COMMISSIONING OF THE SLS THIRD HARMONIC SUPERCONDUCTING RF SYSTEM

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INTRODUCTION

The RF system of the SLS storage ring consists of four f_{RF}=500 MHz copper cavities that can generate a total RF voltage of 2.4 MV and deliver 400 kW to the beam [1,2].

In order to improve the beam lifetime, which is dominated by Touschek scattering, a complementary 3rd harmonic RF system, to lengthen the bunches and therefore to reduce their charge density [3], has been implemented and commissioned in 2002. In the past, several laboratories developed for the same purpose such idle harmonic systems, but mainly made out of copper. At the SLS, for the first time in a storage ring based light source, a Superconducting 3d Harmonic Cavity has been successfully used.

Within the so-called SUPER-3HC collaboration framework including Sincrotrone Trieste, CEA/Saclay and PSI [4], two identical modules have been produced. The second system installed at ELETTRA will be commissioned in January 2003.

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, separated by a middle tube where are located the couplers for the damping of the Higher Order Mode (HOM) resonances [7] (Fig. 1). The frequency of each cell is independently tuned by a mechanical system, which changes the cell length within the limits of the elastic deformation (± 500 kHz range, 10 Hz accuracy).

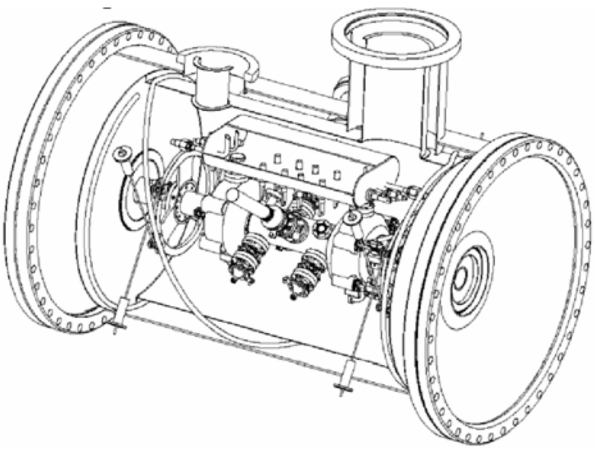

Fig. 1: S3HC cryostat, visible the liquid He baths surrounding both cells and the 6 HOM couplers mounted on the central tube.

For a maximum bunch lengthening of approximately a factor of 3, the beam-induced voltage is adjusted using the frequency tuners up to one third of the overall voltage given by the main RF system. For a main voltage of 2.4 MV this correspond to 800 kV (4 MV/m) at the third harmonic. Under these conditions one expects theoretically a 2 - 3 times longer beam lifetime

CRYOGENIC SYSTEM COMMISSIONING

Fig. 2 shows a global scheme of the cryogenic system. A Liquefier continuously produces LHe, to compensate the losses in the cryo-module. Both cavity reservoirs are filled with LHe at 4.5 K from the bottom; on the top a common vessel (PS2) recuperates the cold GHe. Part of this cold GHe is returned back to the refrigerator while the rest is used to cool the copper thermal shield (60 K) and the two cavity extremity tubes (4.5 - 300 K). The superconducting inner tube and HOM couplers are conduction-cooled at 4.5 K.

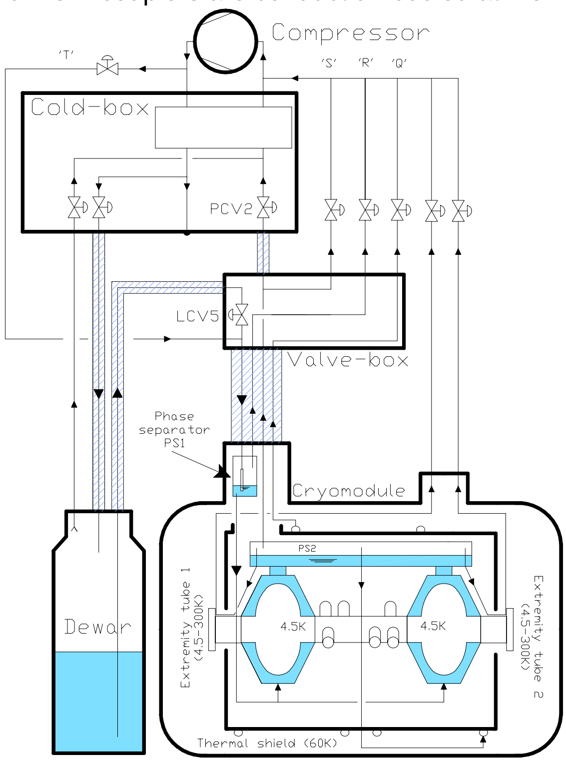

Fig. 2: Scheme of the S3HC cryogenic system.

The cryogenic source is a HELIAL 1000 refrigerator-liquefier manufactured by AIR LIQUIDE. The 500 l Dewar, the cryogenic transfer lines and the valve-box are also parts of the AIR LIQUIDE supply.

The commissioning of the cryogenic source without cavity took place in July 2002. The required liquefier performance at 4.5 K in mixed mode (refrigeration + LHe), and the measured one, are listed in Table 1. The cryo-source can be operated with a large safety margin, resulting in an increased reliability of the system.

Components	Load	Comments
2 RF cells	22 W	Directly in LHe bath
2 L-couplers	3 W	Cooled by conduction
4 T-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		

Table 1: Cryogenic load (4 MV/m, 400 mA, Q_o: 2 10^8), and cryo-source performances.

End of September the S3HC cryo-module was finally cooled down. The measured static losses (without RF) were in very good agreement with the estimates made during the design phase.

S3HC COMMISSIONING – WARM OPERATION

The installation of the S3HC module in the SLS storage ring took place during the shut down in the middle of June 2002. Until the end of September the cavity has then been operated in “warm mode”, which was already considered as a possible option in case of cryo-source failure. At room temperature, although the cavity is detuned between two revolution frequency side bands (f_{rev}=1MHz) and the induced voltage largely reduced, the beam can deposit a few 100 W into the cavity. The cavity is cooled by circulating some warm GHe from the compressor, or, as a backup solution, using some purified compressed air, directly in the cryo-module [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 the excitation of a Coupled Bunch Mode (CBM) instability generated by the fundamental mode of the warm third harmonic cavity. Better performance could eventually be achieved by improving the cavity gas cooling. At the same current level a second CBM, uncorrelated with the S3HC system, was observed as well. This second instability is probably related to the excitation of a high order mode in the main RF system, and could be eliminated with an improved tuning of the normal conducting 500 MHz cavities.

S3HC COMMISSIONING – COLD OPERATION

The S3HC “cold operation” started October 1st, just after the first cavity cool down.

In cold operation and when excited sufficiently far from resonance ($\delta f >> f_r/Q$), the voltage and the power losses are given by [1]:

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

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~2.10^8 the quality factor. The global R/Q of the cavity is 88.4 Ohms.

In the parking position, where the cavity frequency is set 500 kHz above the third harmonic ($f_r=3f_0$+500 kHz), the cavity is almost transparent to the beam and the induced voltage is negligible. In this position the stable operation of the storage ring is still limited to 200 mA because of the second CBM described above and correlated with a high order mode of the main RF system. With increased third harmonic voltage this instability no longer limits the SLS operating current because of the additional Landau damping introduced by the superconducting cavity. This increased stability is a consequence of the 20% empty RF buckets in the bunch train used to suppress ion trapping. Because of the empty gap, the beam loading in the S3HC cavity is not uniformly distributed along the bunch train, generating finally a bunch phase chirp.

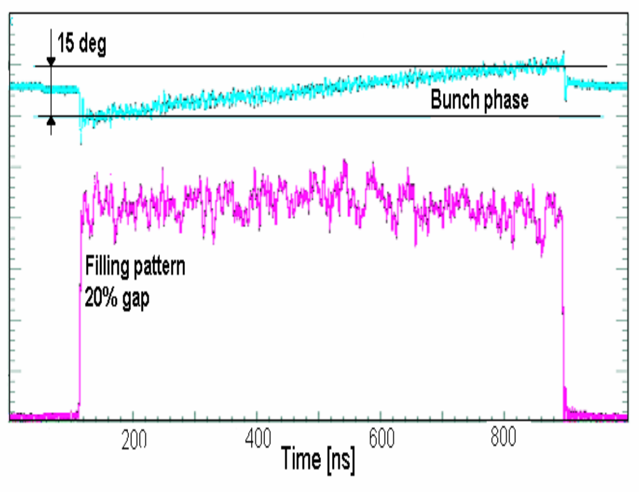

Fig. 3: Filling pattern with 20% empty RF buckets (200 *ns*/1μ*s*).: 300 mA - 2.08 MV main RF system – 557 KV in the harmonic system.

A measurement at 300 mA of the bunch phase spread along the train is shown on Fig. 3. This situation corresponds since October to the new nominal operation point of the SLS. At this current the system becomes longitudinaly unstable for voltages below 480 kV.
High-resolution streak camera measurements, as well as the damping of the residual CBM oscillation, have been performed at 320 mA for different tuning of the cavity. Fig. 4 shows the streak camera snap shot made at the maximum average elongation (factor ~3.2). As we can observe the phase shift along the bunch train increases considerably reaching 38 deg. Although showing globally an average of 42 ps, the bunch length changes along the train from a maximum of 66 ps to a minimum of 24 ps. A detailed analysis of each single bunch shape shows nevertheless that the charge distribution within each bunch deviates only marginally from a Gaussian.

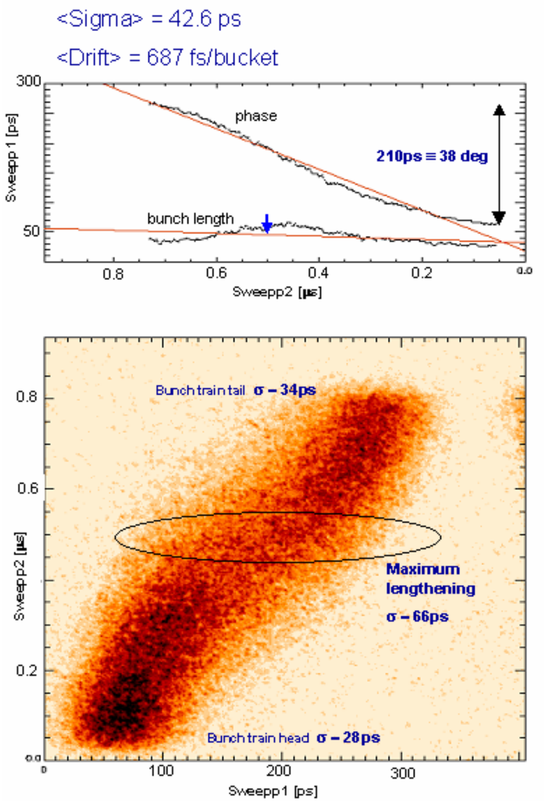

Fig. 4: Streak camera measurement at 320 mA and maximum average lengthening.

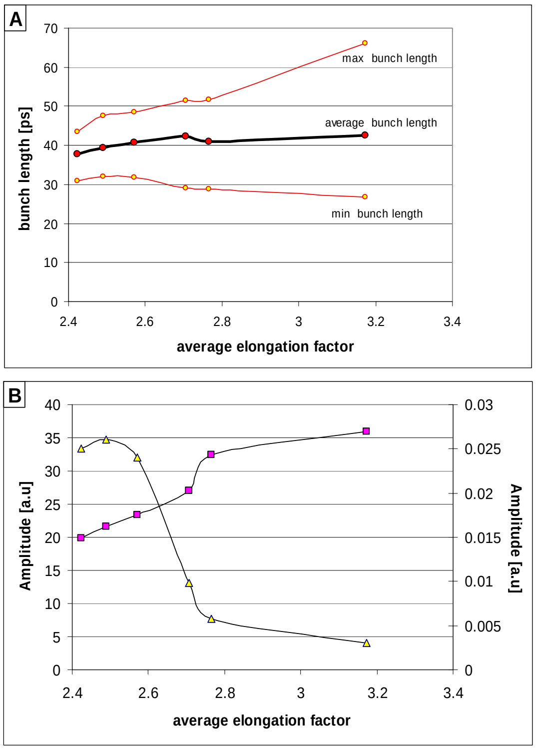

Fig. 5: Average bunch length (A), phase drift and CBM amplitude (B) at 320 mA.

In Fig. 5 the streak camera measurements, as well as the relative amplitude of the CBM are summarized versus the elongation factor calculated according to the measured average synchrotron frequency. As expected, we observed an increase of the length and phase dispersion versus the elongation, which results in additional damping of the CBM.

During the first days of commissioning of the S3HC cavity in lengthening mode, stable operation at the design current of 400 mA has been demonstrated. The measured lifetime at 400 mA was approximately 8 hours, a factor of two higher than the expected one without third harmonic system.

A systematic beam lifetime measurement versus the induced voltage in the superconducting cavity has been performed at 180 mA, below the CBM instability threshold, and with a main RF voltage of 2.08 MV (Fig. 6).

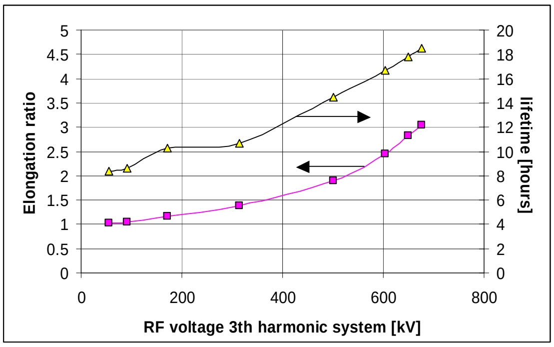

Fig. 6: 180 mA - 2.08 MV operation, average elongation ratio and lifetime versus S3HC voltage.

As shown in Fig. 6, the expected maximum elongation of a factor of 3 is reached with a voltage of ~690 kV. While increasing the voltage the lifetime progressively improves up to a factor 2.2.

CONCLUSIONS

The third harmonic superconducting system installed in the SLS storage ring significantly improved the machine performance in terms of current and lifetime. The dispersion in phase generated by the harmonic system was demonstrated to be an efficient way to longitudinally de-correlate the beam (additional Landau damping). This effect allowed the first 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.

AKNOWLEDGEMENTS

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 W. Gloor at PSI.

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