PERFORMANCE OF THE 3RD HARMONIC SUPERCONDUCTING CAVITY AT ELETTRA

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Abstract

A superconducting cavity designed to operate at ELETTRA at 1.5 GHz, the third harmonic of the main RF frequency, has been constructed in the frame of the SUPER-3HC collaboration with CEA, SLS and CERN. The 2-cells Nb-Cu cavity, derived from the SOLEIL design, was installed on the ELETTRA storage ring during the summer 2002 shutdown. After a commissioning period it was operated for the first time during user shifts in February 2003. Activation of the 3rd harmonic cavity allows to have a longitudinally stable beam at 2.0 GeV, 320 mA, due to the Landau damping induced by the cavity. At the same time the beam lifetime is increased by more than a factor two. The cavity is now routinely operated during user shifts at 2.0 GeV. We will discuss the performance of the cavity and of the cryogenic plant along with the first results of the beam-cavity interaction studies.

INTRODUCTION

The third generation synchrotron radiation source ELETTRA, located at Trieste, Italy, started its operation in 1993. It is a 2.0 (to 2.4) GeV, 320 (140) mA users' facility, operating 24 hours a day for about 6500 hours a year (5000 hours for users). As for other light sources of the same generation an increase of the brightness of the radiation, by reducing the beam emittance, is an important challenge for ELETTRA. For intermediate energy light sources a further critical issue is the beam lifetime that is dominated by large angle intrabeam elastic scattering, i.e. the Touschek effect. Consequently a reduction of the emittance also leads to an increase in the bunch density and therefore to a reduction in lifetime.

The installation of a cavity operating at the 3rd harmonic of the main RF frequency was then decided to lengthen the electron bunches and increase correspondingly the beam lifetime without affecting the emittance. Given the boundary conditions at ELETTRA, a superconducting passive cavity was the solution chosen for the 3rd harmonic cavity. The SUPER-3HC collaboration was then established in 1999 with the Paul Scherrer Institut, interested in the same solution for the Swiss Light Source, and the CEA-Saclay, interested in the design of a new structure at 1.5 GHz based on the 350 MHz SOLEIL cavity design [1]. The optimised scaling to 1.5 GHz resulting from the design phase was validated on a copper model. The Nb-Cu two-cell cavity was built and tested in collaboration with CERN. Assembling (fig. 1) in the cryomodule and testing followed at CEA [2].

The design of the cryogenic plant has been also part of the collaboration. A refrigerator working in mixed liquefaction/refrigeration mode was chosen as the cryogenic source.

The cavity and the cryogenic plant were installed at ELETTRA during the 2002 Summer shutdown. A commissioning period followed, first for the cryogenic plant then for the cavity with beam. Routine operation of the cavity started in July 2003. Beside improving significantly the beam lifetime, it allows the complete suppression of all longitudinal coupled bunch instabilities.

Fig. 1: SUPER-3HC cavity during assembling at CEA.

SUPER-3HC PERFORMANCE

The total refrigeration power needed at 4.5 K is 45.3 W. The warm helium gas return flow from the two extremity tubes and from the thermal shield of the cryomodule amounts to 0.171 g/s, which corresponds to a liquefaction duty of 5.2 l/h. By including a 50% safety margin, a refrigeration power of 65 W with at the same time a liquefaction capability of 7.5 l/h was specified [3].

The HELIAL 1000 refrigerator-liquefier manufactured by the company AIR LIQUIDE was chosen for the system. A refrigeration power of 135 W was measured during the acceptance tests, while the liquefaction duty attained to more than 30 l/h. The refrigerator can sustain the full load of the operating cavity maintaining still a liquefaction capability between 10 and 20 l/h.

The cavity cells have met the specifications both in the vertical cryostat test at CERN ($Q_0 = 2\ 10^8$ at 4.5 K and 5 MV/m) and in the loaded test in the cryomodule at Saclay (Q loaded larger than $1\ 10^8$ at Eacc 5 MV/m) [4].

The nominal 3rd harmonic voltage for ELETTRA is 600 kV, since the nominal voltage provided by the 500 MHz normal conducting RF cavities is 1.8 MV. For a beam current intensity of 320 mA the cells are tuned to +60 kHz from the 3rd harmonic; for this tuning the voltage in the cavities exceeds the nominal value.

In the design of the RF structure particular care was given to achieve the specifications in terms of Higher Order Modes (HOM) damping. The Q_{ext} of the HOM measured in the laboratory showed that the quite stringent ELETTRA specifications were met, almost without safety margins. A very successful result of the design is that the SUPER-3HC structure does not drive any unstable coupled bunch oscillation of the beam at ELETTRA. This is true both for the users' operation mode at 2.0 GeV, 320 mA, and for the injection energy, 0.9 GeV. There is no limitation coming from the harmonic cavity also during the energy ramp to the final energy.

Table 1: SUPER-3HC cavity performance.

3rd Harmonic Frequency	1498.955 MHz
Cavity tuning @ 320 mA	1499.015 MHz
Detuning, Δf @ 320 mA	+ 60 kHz
Nominal 3rd harm. voltage	600 kV
Accelerating field gradient	3.0 MV/m
Vacuum pressure @ 320 mA	< 5 10^{-9} mbar
Parking position	1499.200 MHz
HOMs excited by the beam	None
Longitudinal HOM damping spec	f_r*$R_{//}$<7.0 kΩ*GHz
Transverse HOM damping spec	$R_\perp$ < 130 kΩ/m

OPERATING EXPERIENCE

During the commissioning period of the cryogenic system, from October to December 2002, the cavity remained at room temperature. In this operation mode, foreseen as a back-up solution in case of cryogenic plant downtime periods, the cavity is cooled by Helium gas flow or, as an alternative, by purified compressed air. In warm operation the cavity is parked in-between two revolution frequencies, to minimize the interaction with the beam. However the beam deposits in the structure still a few 100 W. At high current the interaction with the beam spectrum (Coupled Bunch Modes, CBM) is sufficient to overheat the cavity, which frequency decreases enhancing the interaction with the CBM 427, at lower frequency. Since this effect can be compensated at 2.4 GeV, 140 mA, but not at 2.0 GeV, 320 mA, beam time was rescheduled at 2.4 GeV until December.

After commissioning the cryogenic system, on the 16th of January 2003 it was possible to operate for the first time the storage ring with the cold cavity. The first successful achivement was the demonstration that in the parking position the cold cavity is invisible to the beam.

A period of commissioning with beam followed until July, during which great operational experience with the system has been gained, while solving successfully quite tricky problems, like a leak in the insulation vacuum of a cold Helium gas line and the malfunctioning of one tuning system, replaced by CEA with an improved version. The cryogenic plant has proved to be quite reliable, even if it suffered from a few stops, mainly caused by electrical power interruption. To overcome the problem, the whole system will be soon connected to the UPS of the laboratory, upgraded to sustain also this load.

Since July the cavity is routinely in operation during users' shift at 2.0 GeV. The activation of the cavity is optimized to fit the ELETTRA refill process that is divided in injection at 0.9 GeV, energy ramping of the storage ring to 2.0 GeV, delivery of the beam to the users at 2.0 GeV. The harmonic voltage build-up by increasing the accumulated current during injecton sometimes may reduce the injection efficiency, therefore the cavity is kept parked during injection for maximum reliability in the injection procedure. The cavity is then activated while correcting the beam orbit at 2.0 GeV. Before tuning it to the operating position of +60 kHz the transverse multibunch feedbacks, vertical and horizontal, are activated. At this point the beam is strongly unstable in the longitudinal plane, but the instability is suppressed after tuning the harmonic cavity. Hence for the first time a 320 mA, 2.0 GeV longitudinally completely stable beam is delivered to the ELETTRA users.

A voltage control loop is then activated which keeps the voltage constant by further tuning the cavity to follow the beam current decay. The slow, software controlled, loop is opened at +50 kHz as a safety measure, since for detunings smaller than about +45 kHz instabilities may cause a beam loss. The cryogenic plant can easily manage the rather fast power load changes in the refill process and between parked and tuned cavity, as well as the slow power decrease when the voltage control loop is opened.

BEAM EXPERIMENTS

Before the installation of the harmonic cavity, ELETTRA was operated with a controlled excitation (coherent oscillation) of a longitudinal coupled bunch mode (91 or 363). A fine tuning of the temperature of one of the 500 MHz RF cavities was required to keep this controlled excitation, which prevented the raise of transverse multibunch instabilities - before the installation of the feedbacks - and at the same time gave some improvement in beam lifetime. By properly keeping under control the instability, the deterioration of the beam emittance was kept to a level acceptable to the users.

Discussing the effect of the 3rd harmonic cavity on the beam, we have always to bear in mind that in the starting condition (2.0 GeV, 320 mA and harmonic cavity parked) the beam is now transversely stable, thanks to the feedbacks, but still longitudinally unstable, with the correlated increase in lifetime due to the bunch dilution.

A typical activation process of the SUPER-3HC cavity is shown in fig. 2. The upper plot shows the synchrotron frequency and the related average elongation factor of the bunches versus the cavity detuning; the lower plot shows the beam lifetime and the oscillation amplitude of the CBM 363 versus the elongation factor. When the cavity is parked, CBM 363 amplitude is higher than 20º and the lifetime is 19.7 hours, due to the strong instability. The effect of the 3rd harmonic cavity starts to appear at an elongation factor of 1.4 (detuning at this point is +85 kHz), where the CBM 363 starts to be damped. The landau damping effect increases until the elongation factor reaches the value 3, at that point the beam becomes longitudinally stable. The measured lifetime is 26.7 hrs, that is 3.5 times the theoretical lifetime for this storage ring optics, i.e. 7.7 hours.

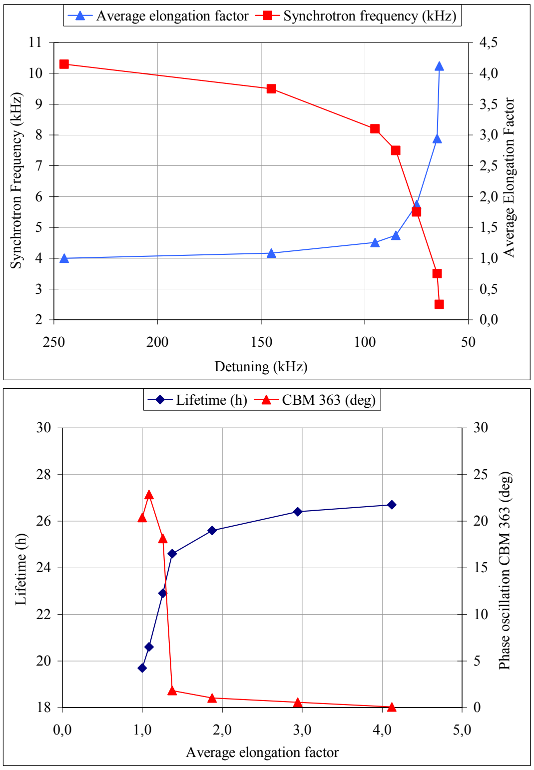

Fig. 2: Lifetime and CBM 363 vs the elongation factor.

The effect of the activation of the 3rd harmonic cavity on the beam current decay is shown in figure 3, where we compare a day with the 3rd harmonic tuned (beam stable longitudinally) to a day when it is parked (controlled longitudinal excitation). The final current, before dumping the beam, doubles when the cavity is active.

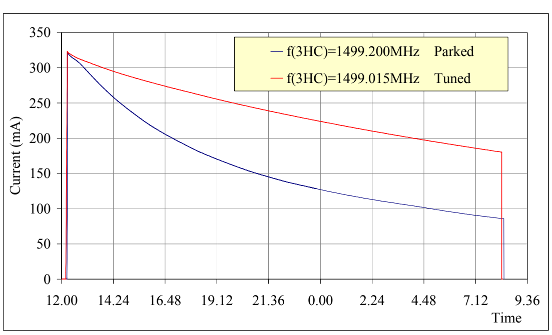

Fig. 3: Beam current decay with SUPER-3HC active (red) and parked (blue).

Two streak camera images taken at 250 mA, 2.0 GeV are shown in figure 4. On the left the cavity is parked and the beam is performing a coherent longitudinal oscillation. The length of the slightly diluted bunches is between 25 to 35 ps. On the right the cavity is activated and the bunch train is stable. The bunch length attains 60 ps, that is about three times the theoretical bunch length without SUPER-3HC, i.e. 18 ps.

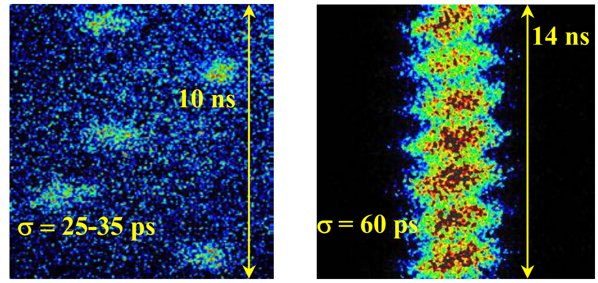

Fig. 4: On the left, unstable beam when the cavity is parked, on the right stable beam when the cavity is active.

Measurements with the streak camera allow also to characterize the phase modulation along the bunch train when a gap is present. At ELETTRA a gap of about 43 subsequent empty buckets in the 432 buckets of the ring (10%, 86 ns) allows to clear trapped ions. This 10% gap induces a phase modulation along the bunch train. Figure 5 shows that, for the minimum detuning of +60 kHz at 320 mA, the phase shift between the first and the last bunch in the train is about 30 degrees. The bunch length changes from 32 ps to 76 ps, with an average value of about 55 ps, that is three times the value without SUPER-3HC (18 ps).

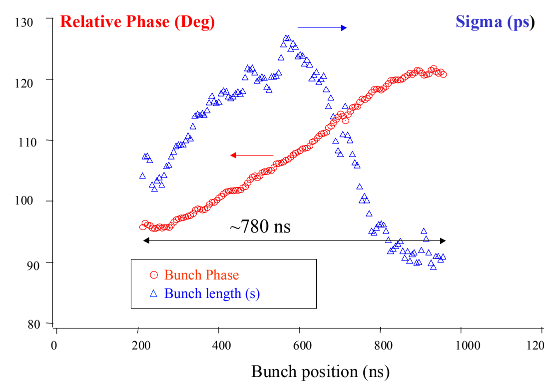

Fig. 5: Phase Modulation along the bunch train.

CONCLUSIONS

The superconducting 3rd harmonic cavity has been successfully tested at ELETTRA. Excellent results have been achieved in terms of beam lifetime improvement, which has been measured up to more than three times the theoretical value, and landau damping of the longitudinal instabilities. The cavity itself does not cause any unstable interaction with the beam.

The SUPER-3HC cavity is now running routinely during users' operation, with a relevant contribution to the increase in brightness and integrated flux of the light source.

REFERENCES

[1] M. Svandrlik et al, EPAC2000, p. 2052.
[2] P. Bosland et al., this workshop.
[3] P. Marchand et al., EPAC2002, p. 2268
[4] P. Bosland et al, EPAC2002, p.2217.