THIRD HARMONIC SUPERCONDUCTING PASSIVE CAVITIES IN ELETTRA AND SLS

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Abstract

Two identical cryomodules Super-3HC have been installed in ELETTRA and SLS since mid of year 2002. For both machines these third harmonic superconducting systems, operating in bunch lengthening mode, improve performances in term of stability and lifetime.

The general design of the cryomodule was demonstrated to reach very tight specifications for HOMs damping, tuning resolution and maximum tuning range. Goals for accelerating fields, cryogenic losses, and vacuum were also reached with large margins. At ELETTRA some technological problems delayed for some months the complete system operation, whereas the SLS unit has caused no direct interlock trip since the end of the commissioning.

INTRODUCTION

The 2 Super-3HC cryomodules have now been operated for about one year on the synchrotron light sources SLS and ELETTRA. These 3rd harmonic superconducting cavities are used to lengthen the electron bunches and increase the corresponding beam lifetime dominated by the Touschek effect. In addition, the Landau damping effect allows the suppression of longitudinal instabilities of the beam. The Super-3HC RF structure is based on the SOLEIL cavity scaled to the 1.5 GHz frequency. It allows an efficient damping of the HOMs with superconducting loop couplers [1]. The passive cavities are powered by the electron beam, tuning their frequency towards the 3rd harmonic of the machine.

The Super-3HC project is collaboration between CEA, PSI, Sincrotrone Trieste, and CERN. The 2 cryomodules were developed, assembled, and tested by CEA Saclay. CERN fabricated the 2 sputtered Nb/Cu cavities at 1.5 GHz, and performed RF tests in vertical cryostats.

The project started end of 1999, just at the end of the SOLEIL cryomodule prototype development, [2]. Studies of the Super-3HC cryomodules have benefited from these first developments and results.

SPECIFICATIONS

The specifications are summarised in table 1. Super-3HC cryomodule is a small cryomodule with several RF ports producing a heat load to the cryogenic system. This is the reason why RF dissipations of the 1.5 GHz cavities don't need to be optimised by cooling at 1.8 K with a complex cryogenic system. At 4.5 K RF losses are about half the total cryogenic loads. The maximum total voltage of 1.0 MV/m corresponds to 5MV/m of accelerating gradient in each cell of the cavity. The maximum tuning range of ± 500 kHz is needed to park the cavities (at 4K or at 300K) between two harmonics of the machine. This is a very broad tuning range, and the distribution of the cavity cell thickness had to be optimised in order to reach these specifications without plastic deformation of the copper cavities walls that could damage the niobium coating. The tuning resolution of 10Hz could not be verified because these cavities are not loaded by a power coupler and are very sensitive to helium pressure variations. In operation, the frequency stability and resolution are quite satisfactory for both machines SLS and ELETTRA.

Table 1: Specifications

Frequency at 4K	1498.95 MHz
Working temperature	4.5 K
Maximum total voltage	1.0 MV
Q_0 vertical tests at 5MV/m and 4.5K	$2.\ 10^8$
Q_L loaded at 4MV/m and 4.4K	$1.\ 10^8$
Tuning range	± 500kHz
Tuning resolution	~ 10Hz
Longitudinal HOMs damping $f_R.R_{//}$	7.0 kΩ.GHz
Transverse HOMs damping $R_\perp$	130 kΩ/m

Among these specifications the tighter ones are the HOMs damping values. These requirements need to be stringently reached for ELETTRA. Super-3HC cavities shall not drive any coupled bunch instability on both injection mode at low energy and high current (0.9 GeV and 320 mA), and also during users' run at 2.0 GeV and 320 mA.

The maximum length of the cryomodule was limited to 1.1m, not including external tapers.

THE RF STRUCTURE

The optimisation of the HOMs damping was previously described [3]. The specifications for HOMs damping on Super-3HC cavities were about tighter than for SOLEIL cavities, and it was necessary to reoptimise the geometry of the dampers. This was made in 2 steps. Calculation of the optimum position of the coupler along the inner pipe of the RF structure was first made, and then the optimum geometry of the loop couplers was experimentally determined in a second step by direct measurements on a copper model cavity (see Fig.1).

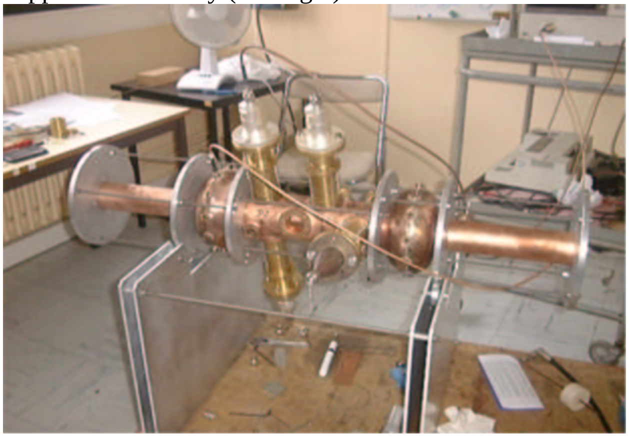

Figure 1: Model cavity for HOMs damping optimisation.

Ten transverse (F_{cutoff}=2.88 GHz) and ten longitudinal (F_{cutoff}=3.76 GHz) HOMs were carefully analysed to reach the specifications for each mode summarised in table 2:

Table 2: HOM damping specifications

F (MHz) Long.	R/Q (Ω)	Q_{max}	F (MHz) Trans	R/Q (Ω/m)	Q_{max}
2466	0.17	16000	1721	20.0	6500
2532	2.60	1100	1723	21.8	600
2606	11.0	240	1935	0.01	1.10^7
2695	0.12	22000	2056	255	510
2826	6.57	380	2103	27.6	4710
2979	8.61	270	2148	437	300
3084	1.93	1200	2303	10.1	12900
3180	0.30	7500	2503	11.1	11700
3358	0.86	2400	2712	63.8	2040
3594	0.43	4500	2865	10.3	12600

The final RF structure (see Fig.2) reaches damping requirements exept for one transverse mode at 2.15 GHz which is slightly above specifications: 145 kΩ/m for 130 kΩ/m specified. Four transverse modes couplers plus two longitudinal modes couplers are placed on the large inner tube between the two cells. Two other ports, one for each cell, were added on the inner tube to mount an incident power antenna for RF measurement in vertical cryostat. The two pick-up ports are placed on the smaller outer tubes of the structure.

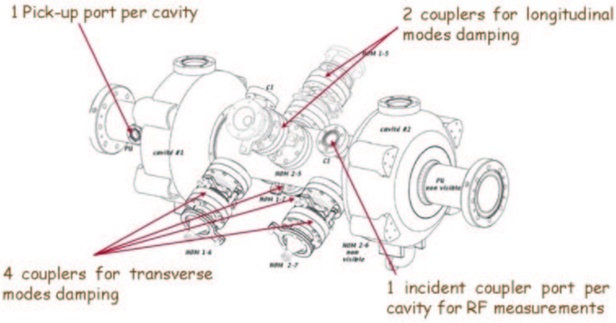

Figure 2: Super-3HC cavity with HOM couplers.

CAVITY MECHANICS

For a constant wall thickness of 3 mm the elastic limit of copper (σ_{max}=60 MPa) is reached for a detuning of ± 400 kHz lower than requirements (± 500 kHz). Large detuning of the cavities may be performed before each beam injection, at a frequency of about one injection per day. The accumulation of plastic deformation may cause blistering of the niobium coating. In order toincrease the deformation range within the plastic limit of the copper cavities, we determined a non constant profile of the cell walls that redistributes the stresses along the wall. An automatic cell generation code coupled to CASTEM was developed to optimise the wall thickness distribution. We found an optimum profile that avoids plastic deformation within the whole maximum tuning range of ± 600 kHz which is larger than specifications.

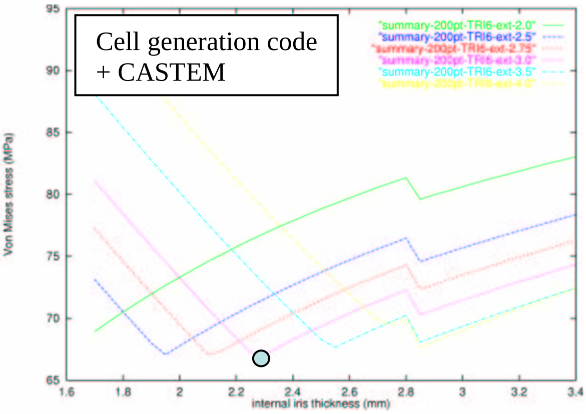

Figure 3: Von Mises stresses for a constant deformation of 0.2 mm applied on cavities of different thickness wall at the internal and external irises.

The sensitivity for tuning deformation was calculated and measured to be 3.2 MHz/mm. The calculated sensitivity of the frequency to helium pressure variations was comprised between 150 Hz/mbar (free cavity ends), and 35 Hz/mbar (fixed cavity ends). The measured sensitivity with the tuner mounted on the cavity is 65 Hz/mbar, which is in good agreement with previous calculations taking into account the flexibility of the tuner components.

CAVITY FABRICATION

The Nb/Cu cavities at 1.5 GHz were fabricated and tested in vertical cryostat at CERN (see Fig.4). The half cells were machined in copper rods in order to obtain the thickness distribution required.

Figure 4: Super-3HC cavity with 2 separate stainless steel helium tanks around the cells.

Electropolishing of the half cells was performed before electron beam welding, and a usual SUBU chemical polishing was then made on the final cavity to prepare the surface for the niobium sputtering [4]. A new small magnetron cathode was developed to sputter the niobium into the Super-3HC cavities, specially into the small outer tubes of diameter Φ61 mm.

RF tests were performed in vertical cryostat at 4.2 K. Measurement results are plotted on Fig.5.

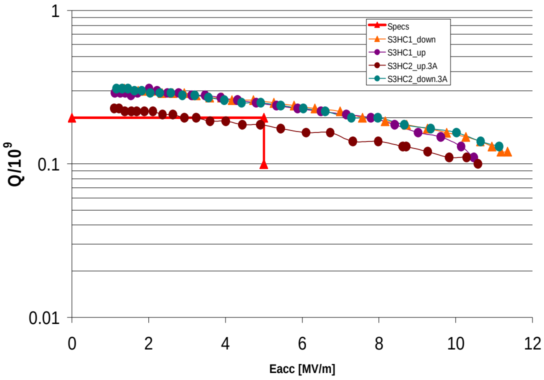

Figure 5: Q_0 measured as a function of the accelerating field for the 4 cells of the 2 cavities.

One of the cells showed a Q_0 slightly lower than the 3 others and than specifications. Nevertheless it was accepted by ELETTRA because its maximum accelerating field is far above requirements, and the helium liquefier which delivers more cryogenic power than needed, can easily compensate for the corresponding surplus of RF losses.

COLD TUNING SYSTEM

The tuner is the element that controls the accelerating voltage in the passive cavities by tuning them with respect to the 3rd harmonic frequency of the machine. This tuner is a smaller version of the SOLEIL tuning system [5], adapted to the smaller size of Super-3HC cryomodules. It is composed of a double lever mechanism (1/120), a screw-nut system, a gear box, and a stepping motor (see Fig.6).

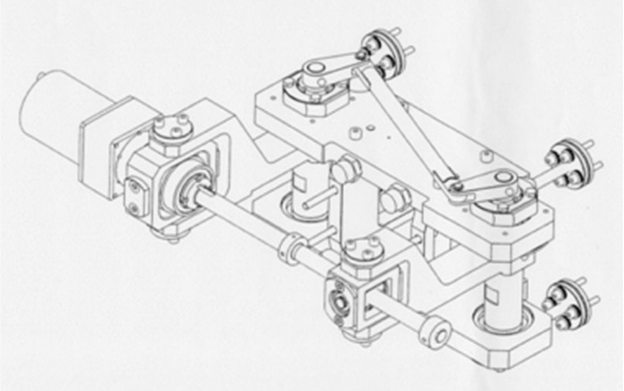

Figure 6: schematic view of the Super-3HC tuner

The whole system works in vacuum at 4K, and lubricating treatments were applied to the surfaces submitted to friction. The tuner is attached to the helium tank which is the mechanical reference.

The stiffness of the whole tuner was measured at room temperature higher than 1000kN/mm. Taking into account the stiffness of the helium tank (284 kN/mm calculated), on which the tuner is attached, the total mechanical stiffness of the tuning system is about 220 kN/mm, that is 10 times higher than the cavity stiffness.

CRYOMODULE ASSEMBLING

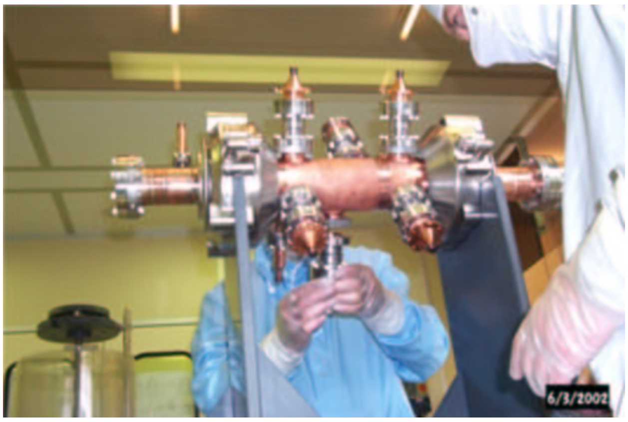

Figure 7: Super-3HC cavity assembling in clean room at Saclay

Before assembly, the cavities were high pressure rinsed at 100 bars with ultra-pure water in the class 100 clean room at Saclay. After cleaning, rinsing and drying in the same clean room, all components in contact with the cavity vacuum were mounted onto the cavity (see Fig.7).

The cold mass is a compact assembly of all components because of the small size of the cryomodule (Fig.8).

The vacuum tank is closed by concave domes in order to keep the length between the 2 external flanges within 1.1 meter (see Fig.9).

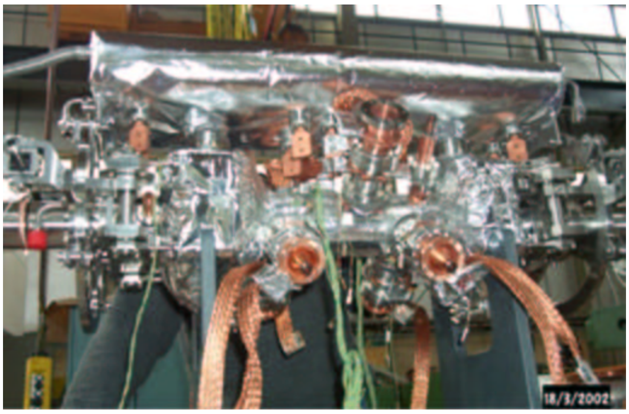

Figure 8: cold mass assembling in the workshop.

Cryogenic and RF tests were performed at Saclay prior to the delivery to the machines. These tests consisted in usual cryogenic measurements to determine the time needed to cool down and warm up, static and dynamic losses with RF on, thermal stability of the different couplers associated with their RF lines. RF measurements were also performed to determine the Q_{ext} of all couplers; a special care was taken to tune the notch filter of the dipolar modes couplers in order to reject the fundamental mode of the cavities. After measurement of the Q_0 curves the incident power cables were removed and the antennas were shortcut.

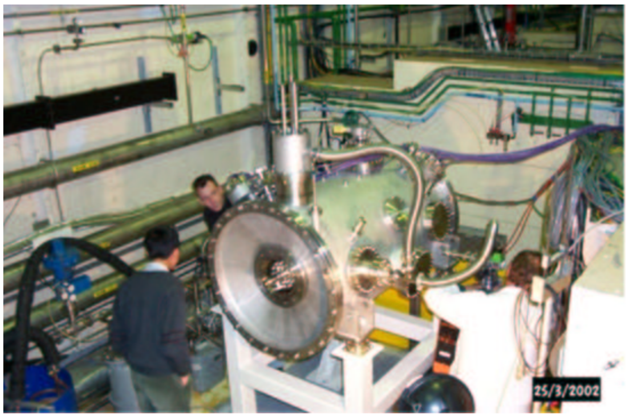

Figure 9: preparation of cryogenic and RF tests of the cryomodule at Saclay before delivery to the machine.

In operation on the machines, before injecting the beam we tuned the passive cavities using the dipolar HOM couplers. This was possible because the notch filters are not perfectly tuned and some fundamental power can be send by a power supply through the dipolar couplers (typical $Q_{ext} \sim 2\ 10^9$).

CRYOGENIC SYSTEM

A mixed liquefaction/refrigeration mode refrigerator was chosen to feed liquid helium into the cryomodules for both machines. The HELIAL 1000 liquefier manufactured by AIR LIQUIDE allows operation with a large safety margin as it is shown in table 3.

Table 3: estimated cryogenic loads with cavities at 4MV/m gradients and Q_0=2.10^8, and cryogenic source performance.

Components	**Loads**	**Comments**
2 RF cells	22 W	Directly in LHe bath
2 L-HOM couplers	3 W	Cooled by conduction
2 T-HOM couplers	8.5 W	Cooled by conduction
2 extrem. Tubes	0.2 W	With 2x0.05 g/s cold GHe
Static losses	5.1 W	With 0.071 g/s GHe in thermal shield at 60 K
Cryo-lines	6.5 W	
Total power needed at 4.5 K: 45.3 W refrigeration **With total GHe flow: 1.17 g/s = 5.2 l/h liquefaction**		
Specified power at 4.5 K: 65 W With specified liquefaction duty: 7.5 l/h		
Max measured power at 4.5 K: 150W refrigeration **With measured liquefaction duty: 9.5 l/h**		

The measured static losses were in good agreement with anticipated values.

SLS CRYOMODULE

We report here a summary of the first year operation at SLS which is described with more details in [6].

The first cryomodule was installed on SLS ring in June 2002 (see Fig.10).

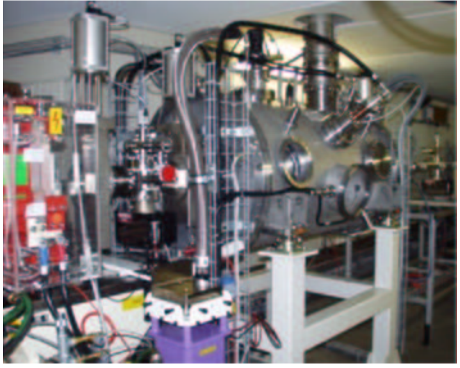

Figure 10: the cryomodule on SLS storage ring.

The cavities were kept at room temperature and detuned until September. Helium gas flow circulation was made in the internal cryogenic pipes in order to evacuate the power dissipated in the cells, and the insulating vacuum was pumped out. In these conditions the interaction between the fundamental mode of the warm cavity with the third harmonic limits the maximum current at 200 mA due to overheating of the cells.

The first cool down was performed on September 23rd. In the parked position, i.e 500 kHz above the third harmonic, the interaction between the beam and the superconducting cavities was negligible. No abnormal heating occurred on any internal component, and it was then possible to activate the cavities by tuning them closer to the third harmonic frequency of the machine. As expected, Landau damping suppressed the couple bunch mode instabilities that previously limited the current to

200 mA. It was then possible to increase the current to 400 mA. Stable operation at this maximum design current was demonstrated, with a lifetime about two times longer than the expected one without the harmonic cavities.

At 180 mA the expected elongation factor of 3 was demonstrated for a voltage of ~ 690 kV, with a corresponding lifetime increase of a factor 2.2.

Since the commissioning, stable users operation was performed at 300 mA with a reduced 3rd harmonic cavity voltage. No interlock trip was directly caused by the Super-3HC cryomodule during the first year of operation. Unfortunately, after one year of helium production, a turbine of the liquefier broke, setting operation at limited current, in a parked mode and at room temperature, until repair.

This Super-3HC cryomodule was the first demonstration of a Landau cavity on synchrotron radiation light source.

ELETTRA CRYOMODULE

In the following paragraphs we report a summary of the first operation of ELETTRA cryomodule which is described with more details in [7].

The ELETTRA cryomodule was implemented on the ring during the shutdown of August 2002 (see Fig.11)

Figure 11: the cryomodule on ELETTRA storage ring.

Warm operation in parked mode began in September 2002. Cooling of the cavities was delayed by the commissioning of the liquefier until January 2003.

When the warm cavity is parked between two revolution harmonics, the power deposited by the beam at 2.0 GeV and 300 mA, cannot be efficiently evacuated by the air circulation in the helium tank. This results in the warm up and the detuning of the cavity, which forbids the operation mode at 2.0 GeV.

When the cryomodule is warm, at 2.4 GeV and 180 mA the cavity can be tuned transparent to the beam. This operation mode is stable, and it was necessary to use it until the cooling of the cavity.

The cavity was cooled down on January 9th, and since the 16th it was possible to operate with beam and cold cavity. During the following period of commissioning several technical problems delayed the optimisation of the harmonic cavity operation.

Operational experience was gained with the system and since July the cavity has been routinely in cold operation during user's shift at 2.0 GeV.

The harmonic cavities don't influence the beam injection at 0.9 GeV and 320 mA, and the energy ramping to 2.0 GeV (or 2.4 GeV). No instability generated by the harmonic system was observed during these injection and ramping periods, demonstrating the HOMs damping efficiency of the SOLEIL type RF structure. The Landau damping generated by the 3rd harmonic system allows to suppress the longitudinal coupled bunch instabilities. For the first time ELETTRA could deliver to users a 320 mA, 2.0 GeV longitudinally completely stable beam. A mean bunch elongation factor of 4 was demonstrated, with corresponding increase of the beam lifetime by a factor of 3.5.

CONCLUSIONS

Super-3HC is the first demonstration of a superconducting Landau damping cavity for synchrotron light sources. It has been successfully tested and operated both at SLS and ELETTRA. The Landau damping effect of this system is a very efficient tool to suppress longitudinal coupled bunch instabilities. Excellent results were also achieved in terms of bunch lengthening and beam lifetime. The very good HOM damping efficiency of the SOLEIL RF type structure was demonstrated, and no unstable interaction with the beam was observed.

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