# Investigation of the Higher Order Modes in the ELETTRA Cavities.

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*Abstract*

An important task of the commissioning of the ELETTRA Synchrotron Light Source was the exploration of the modes in the RF accelerating cavities, which can cause instabilities if they are excited by the beam. An intensive measurement program has thus been performed on the cavities under various operating conditions. An important goal was to verify if, as expected, the coupling of the dangerous cavity modes to the beam can be avoided by changing the cavity reference temperature and consequently the working point of the external mechanical frequency tuning system.

## 1. INTRODUCTION

For the multibunch operation mode for ELETTRA a maximum of 432 bunches is stored with a nominal current of 400 mA [1], [2]. The high number of bunches requires a careful investigation of the probability to drive multibunch instabilities (MBI) by interaction with the higher order cavity modes (HOM). The results revealed a quite high probability to excite longitudinal MBI and a lower probability to drive transverse MBI [3].

The damping of the more dangerous modes by means of dedicated couplers was not seen as the preferred solution, due to the well known problems that can arise with that devices. Thus two different solutions have been taken into consideration. The first was to install on the machine four resonators with no HOM dampers at all. The coupling of the sharp, high Q resonances present in the cavity to the beam harmonics can be avoided by a proper setting of *the cavity reference temperature, $T_{ref}$*. In this way overlapping between dangerous HOM and beam harmonics can be avoided. The second direction of research was the design of an almost HOM free resonator where the HOM modes are suppressed by means of a broad band waveguide damping systems [4], [5]. The second solution will be applied if the first one should be not as effective as expected.

The first solution is very friendly since it doesn't affect at all the fundamental mode parameters and it doesn't require a supplementary device to be inserted in the cavity. The design of the ELETTRA cavities [6] facilitates this method to fight against MBI. They are smooth shaped, with no nose cones, to allow the modes resonating above the beam tube cut-off to easily propagate. The tuner is a mechanical external cage, thus limiting the effect on the HOM which are only shifted in frequency without an increase in their number. The cooling system allows a wide regulating range for the reference temperature of the cavity, keeping it constant in the ±0.05 °C range (±0.4 KHz frequency stability for the accelerating mode). The nominal temperature range is now 50.0÷60.0 °C, but these limits could be trespassed if becomes necessary to eliminate MBI.

The tolerances for the mechanical machining of the cavities were not very strict, so that slight mechanical differences among the cavities are present. The different effects of the mechanical and thermal tuning systems on the various cavity resonances allows to have four cavities where each one is tuned to the $f_{RF}$ of 499.654 MHz, but with a completely different HOM frequency spectrum.

The revolution frequency, i.e. the interval between two successive revolution harmonics, is equal to 1.1566 MHz. The synchrotron frequency, $f_s$, is around 5÷10 KHz, depending on the energy and the RF voltage, while the nominal betatron frequencies are 350 KHz for the horizontal plane, $f_x$, and 230 KHz for the vertical plane, $f_y$. The -3dB bandwith of the HOM impedances measured as seen by the beam are lower than 100 KHz; thus, if the frequency shifts obtained by changing $T_{ref}$ in the operating range are above 100 KHz, it should be possible to shift the cavity modes away from the unstable sidebands of the beam harmonics, to frequencies where they definitively don't overlap any harmonic.

## 2. CHARACTERIZATION OF THE CAVITIES

The method chosen to reduce the risk of exciting MBI requires the information about the Q and the Rsh of the mode, and the frequency shift that can be obtained changing the cavity reference temperature, $T_{ref}$.

After the cavities were assembled on the storage ring in their final configuration the mode spectrum has been measured. First the resonance frequencies at $T_{ref}$ = 54 °C were measured, then the temperature was changed by ± 1.0 °C keeping the fundamental mode frequency constant at 499.654 MHz by means of the frequency tuner. The frequency shift of the HOM has then been registered. To take into account also the effect of beam loading, the frequency of the accelerating mode has been shifted by a fixed amount of ± 10.0 KHz, keeping constant $T_{ref}$ and measuring again the HOMs' $\Delta f$.

The results of both measurements are shown in table 1 for the longitudinal (L1÷L6) and for the dipole (D1÷D7) modes, together with the other relevant parameters of each mode. It should be noted that the values quoted for the resonance frequency and for the frequency shifts are averages of the values measured on the four cavities. The quality factor and the shunt impedance were calculated with OSCAR2D (longitudinal modes) and URMEL-T (transverse modes); there are only small differences to the values measured on the cavities. The shunt impedance (electrical definition) is the effective one, i.e. transit time corrected; for dipole modes it was evaluated 5.0

cm off-axis (beam tube radius). Only modes below the drift tube cut-off frequency are quoted. The two polarizations of the dipole modes, a and b, are not listed in the table; since their resonance frequencies differ slightly, they are both shown in the following plots of frequency vs $T_{ref}$.

Table 1
Cavity modes characterization

| mode | $f_r$ @54°C MHz | $\Delta f_r / \Delta T$ KHz/°C | $\Delta f_r$, KHz $\Delta f_0$ -10 KHz | $Q_0$ | $R_{sh}$ KΩ | $R_{sh}/Q_0$ Ω |
|---|---|---|---|---|---|---|
| L1 | 949.6 | -12.3 | -6.0 | 46000 | 1300 | 28 |
| L2 | 1054.9 | -18.7 | 4.0 | 61000 | 40 | 0.7 |
| L3 | 1420.2 | -43.6 | 19.7 | 54000 | 260 | 4.8 |
| L4 | 1513.0 | -31.4 | 5.3 | 63000 | 310 | 4.9 |
| L5 | 1599.0 | -60.3 | 37.7 | 75000 | 680 | 9.1 |
| L6 | 1876.9 | -33.0 | 2.3 | 56000 | 20 | 0.4 |
| D1 | 741.1 | -38.8 | 29.0 | 55000 | 147 | 2.9 |
| D2 | 745.0 | -14.2 | -1.5 | 57000 | 523 | 10 |
| D3 | 1108.7 | -24.7 | 3.7 | 48000 | 812 | 18 |
| D4 | 1220.3 | -24.5 | 4.5 | 93000 | 14 | .16 |
| D5 | 1238.5 | -60.0 | 20.0 | 67000 | 393 | 7.5 |
| D6 | 1302.0 | -38.0 | 17.7 | 69000 | .06 | .09 |
| D7 | 1562.0 | -36.0 | 11.5 | 52000 | 4.1 | .09 |

The $\Delta fr/\Delta T$ is the parameter of interest here. As an example the resonant frequency of the mode L1 will increase by 12.3 KHz, when the reference temperature of the cavity is changed by -1.0 °C, keeping the fundamental mode still at 499.654 MHz. On the other hand the frequency of the mode changes by only -6.0 KHz when the fundamental mode resonance is shifted by -10.0 KHz, keeping constant the reference temperature (fourth column in table 1). To compensate the reactive part of the beam loading detuning of some ten KHz is required.

The challenging point is now to find for each cavity a working temperature, $T_{ref}$, at which there is no overlapping between beam harmonics and corresponding cavity modes, at least for the more dangerous resonances. To achieve this goal we plot the frequency difference between the cavity resonances and the closest beam harmonic vs $T_{ref}$. The points crossing the zero line in these plots identify temperatures at which the frequency of the cavity HOM and the frequency of the unstable sideband of the closest beam harmonic are equal. We consider the upper synchrotron sideband, $f_s$, for the longitudinal case and the lower betatron sidebands for the transverse case, $f_x$ horizontal and $f_y$ vertical. Hence if the cavities are set to a $T_{ref}$ at which there are no crossings of the zero-line, the growth of instabilities will be suppressed.

The plot for the cavity named S3 is shown in figure 1. It can be observed that at 54.5 °C the 821st harmonic of the beam, at 949.574 MHz, and the resonance frequency of the first longitudinal HOM ($TM_{011}$-like mode) are coincident, since the corresponding line crosses the zero at that temperature. If the temperature is set to around 54.5 °C the growth due to instability becomes very likely. On the contrary, at higher and lower temperatures, there should be no risk of driving MBI, for all longitudinal HOMs of cavity S3.

The nominal temperature interval is almost overlap-free also when the transverse horizontal case is considered. The plot in fig. 2 shows an unique overlap at 58.5 °C. At this temperature the D5b resonance frequency is equal to that of the lower betatron sideband of the 1072nd harmonic of the beam.

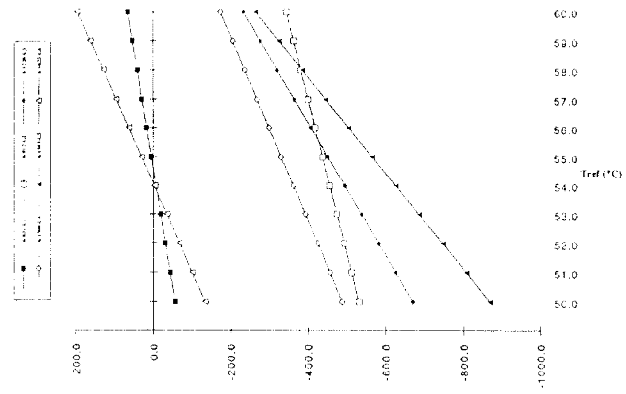

Figure 1. Cavity S3, longitudinal modes.

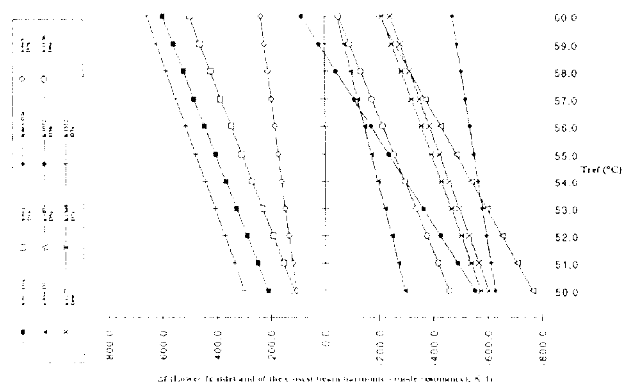

Figure 2. Cavity S3, transverse horizontal case, $f_x$ = 350 KHz.

Taking into account also the vertical case, shown in figure 3 with fy = 230 KHz, two stable temperature region can be identified, the first between 50.0 and 52.0 °C and the second between 59.0 and 60.0 °C.

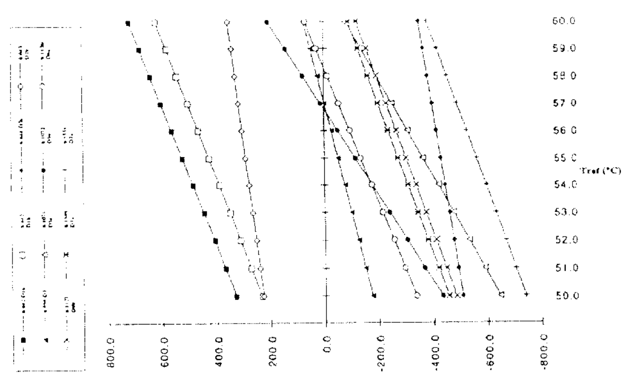

Figure 3. Cavity S3, transverse vertical case, $f_y$ = 230 KHz.

## 3. VERIFYING STABLE TEMPERATURE SETTINGS

The identification of the stable temperature for all cavities is based on the results of the procedure described above. The measurements considered there have been taken on the cavities under operating conditions, but with no RF power and no beam. Thus the zero line crossing points found from those measurements could slightly differ from the actual ones.

To verify the accuracy of these crossing points, the amplitude of the beam revolution harmonics has been measured as a function of $T_{ref}$. The machine was filled in single bunch, to guarantee repeatable excitation of the harmonics making the measurement independent from successive injections. At the temperatures corresponding to the overlaps with a mode, the amplitude of the correlated harmonic, measured on a spectrum analyzer, is expected to be maximum. The results are shown in fig. 4 for cavity S3. The beam harmonics correlated to longitudinal cavity modes are considered, thus the result should be compared with the plots in fig. 1. They agree fairly well, particularly for the harmonics 821 and 1623. Their maximum values are found at 54.0 °C, close to the crossing points in fig.1. The results of the other cavities agree also with an accuracy of around 1.0 °C.

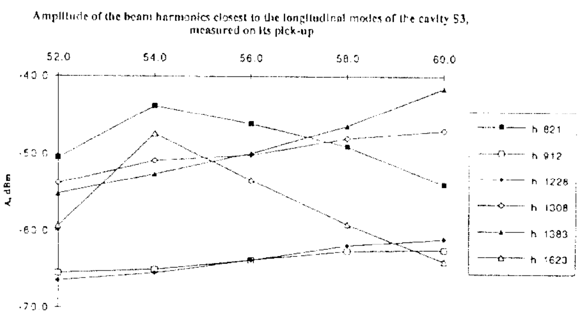


Figure 4. Beam harmonics amplitude vs cavity S3 $T_{ref}$.

The reliability of the method has been confirmed observing the growth of instabilities when $T_{ref}$ is approaching the zero-line crossing values. For example, setting cavity S3 to 55.0 °C causes a strong interaction between the beam harmonic 821 and the L1 cavity mode. The interaction is strongly reduced increasing $T_{ref}$ to 59.0°, as expected from fig.1.

Cavity S2 shows the possibility of exciting a transverse instability if $T_{ref}$ is set between 57.0÷59.0 °C depending on the value of $f_x$. In fact the second dipole mode ($TE_{111}$-like) crosses the lower, unstable, $f_x$ sideband of the harmonic 644 at 57 °C if $f_x$ is the nominal one (fig. 5). If the horizontal betatron frequency increases to 360 KHz, the lower $f_x$ sideband is excited when $T_{ref}$ is set to 59.0 °C (fig. 6). Decreasing $T_{ref}$ below that limit both $f_x$ sidebands disappear as well as the instability. More details on the MBI treatment in [1], [7].

## 4. CONCLUSION

A very simple method to fight against MBI has been presented. It is based on the research of cavity temperature settings at which there is no interaction between cavity HOM and beam harmonics. Applying it to all four ELETTRA cavities allowed to limit satisfactorily the growth of MBI.

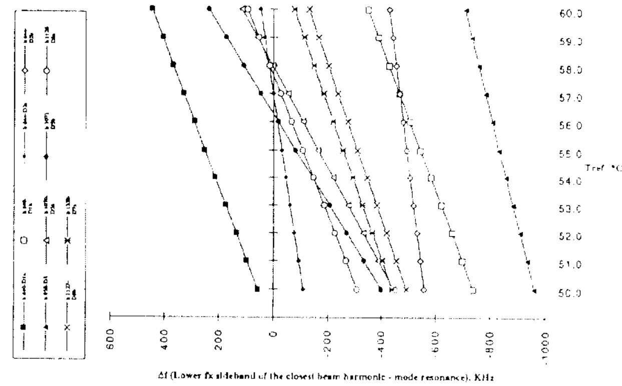


Figure 5. Cavity S2, transverse horizontal case, $f_x$ = 350 KHz.

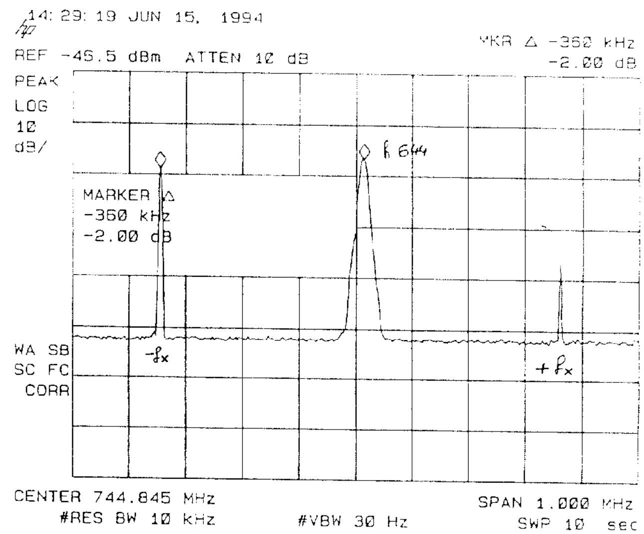


Figure 6. Lower betatron sideband of the harmonic 644, excited when $T_{ref}$ S2 is above 59.0 °C ($f_x$ = 360 KHz).

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