FIRST YEAR OF OPERATION OF SUPER-3HC AT ELETTRA

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Abstract

Since July 2003 a superconducting third harmonic cavity has been in routine operation at ELETTRA. When the cavity is activated the stored electron bunches are lengthened by about a factor of three. The related longitudinal Landau damping has allowed first time operation at 320 mA, 2.0 GeV with a beam completely free of longitudinal coupled bunch instabilities. With the cavity active the lifetime at 320 mA, 2.0 GeV is three times the theoretical value for nominal bunch length. The increase in beam stability and lifetime contributed significantly to enhance the brightness and the integrated flux of the source. We will discuss the operating experience with the superconducting cavity and the cryogenic system, analysing the impact of the new system on machine operation and uptime. We will also report on the characterization of the cavity performance for different filling patterns of the storage ring and relate the results to preliminary beam-cavity interaction studies.

INTRODUCTION

A third harmonic superconducting passive cavity was installed in 2002 in the storage ring of the third generation synchrotron radiation source ELETTRA. The purpose of this installation has been to lengthen the electron bunches and increase correspondingly the beam lifetime without affecting the emittance; at the same time Landau damping of the longitudinal coupled bunch instabilities is expected.

The superconducting cavity has been constructed in the frame of the SUPER-3HC (3HC) collaboration 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 Nb-Cu two-cell cavity was built and tested in collaboration with CERN. Assembling in the cryomodule and testing followed at CEA [2]. The cavity and the cryogenic plant were installed at ELETTRA during the 2002 summer shutdown. A commissioning period followed, first for the cryogenic source - a refrigerator working in mixed liquefaction/refrigeration mode - then for the cavity with beam. Routine operation of the cavity started in July 2003.

The cavity significantly improves the beam lifetime and allows curing all longitudinal coupled bunch instabilities. The beam-cavity interaction is influenced by the filling pattern of the storage ring, as expected. Extensive studies of this effect have been carried out, allowing identifying the optimum filling pattern of the ring for user's operation.

SYSTEM PERFORMANCE

During the first year of operation of the system the general reliability has been very good. After gaining the necessary operating experience with the system and after defining properly the maintenance procedures, stops of the cryogenic plant are almost exclusively caused by electricity power interruptions. However all other storage ring systems are stopped in this case. From July 2003 to June 2004 only one event of user's downtime caused by 3HC was registered, in January. In that occasion the cryogenic plant was stopped for about 12 hours after a fault of the insulation vacuum pump of the valve-box. This vacuum system was replaced with a fail-safe one in the following shutdown.

Full operability of the cavity has been limited in 2003 by its frequency tuning system, which is installed inside the cryomodule, in vacuum and at cold temperature. Each cell has its own system; two malfunctions, in March and November 2003, were registered for the system of cell 1. After the complete replacement of motors and gear-boxes with improved components, performed in January 2004 by CEA experts, the system is behaving well. However duration tests performed at Saclay showed that the gear boxes could suffer from overheating after more than 150,000 motor turns [3], equivalent to more than 3 years of operation at ELETTRA. While CEA is studying an improved solution for the tuning system, to be installed outside of the cryomodule, at ELETTRA we are limiting the motor turns to what is strictly necessary for system operation. This has implied also to find a parking position for the cavity during the refill process (injection of 320 mA at 0.9 GeV and energy ramping to 2.0 GeV) closer to the operating position than it was before.

Since January 2004 the 3HC cavity is in fact tuned during the refill at the frequency f_{3HC} = 1499.050 MHz, that is 92 kHz above the 3rd harmonic frequency, f_{3RF}=1498.958MHz; before it was parked at +242 kHz. After ramping 320 mA to 2.0 GeV the cavity is then moved to the working frequency, 1499.020 MHz, that is $\Delta f = f_{3HC} - f_{3RF}$ = +62 kHz. Since longitudinal stability is already obtained at Δf = 100 kHz, the whole refill process is performed with longitudinal stable beam and active transverse feedbacks.

3HC has allowed to increase the interval between two subsequent refills from 24 to 36 hours. In 36 hours the beam current decays from 320 mA down to roughly 115 mA (fig. 1). During this decay the cavity frequency is now kept fixed, compared to 2003 when a voltage control loop was active, in order to minimize activations of the tuning system. With an effective filling of 96%, newly set as the result of the optimisation studies discussed in the next section, the lifetime at 2.0 GeV, 320 mA, attains now

22-23 hours, for 70 ps long, slightly overstreched bunches.

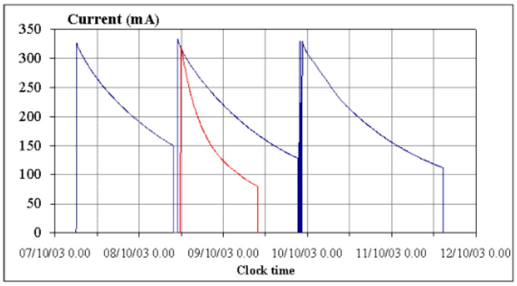


Figure 1: blue line, with 3HC 36 hours between refills, only 3 refills in 5 days operation; red line, shows one day without 3HC, for comparison.

MACHINE FILLING STUDIES

ELETTRA has operated for several years with an empty gap in the bunch train for ion clearing. Before 3HC the gap included about 43 contiguous empty buckets (~10%, 86ns) in the 432 buckets of the ring.

The gap in the filling pattern induces a beam loading in the passive third harmonic cavity, which results in a phase modulation along the bunch train [4]. Thus, each bunch samples a different harmonic voltage according to its own phase and, as a consequence, also the rms bunch length is modulated. Figure 2 shows the results of a streak camera measurement for a beam current of 315 mA at 2 GeV with a 10% gap. The bunch relative phase (left) and the rms bunch length (right) along the bunch train are plotted for six different 3HC positions, from 1499.060 MHz (Δf = +102 kHz) to 1499.015 MHz (Δf = + 57kHz).

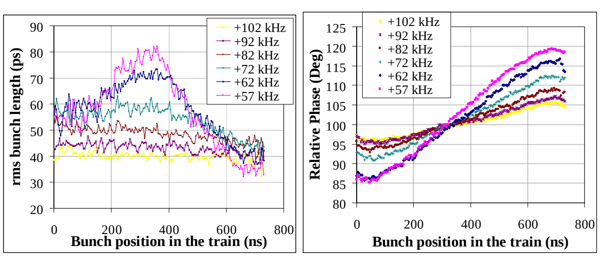


Figure 2: Phase shift and rms bunch length along the bunch train at 315mA, 2.0GeV for an empty gap ~ 10%.

For maximum tuning (Δf = 57kHz) the phase shift between the first and the last bunch is about 35 deg, while the rms bunch length ranges from 35ps at the end of the train to 80ps in the middle of the train. The average value is about 62ps, i.e. three times the zero current rms bunch length (21ps).

The global effect is thus reduced compared to the bunch lengthening of more than a factor 4 which is expected for uniform filling [5]. Of course this is also a limiting factor for the gain in beam lifetime. However the spread of the bunch synchrotron frequency produced by an empty gap [6] contributes to the Landau damping effect of 3HC, which cures the longitudinal instabilities of the beam.

Several experiments have been therefore carried out for different fillings, from uniform 100% filling (no gap) to 70% filling (~129 empty buckets, 258 ns gap). Amplitude of coupled bunch modes, phase shift, bunch length and lifetime have been measured for each filling.

The interaction between filling and landau damping can be understood from Figure 3, where the amplitude of the coupled bunch mode (CBM) oscillations is shown for four different fillings: 70%, 80%, 90%, 100%. When 3HC is almost parked (f_{3HC} = 1499.150 MHz, i.e. Δf = 192 kHz), the beam is more unstable for smaller gaps; in fact for 100% filling the CBM oscillation reaches 25°. By tuning the 3HC the harmonic voltage increases and the CBM oscillations are progressively damped; for smaller gaps the damping process is faster. For 100 % filling the beam is already stable at Δf = 102 kHz, while for 70% filling the unstable oscillations, quite low when 3HC is parked and even lower than 1° as the cavity is progressively activated, can not be damped until 3HC is tuned at Δf ~ 67kHz.

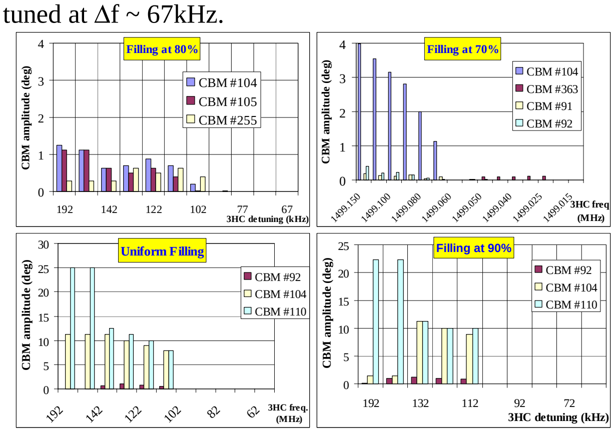


Figure 3: Landau damping for different filling patterns

It is evident that the Landau damping effect is influenced by the different contribution of the increasing gap width and of the average bunch length, which is reduced as the gap increases, as shown in figure 4. The phase shift between head and tail of the bunch train is shown on the left as a function of the cavity detuning, starting from the detuning where the beam reaches longitudinal stability. While the phase shift is almost negligible for uniform filling, it becomes already significant for 98% filling, at Δf =62 kHz about 7°, and it increases rapidly to 20° for 96% and even more for larger gaps. This phase shift significantly affects the rms bunch length, averaged along the train. For the same detuning, in the plot on the right it reaches almost 100 ps for uniform filling and only slightly more than 40ps for 70% filling.

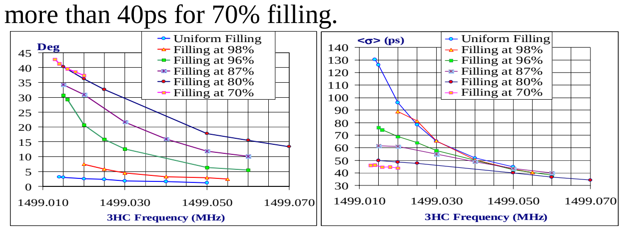
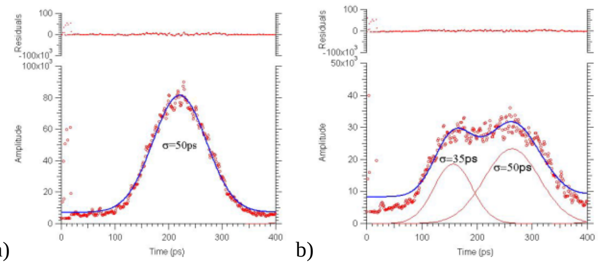


Figure 4: Head-tail phase shift and rms bunch length averaged on the bunch train vs. 3HC detuning.

With the ESRF tracking code [7] we have found that the optimum 3HC detuning in case of uniform filling at 320 mA is Δf = 77kHz (f_{3HC}=1499.035MHz). Beyond the optimum detuning the code foresees that the bunch profile is overstretched; accordingly the lifetime should get worse until the growing instability eventually kills the beam. Figure 5 shows the bunch profile measured in case of uniform filling for larger (a) and lower (b) detuning than the optimum.



a) b)

Figure 5: a) Δf=+82 kHz: the bunch is lengthened and not overstretched; b) Δf=+62 kHz: the bunch is overstretched. Good confidence of fitting is demonstrated by residuals.

If we simulate fractional fillings, we find that the modulation in the bunch lengthening overstretches the central bunches already before reaching Δf = 77kHz. Therefore, in all our experiments we entered in the overstretching regime that explains the large rms bunch length measured at small detuning. In fact in this condition the bunch profile is better fitted by the sum of two gaussian waveforms (fig. 5b). Unexpectedly, for all fractional filling patterns set in our experiments, we registered an improvement in the beam lifetime during the first overstretching phase. Only beyond the detuning of Δf = 62kHz (at 320mA) the lifetime decays to a few hours; beam is suddenly lost by further tuning 3HC towards f_{3RF}.

In Figure 6 we present the measurements of the maximum value of lifetime obtained at 320mA when 3HC is tuned to 1499.020MHz (Δf = 62kHz) for different fractional fillings. Several new components have been installed in the ELETTRA storage ring during the first part of 2004, thus the machine vacuum conditioning was not yet complete when performing the measurement.

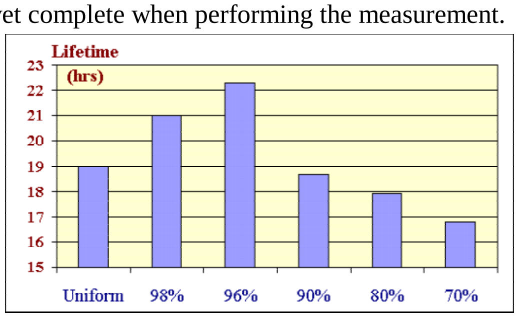


Figure 6: Lifetime at 320mA with 3HC tuned to 1499.020MHz for different filling patterns.

The best performance in terms of lifetime is obtained with a fractional filling of 96%. By further increasing the filling, the maximum attained lifetime is lower, suggesting that the optimum setting for ELETTRA requires a small amount of "empty gap". The effective fractional filling at 96% is now taken as the new standard filling pattern for User's Operation Mode (320mA, 2.0GeV). In this condition 3HC is usually tuned from 1499.050MHz (Δf=92kHz) to 1499.020MHz (Δf=62kHz).

CONCLUSIONS

The superconducting third harmonic cavity has now been in routine operation at ELETTRA for one year. It has contributed in improving the beam stability and lifetime, since it allows complete suppression of the longitudinal CBM instabilities and it allows refilling the ring every 36 hours, instead of every 24. The cryogenic plant has proven to be very reliable, but it requires constant maintenance and surveillance, since in case of faults downtimes may be rather long.

The cavity is operated at a detuning of Δf = 62kHz, where the bunches are slightly overstretched (70ps) and where we measure the larger value of lifetime for the present machine conditions (22-23 hours at 320 mA). The behaviour of the cavity has been extensively studied for different fillings of the storage ring, leading to determine an optimum filling of 96%. Further studies will be carried out in order to fully understand the related phenomena, also with the help of tracking simulation codes.

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REFERENCES

[1] M. Svandrlik et al, "The SUPER-3HC Project: An Idle Superconducting Harmonic Cavity for Bunch Length Manipulation" EPAC2000, Vienna, p. 2052.

[2] P. Bosland et al., "Third Harmonic Superconducting Passive Cavities in ELETTRA and SLS", SRF 2003, Travemunde, September 2003.

[3] P. Bosland, private communication.

[4] J. Byrd et al., "Transient Beam Loading Effects in Harmonic RF Systems for Light Sources", Phys, Rev. ST Accel. Beams, vol. 5, 09001, 2002.

[5] P. Marchand, "Possible Upgrading of the SLS RF system for Improving the Beam Lifetime", PAC99 New York, p.989.

[6] O.Naumann, "Landau Damping of Longitudinal Multibunch Instabilities in Electron Storage Rings", PhD Thesis, Univ. of Berlin, 1999.

[7] V. Serriere, "Longitudinal Beam Dynamics in Electron Storage Rings with a Harmonic RF System for Bunch Lengthening", PhD Thesis, Univ. of Paris XI, 2002.