became the nominal mode of operation of the storage ring. The measurement made at SLS shows bunch lengthening up to a factor of 3 and a lifetime increase greater than a factor 2. The additional Landau damping, generated by the increased non-linearity of the global RF voltage, allows stable top-up operation at the maximum design current of 400 mA. The commissioning and the operational results obtained with this system are reported here.

INTRODUCTION

The SLS is a third generation synchrotron light source, recently built at the Paul Scherrer Institut in Villigen near Zurich. The commissioning of the 2.4 GeV accelerator facilities took place in the early 2001 [1] and the first user operations started in August 2001. The characteristic of this type of machine is a low emittance (4.8 nmrad for the SLS), which is suitable to produce a high brightness photon radiation, but in return lead to relatively short beam lifetime. The high space charge density associated with the low emittance increases indeed the intra-beam scattering (Touschek effect). In order to overcome this phenomenon without affecting the emittance, a complementary third harmonic RF system for lengthening the bunches, and thus reduce the charge density, was propose in 1998 by P. Marchand as possible upgrade of the SLS RF system[2]. PSI and Sincrotrone Trieste decided to choose a common approach, opting for a passive superconducting cavity.

The conceptual design and the fabrication of the cavity modules were realized within the framework of the SUPER-3HC collaboration involving Sincrotrone Trieste, CEA/Saclay, CERN and PSI [3-4].

The system is based on a “scaling at 1.5 GHz” of the 350 MHz two-cell-cavity developed at Saclay for the SOLEIL project [5,6]. It consists of two Nb/Cu cells, connected with a tube on which stand the couplers for the damping of the Higher Order Modes [7] (Fig. 1).

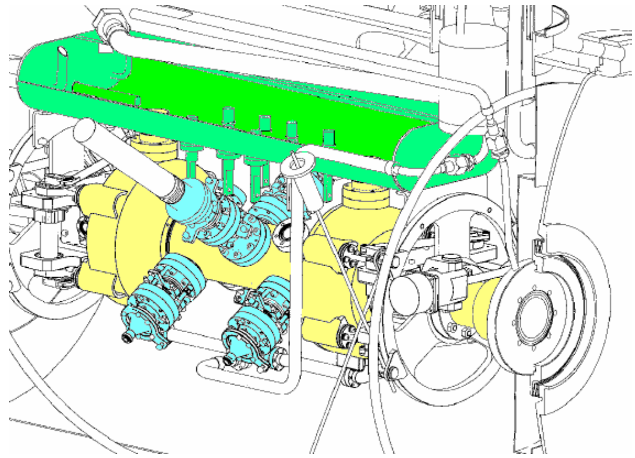


Figure 1: 3D view inside the S3HC module, showing the liquid He tanks surrounding both cells and the six HOM couplers mounted on the central tube.

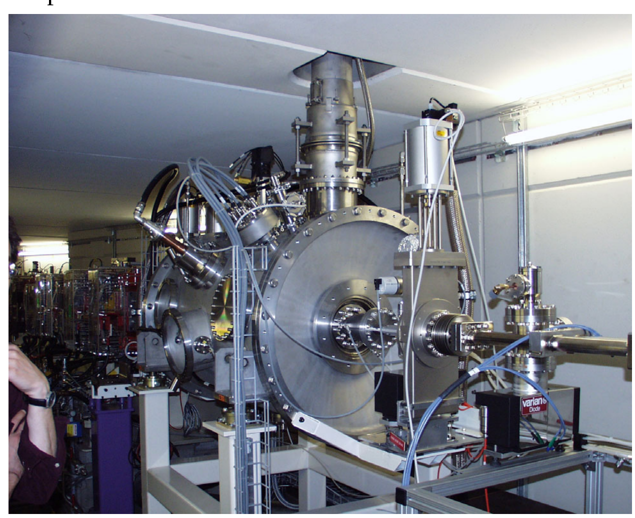


Figure 2: S3HC cryo-module in the SLS storage ring.

The maximum bunch lengthening is achieved when the 3rd harmonic beam-induced voltage is about one third of the overall voltage produced by the main 500MHz RF system. For the typical SLS operating conditions (4 MV at 500 MHz) this voltage corresponds to about 800 kV (4 MV/m) at 1.5 GHz.

CRYOGENIC SYSTEM

ELETTRA and SLS chose as well a common approach for the cryogenic system that feeds liquid Helium into the cryo-module. This system, thoroughly described in [8], is based on the use of the HELIAL 1000 refrigeratorliquefier manufactured by the company AIR LIQUIDE. A substantial support during the specification, the design, the assembly and the commissioning phase of the overall cryogenic system, came from CRPP-EPFL and the cryogenic group of PSI

Table 1 summarises the cryogenic load at full voltage, the required liquefier performance at 4.5 K in mixed mode (refrigeration + liquefaction) and the maximum cryogenic power produced during the commissioning. As shown below, the performances of the cryo-source are well above the specified requirements, resulting in increased system reliability.

Table 1: Estimated cryo-load with 4 MV/m gradient (Q_o=2 10^8) and measured cryogenic source performance

Components	Load	Comments
2 RF cells	22 W	Directly in LHe bath
2 L-HOM couplers	3 W	Cooled by conduction
4 T-HOM couplers	8.5 W	Cooled by conduction
2 Extrem. Tubes	0.2 W	With 2x0.05 g/s cold Ghe
Cryo-module static losses	5.1 W	With 0.071 g/s cold GHe in thermal shield (60K)
Cryo-lines	6.5 W	
Total power needed at 4.5 K: 45.3 W refrigeration With tot GHe flow: 1.171g/s = 5.2 l/h of liquefaction		
Specified power at 4.5K: 65 W (50% safety margin) With specified liquefaction duty of 7.5 l/h		
Max measured power at 4.5 K: 150 W of refrigeration With measured Liquefaction duty of 9.5 l/h		

After cooling of the S3HC cryo-module the measured static losses (without RF) were in good agreement with the anticipated values.

S3HC OPERATING EXPERIENCE

SLS Warm Operation

The warm regime is an important back up solution to allow operation of the SLS in case of failure of one component of the cryogenic system. In this mode the cavity is parked, in order to minimize the induced voltage which could perturb the electron beam stability. At room temperature this condition is achieved when parking the cavity between two revolution frequency side bands, 5.5 MHz below the third harmonic (figure 3). In spite of this precaution, in the warm parking position the beam can still deposit a few 100W into the cavity.

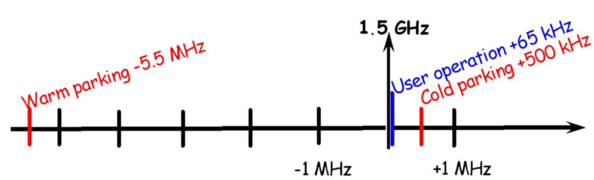


Figure 3: Operation diagram. The range of the tuning system in warm and cold regime is ±600kHz. The 5 MHz frequency shift between cold and warm operation is due to the mechanical shrinking of the cavity.

To avoid overheating, the cryo-module is then cooled by circulating some warm GHe from the compressor directly into the cryo-module, or as a backup solution using some purified compressed air [8]. Under these conditions the SLS has been operated with stable beam up to 200 mA of stored current. At higher current an overheating of the module was observed, which led to a run away process resulting in the excitation of a Coupled Bunch Mode (CBM) instability generated by the fundamental mode of the warm third harmonic cavity. That could eventually be overcome by improving the cavity gas cooling efficiency. At about the same current level a second CBM, related to the excitation of an HOM in the main RF system was also observed. This instability could eventually be eliminated with an improved fine tuning of the main RF system [9]. No HOM of the S3HC cavity have been ever observed during the warm operation

SLS Cold Operation

In cold operation and when excited sufficiently far from resonance ($\delta f >> f_r/Q$), the induced RF voltage and the power losses are given by [2]:

$$V = I_b\,(R/Q)\,f_r/\delta f \quad \text{and} \quad P_b = V^2/(2R) \qquad (1)$$

Here I_b, f_r and $\delta f = f_r - 3f_{RF}$ are respectively the beam current, the cavity resonant frequency and the detuning. R is the shunt impedance and $Q \sim 2.10^8$ the quality factor. The global R/Q of the cavity (2 cells) is 88.4Ohms.

In the SLS, the S3HC "cold operation" started on October 1st, 2002, just after the first cavity cool down, while in ELETTRA it began in January 2003[10].

In the parked position, when the resonant frequency of the cold cavity is set 500 kHz above the third harmonic ($f_r = 3f_{RF} + 500kHz$), the cavity is almost transparent to the beam and the induced voltage is negligible. Under these conditions, stable operation of the storage ring is presently limited to 200mA because of the above-mentioned CBM, which is correlated with an HOM of the main RF system. When the S3HC cavity is tuned closer to resonance, the third harmonic RF voltage becomes larger and the increased non-linearity of the global RF voltage generates additional Landau damping and the CBM instability no longer limits the operating current. This effect is re-enforced by the 20% empty RF buckets in the 1µs bunch train, used to suppress ion trapping. The transient beam loading due to the empty gap, results in phase dispersion along the bunch train, which produces a broadening of the synchrotron frequency and that contributes also to increase the Landau damping.

Since the SLS is nominally operated in top up mode at constant current [11], there is no specific need of a tuning loop to control the harmonic voltage. The cavity tuning is usually adjusted to insure enough Landau damping during the current ramping, up to the operating current.

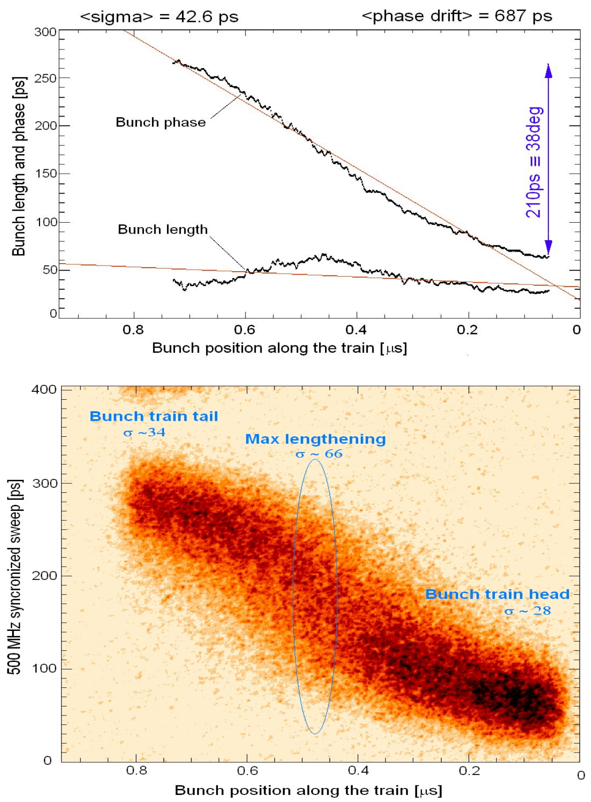
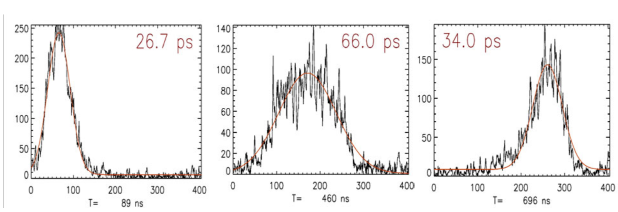


Figure 4: Streak camera snapshot at 320mA. Bunch σ and phase in ps versus position in the bunch train.

Figure 4 shows a high resolution streak camera snap shot made at 320 mA for an average bunch elongation factor of ~3. One can observe that the gap induces a phase shift along the bunch train which reaches 38 deg. The bunch length also changes along the train from a maximum of 66ps to a minimum of 24ps for an average value of 42 ps (~13ps without harmonic system). A detailed analysis of each single bunch shape nevertheless shows that the charge distribution within each bunch deviates only slightly from a Gaussian profile (figure 5).



In Figure 5: Charge distribution and σ at three different locations along the bunch train, 89, 460 and 696 ns.

In Figure 6 the streak camera measurements, as well as the relative amplitude of the marginally excited CBM are plotted versus the average S3HC cavity voltage. As expected, we observe an increase of the phase drift versus the cavity voltage, and a broadening of the bunch length distribution along the train, that results in additional damping of the CBM. The average bunch length increases here by ~12%.

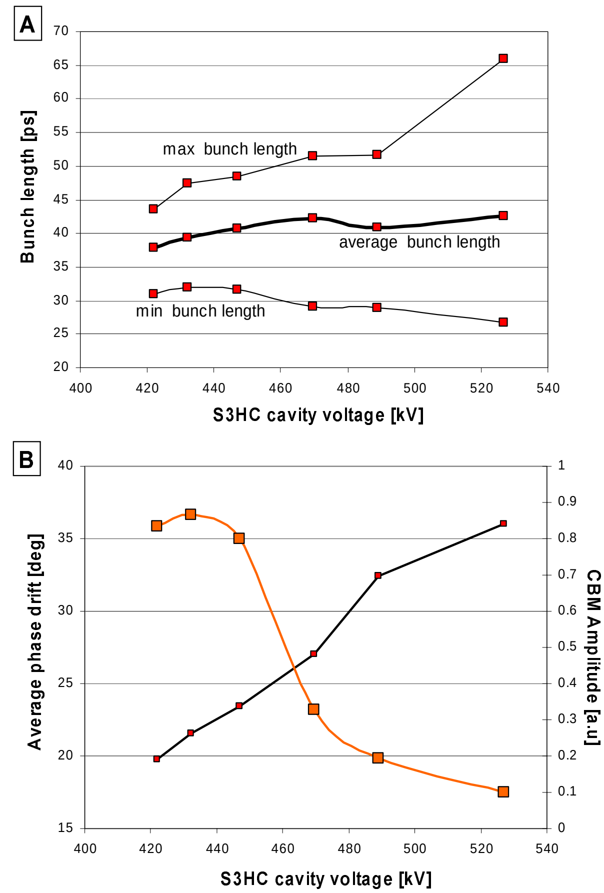


Figure 6: (A) Average bunch length versus cavity voltage, and (B) average phase drift and CBM amplitude versus cavity voltage.

A systematic beam lifetime measurement versus the induced voltage in the super-conducting cavity has been performed at 180mA, just below the CBM instability threshold, with a main RF voltage of 2.08MV (figure 7).

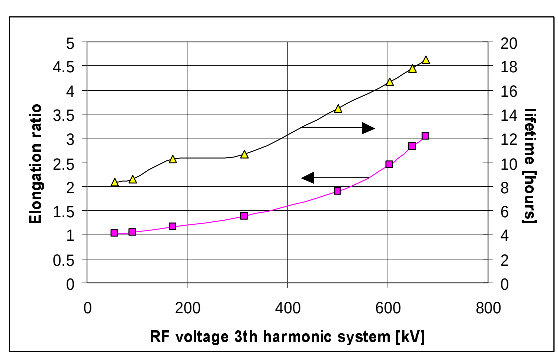


Figure 7: Average elongation ratio and lifetime versus S3HC voltage (180 mA – 2.08 MV operation).

The expected maximum elongation of a factor of 3 is reached for a voltage of ~690kV, with a corresponding lifetime improvement of a factor 2.2.

Stable operation at the design current of 400mA has also been demonstrated, with a lifetime of approximately 8 hours, a factor of two more than the expected one without the third harmonic system.

CONCLUSIONS

The third harmonic super-conducting system installed in the SLS storage ring significantly improved the machine performance in terms of beam stability and lifetime. The additional Landau damping generated by the harmonic system proved to be an efficient way to damp longitudinal coupled bunch instabilities. This effect allowed stable operation of the SLS at the design current of 400 mA. A lifetime improvement slightly higher than a factor of two has been measured up to 400mA. No unstable behaviour of the SLS storage ring, imputable to the third harmonic cavity, has been observed ever in cold operation.

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