FIRST OPERATIONAL RESULTS OF THE 3RD HARMONIC SUPER CONDUCTING CAVITIES IN SLS AND ELETTRA

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Abstract

In both ELETTRA and the Swiss Light Source (SLS), a complementary 3rd harmonic (1.5 GHz) idle super-conducting RF system has been recently implemented and commissioned, in order to lengthen the bunches and therefore improve the Touschek dominated beam lifetime [1]. Here below we report on the commissioning results.

INTRODUCTION

The conceptual design and the fabrication of the cavity modules were realized within the framework of the SUPER-3HC collaboration including Sincrotrone Trieste, CEA/Saclay and PSI [2]. 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 [3,4]. It consists of two Nb/Cu cells, connected by a tube on which stand the couplers for the damping of the Higher Order Modes [5] (Fig. 1).

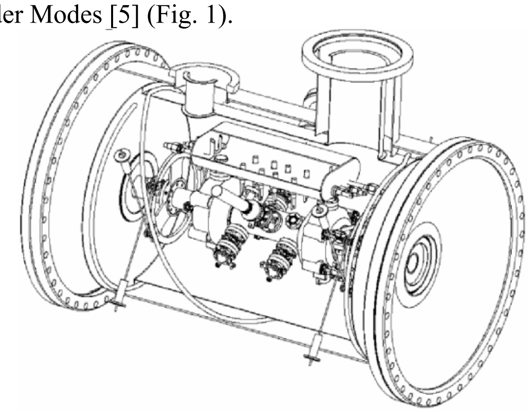

Figure 1: 3D view of the S3HC module, showing the liquid He tanks surrounding both cells and the six HOM couplers mounted on the central tube.

The maximum bunch lengthening (approximately a factor of 3) is achieved when the 3rd harmonic beam-induced voltage is about one third of the overall voltage produced by the main 500MHz RF system. The typical SLS operating conditions correspond to a main voltage of 2.4MV at 500 MHz and 800 kV (4 MV/m) at the third harmonic. Under these conditions one expects 2 - 3 times greater beam lifetime.

CRYOGENIC SYSTEM COMMISSIONING

ELETTRA and SLS chose a common approach for the cryogenic system that feeds liquid Helium into the cryo-module. This system, thoroughly described in [6], is based on the use of the HELIAL 1000 refrigerator-liquefier manufactured by the company AIR LIQUIDE. 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 cryo-source allows operation with a large safety margin that results in increased system reliability.

Table 1: Cryo-load with 4 MV/m gradient (Q_o=2 10^8) and 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 very good agreement with the anticipate values

S3HC COMMISSIONING

SLS Warm Operation

At room temperature, although the cavity is detuned between two revolution frequency side bands (f_0=1MHz) and the induced voltage largely reduced, the beam can deposit a few 100W into the cavity. The cavity is then cooled circulating some warm GHe from the compressor directly into the cryo-module, or as a backup solution using some purified compressed air [6]. 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 efficiency. At about the same current level a second CBM, related to the excitation of a HOM in the main RF system was also observed. This instability could be eliminated with an improved tuning of the main RF system [7].

SLS Cold Operation

In the SLS, the S3HC "cold operation" started on 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 induced RF voltage and the power losses are given by [1]:

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

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 parked position, when the cavity resonant frequency is set to 500kHz 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 CBM described above and correlated with an HOM of the main RF system. When the third harmonic RF voltage become larger the increased non-linearity of the global RF voltage generates additional Landau damping and the CBM instability no longer limits the operating current. This effects 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 a phase dispersion along the bunch train, which produces a broadening of the synchrotron frequency and therefore an increased Landau damping.

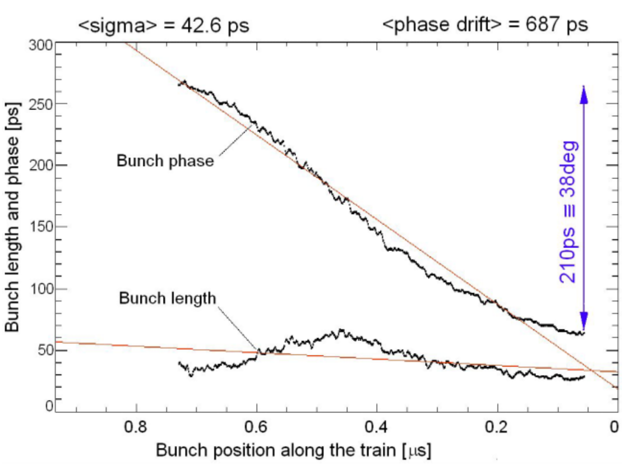

Figure 2: Streak camera measurement at 320mA. Bunch σ and phase in ps versus position in the bunch train.

Figure 2 shows a high resolution streak camera snap shot made at 320 mA for an average elongation factor of ~3. One can observe that the phase shift along the bunch train increases considerably and reaches 38deg. 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.

In Figure 3 the streak camera measurements, as well as the relative amplitude of the marginally excited CBM are plotted versus the elongation factor deduced from the measured average synchrotron frequency.

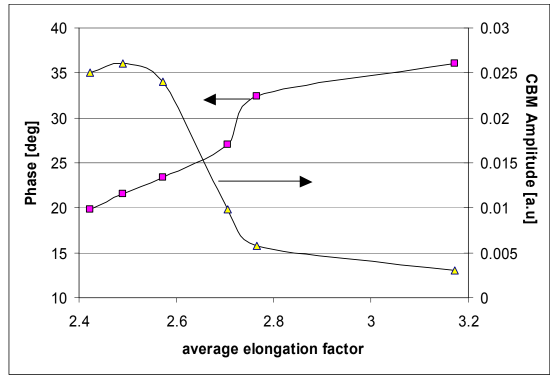

Figure 3: Phase drift and CBM amplitude at 320mA.

As expected, we can observe an increase of the phase drift versus bunch elongation that results in additional damping of the CBM.

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 4).

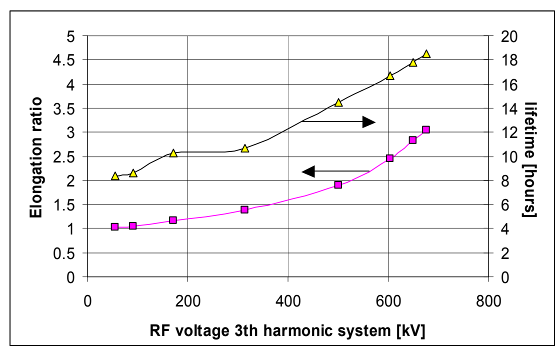

Figure 4:Average elongation ratio and lifetime versus S3HC voltage (180 mA – 2.08 MV operation).

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 higher than the expected one without the third harmonic system.

ELETTRA Warm Operation

The ELETTRA system was assembled during the summer 2002 shutdown. The commissioning of the cryogenic system lasted longer than expected due to some faulty components. Warm operation was required until

December, the cavity being cooled by a purified air flux. When the warm cavity is parked between two revolution harmonics the power deposited in the cavity by the detuned fundamental mode is sufficient to warm up the cavity at 2.0 GeV, 300 mA. This results in an interaction between the parked fundamental mode and the beam spectrum lines such that the operation mode at 2.0 GeV could not be established. Thus an unforeseen operation at 2.4 GeV, 140 mA, where the warm cavity is still transparent to the beam was necessary until December.

ELETTRA Cold Operation

On the 9th of January 2003 the cavity could be finally cooled down. The cryogenic system performance is beyond its specification similar to the SLS system.

The cold cavity is almost invisible to the beam when parked, with a negligible induced voltage. It does not influence injection at 0.9 GeV and energy ramping to 2.0/2.4 GeV. ELETTRA is more sensitive to CBM instabilities at low energies compared to the SLS and therefore the safety margin on the damping factor of the HOM couplers of S3HC is much smaller. We therefore stress that no effects of the HOMs of the S3HC have been observed at ELETTRA, for 300 mA, 2.0 GeV.

Before installing the S3HC cavity the user's operation mode of ELETTRA at 300 mA and 2.0 GeV was with a controlled longitudinal CBM oscillation at a phase amplitude of about 20-25 degrees. The 500 MHz RF voltage at ELETTRA attains presently 1,68 MV thus the corresponding voltage at the third harmonic should be 560 kV, which in turn corresponds to a detuning of 72 kHz for 300 mA of stored beam. A 10% gap in the bunch train is used to avoid ion trapping.

When tuning the S3HC towards the 3rd harmonic frequency, at 300 mA and 2.0 GeV, longitudinal coupled bunch instabilities are suppressed at a detuning of ~100 kHz, where the total 3rd harmonic voltage is ~400 kV. At 90 kHz, 440 kV voltage, that is 80% of the nominal value, a bunch lengthening factor between 2.5 and 3.0 is achieved. The lifetime with these conditions is 12 hours, which is almost twice the theoretical value. Comparison with measured values with a detuned S3HC are not possible, since the beam becomes longitudinally unstable.

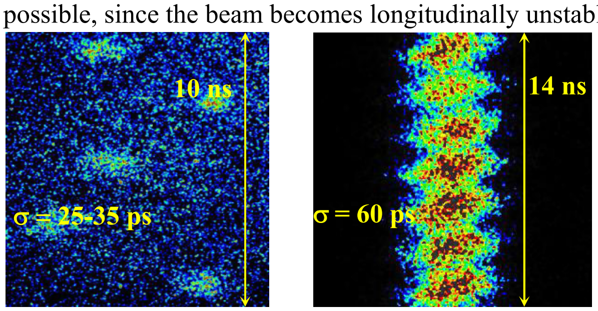

Figure 5: 250 mA, 2.0 GeV, streak camera images. On the left S3HC detuned, longitudinal oscillations present; on the right S3HC tuned, stable beam. Theoretical σ without S3HC is 18 ps.

At ELETTRA injection is performed once a day and the beam current decays in 24 hours from about 300 mA down to 100 mA. To keep constant the effect of the S3HC a voltage feedback has been implemented which acts on the tuning system of each cell. The feedback is opened at about 160 mA because, for lower currents, the S3HC frequency approaches the +3fs sideband; an instability is then observed causing beam loss.

Tuning the cavity close to the nominal voltage is not straightforward. The voltage increase, even for small tuning steps, is large and eventually activates the cavity over-voltage interlock. So far the cavity has not been tuned for a total voltage larger than 450 kV.

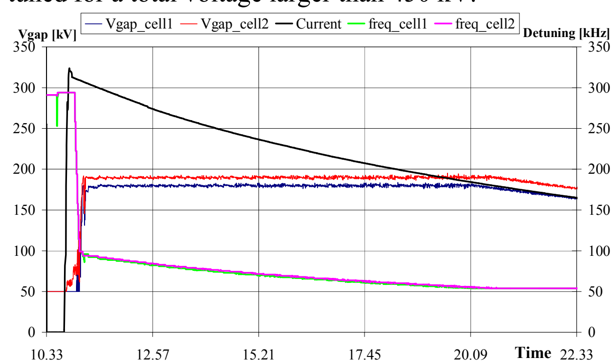

Figure 6: Voltage feedback operation; the measured voltage is 15% less than theory due to calibration errors.

Technological problems are still limiting cavity performance. A leak in the insulation vacuum of a cold helium gas line of the cryogenic plant caused an unstable behaviour of the system. Since mid March the tuning system of cell 1 is out of order; both problems will be sorted out during the next shutdown in June.

CONCLUSIONS

The third harmonic super-conducting system installed in the SLS storage ring significantly improved machine performance in terms of current and lifetime. The additional Landau damping generated by the harmonic system was demonstrated 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.

Also at ELETTRA the results are quite satisfactory, despite technological problems that are still limiting complete system operation. The cavity has been active during operation for users, allowing for the first time to store a beam free of longitudinal coupled bunch instabilities at 2.0 GeV, 300 mA. At the same time a lifetime increase close to a factor two has been observed.

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