THE CURE OF MULTIBUNCH INSTABILITIES IN ELETTRA

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ELETTRA is generally working in a multi-bunch filling mode which gives rise to an instability if a parasitic Higher Order cavity Mode (HOM) is coupled to a multi-bunch oscillation mode. Longitudinal instabilities, even if not destructive, are particular harmful for synchrotron light sources, since they increase the energy variation of the beam and deteriorate in this way the quality of the light spectrum. Multi-bunch instabilities in ELETTRA are cured by tuning the temperatures of the four independent cavities. The effectiveness of the method has been verified by monitoring the spectrum of the SuperESCA beamline. The relation between HOMs and cavity temperature and the variation of this dependence with cavity and machine parameters has been studied. Operational experience and dedicated measurements are presented and compared with theoretical predictions.

I. INTRODUCTION

During operation for users the storage ring is filled in a multibunch mode. Longitudinal Multibunch Instabilities (LMBI) have been studied in ELETTRA already from the beginning of the commissioning and were observed, at injection energy, even at very low currents, i.e. 1 mA. Confirming that LMBI are not destructive, it was possible to store currents as high as 530 mA, and even more, at injection energy (1.0 GeV) [1]. However the expected effects of LMBI on the beam energy variation, on the beam size and stability, and the consequence on the light quality, could be observed.

Beam energy, E	2.0 GeV
Current in normal operation, I_b	200 mA
Nominal RF frequency, f_{RF0}	499.654 MHz
Harmonic number, h	432
Momentum compaction, α	$1.6\ 10^{-3}$
Operating Effective Peak RF voltage, V_{RF}	1.68 MV

Table 1: Relevant ELETTRA parameters.

In case of longitudinal motion the driving source for coupled bunch instabilities is given by the high-Q HOMs of the RF cavities. The instability becomes maximum when a Coupled Bunch Mode (CBM) frequency and a HOM frequency overlap. For small machines like ELETTRA, with high revolution frequency, and for narrow band HOMs it is then possible to tune the HOM away from the CBM frequency and thus reduce the coupling. The experience made during storage ring commissioning shows that the LMBI can be reduced by changing the temperatures of the cavities [2], while changes in the multibunch filling pattern did not bring any improvement. Since ELETTRA cavities are free of damping antennas or loops, a global temperature tuning procedure has been developed.

Transverse Multibunch Instability haven't been observed during machine operation, thus they will not be discussed here. Dedicated experiments during commissioning showed that temperature tuning is very effective also for them [1].

II. A SYSTEMATIC APPROACH TO TEMPERATURE TUNING OF RF CAVITIES

HOMs' temperature tuning can be effective if the frequencies can be regulated in a wide range and if there is good accuracy in the cavity temperature setting and in the knowledge of the HOM frequency. As it is described in [2], [3], a solution was adopted in the design of the RF cavities for ELETTRA to improve the temperature tuning technique. The high Q, not damped, HOMs' frequency can be shifted by some hundreds of kHz since the cavity temperature can be regulated between 40 and 70 °C. The cavity temperature is stable within ± 0.05 °C. The fundamental mode frequency is kept constant by an external tuning cage.

For a systematic analysis, a pair HOM - CBM can be characterised by a *Critical Temperature*, defined as the cavity temperature for which the frequency of the HOM exactly overlaps the frequency of the CBM, i.e. the coupling is maximised. By calculating this temperature for all harmful HOMs and associating to it the temperature interval where the HOM is strong enough to drive the instability, operating temperature settings for the RF cavities can be found where the coupling HOM-CBM is minimised.

A. The Calculation of the Critical Temperature

The critical temperature $T_{ck,n}$ for the longitudinal HOM L_k and the CBM number n is derived in [4], and is equal to

$$T_{ck,n} = \frac{1}{\tau_{Lk}} \Big[(f_{pn} - f_{Lk0}) + \left(\frac{N}{h} - \varphi_{Lk}\right)(f_{RF} - f_{RF0}) + \varphi_{Lk}\,\Delta f_{BL} \Big] + T_0 \qquad (1)$$

f_{Lk0}	= frequency of L_k measured at T_0 and at f_{RF0};
T_0	= cavity temperature when f_{Lk0} is measured;
f_{pn}	= $(pM+n+mQ_s)\omega_0/2\pi$: frequency of CBM number n, with p an integer, M number of bunches, m bunch shape mode (here m=1), Q_s synchrotron tune, $\omega_0/2\pi$ the nominal revolution frequency.
N	= ph+n;
τ_{Lk}	= f_{Lk} change for unitary temperature change;
φ_{Lk}	= f_{Lk} change if L_0 mode frequency changes by 1.0 KHz
Δf_{BL}	= $K_{BL0}\, I_b/V_g$: L_0 mode frequency shift due to the beam loading, typical ~30 kHz.

Table 2: Definitions used in relation (1); see also [3].

The Critical Temperature (1) depends on the RF frequency f_{RF}, on the beam current I_b and, through Q_s , on the energy E and on the RF voltage V_{RF}. Tab. 3 shows typical values of T_c for different I_b, f_{RF} and E for the harmful HOMs of cavity S3 .

HOM	f_{Lk} MHz	CBM n	E, GeV	1.0	2.0	2.0	2.0
			Ib, mA	1.0	1.0	200.0	200.0
			f_{RF}	499.654	499.654	499.654	499.644
L1	950	389	$T_{c1,389}$	57.8	58.2	56.7	57.8
L3	1421	365	$T_{c3,365}$	39.0	39.1	40.5	41.7
L4	1514	12	$T_{c4,12}$	70.1	70.3	70.6	71.8
L5	1600	87	$T_{c5,87}$	64.2	64.3	65.9	67.2
L9	2073	64	$T_{c9,64}$	44.2	43.1	45.2	46.3

Table 3: Calculation of Critical Temperatures for different conditions, for cavity S3.

The largest shifts are caused by I_b and f_{RF}. On the base of these shifts forbidden temperature intervals can be found, as shown in fig. 1 for Cavity S3. A 3dB equivalent bandwidth of the resonance is also included in these intervals.

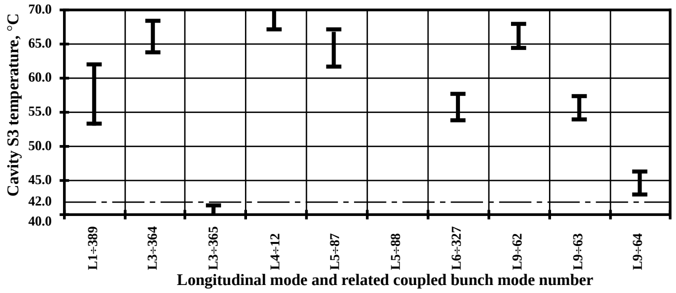

Fig. 1: The forbidden temperature intervals for cavity S3.

The computed values for $T_{ck,n}$ have been verified on the machine. For example, to identify the real value of $T_{c1,389}$, at 1.0 GeV a current of 1.0 mA in a uniform filling has been injected and the excitation of the CBM 389 has been measured as a function of cavity S3 temperature. The plot in fig. 2 shows a maximum between 57.6 and 57.9 °C. The computed value in table 3 is 57.8 °C. Also for the other modes a good agreement, with an accuracy of about ± 0.5 °C, was found.

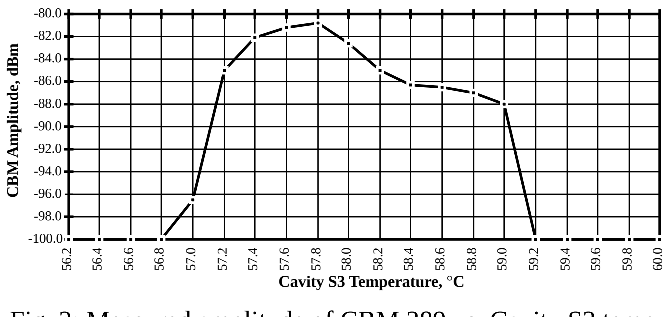

Fig. 2: Measured amplitude of CBM 389 vs. Cavity S3 temp.

There can be a large difference in the critical temperatures for the same pair HOM-CBM among the four cavities, due to the relaxed mechanical tolerances. For example, $T_{c1,389}$ is ~110 °C for Cavity S2, ~65 °C for S8 and ~69 °C for S9.

B. Operational Experience

The cavities are normally operated outside the forbidden temperature intervals. Operational experience with currents up to 250 mA at 2.0 GeV shows that this is sufficient to reduce the HOMs' impedance seen at the CB frequency to a value which eliminates the impact of the LMBI. This is not valid for the mode L1, since the high shunt impedance (851 kΩ) along with the low temperature coefficient (τ = -11.5 kHz/°C) [3] requires a temperature setting far from $T_{c1,389}$ to get rid of the instability. Other high shunt impedance modes (L3, L5, L9) have higher τ (40÷100 KHz/°C), thus their effect is already cured at a few degrees from $T_{ck,n}$. The operating temperature for cavity S3 has thus been set around 42.0 °C (fig.1).

The consequence is that the only marked LMBI effect on the machine performance is due to the coupling between the L1 (TM-011) mode and the CBM number 389 becoming strong when the cavity S3 is tuned in the middle of its temperature range, that is, around $T_{c1,389}$ for this cavity.

The effect of this interaction has been observed looking at the undulator radiation on the SuperESCA beam line. When cavity S3 is set around 57÷58°C large energy oscillations are evident: unacceptable widening of the undulator harmonics is present together with a consistent flux reduction, related to the effective energy spread of the beam produced by the excited LMBI. The typical effect on the fifth harmonic of the undulator spectrum of the L1 HOM exciting CBM 389 is shown in fig. 3. When the cavity is set to bad temperatures the flux is strongly reduced and the harmonic is widened, while setting the cavity to a good temperature (dotted line) the spectrum assumes the wanted profile.

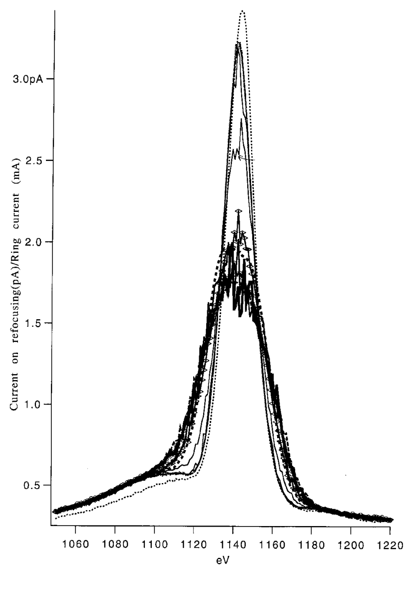

Fig. 3: Effect of the mode L1 on the undulator spectrum.

The second main effect related to LMBI is a Low Frequency beam profile Oscillation (LFO). It is clear that beam profile stability is also of great importance for a light source like ELETTRA. When a cavity is tuned to a temperature at which overlapping between a HOM and a CBM is present, LFOs are present in a typical range from 0 to 30 Hz, depending on the beam current and the energy. At high beam currents a saturation effect seems to be present. The presence of LFOs was found to be insensitive to the beam filling structure, namely once they are excited (i.e. a cavity is tuned to a bad temperature) the LFOs exist under almost any multibunch filling. When the basic longitudinal instability is suppressed, the LFOs disappear and the beam profile returns stable. This is the situation during operation, with the cavities set 58 °C (S2), 41.5 °C (S3), 45 °C (S8) and 52 °C (S9).

III. THE CB INSTABILITY GROWTH RATES AS A FUNCTION OF CAVITY TEMPERATURE.

The growth rate of a longitudinal coupled bunch instability for a beam current I_b stored in M uniform filled and spaced bunches, for a high-Q cavity HOM can be approximated by

$$1/\tau_{\|} = \frac{\alpha I_b}{4\pi Q_s (E/e)} \omega_{pn} Re(Z_{\|}(\omega_{pn}))\, e^{-\left(\frac{\omega_{pn}}{\omega_0}\frac{\sigma}{R}\right)^2} \quad . \qquad (2)$$

The impedance of the resonance, for one cavity, is

$$Z_{\|}(\omega_{pn}) = \frac{\left(\frac{R}{Q}\right)_{0Lk} \cdot Q_{Lk}}{1 + j\, Q_{Lk}\left(\frac{\omega_{pn}}{\omega_{Lk}} - \frac{\omega_{Lk}}{\omega_{pn}}\right)} \quad . \qquad (3)$$

In relation (3) we dropped the summation over all cavities, without a loss of generality. The frequency f_{Lk} of HOM L_k at the generic cavity temperature T and RF frequency f_{RF} and at the beam current I_b can be worked out [4] from relation (1),

$$f_{Lk} = \tau_{Lk}(T - T_0) + \varphi_{Lk}\left[(f_{RF} - f_{RF0}) - \Delta f_{BL}\right] + f_{Lk0} \quad . \qquad (4)$$

The ratio $\Omega_{kn} = \omega_{pn}/\omega_{Lk}$ in (3) is then

$$\Omega_{kn} = \frac{\frac{N}{h} f_{RF} + f_s}{\tau_{Lk}\,\Delta T + \varphi_{Lk}\left[\Delta f_{RF} - \Delta f_{BL}\right] + f_{Lk0}} \quad , (5)$$

with f_{pn} written in terms of f_{RF} and synchrotron frequency f_s. The growth rate (2) becomes then

$$1/\tau_{\|} = \frac{\alpha I_b}{4\pi Q_s (E/e)} \frac{\left(\frac{R}{Q}\right)_{0Lk} \cdot Q_{Lk}}{1 + \left[Q_{Lk}\left(\Omega_{kn} - 1/\Omega_{kn}\right)\right]^2} \omega_{pn}\, e^{-\left(\frac{\omega_{pn}}{\omega_0}\frac{\sigma}{R}\right)^2}$$

which, by relation (5), is a function of T and f_{RF}.

In fig. 4 the computed growth rate for CBM 389 is shown as a function of cavity S3 temperature. It is calculated for a fixed beam current of 150 mA at 2.0 GeV and for the nominal f_{RF}, with the other cavities set to the operation temperatures. The peak is between 56 and 58 °C and corresponds to the critical temperature of the mode L1 for this cavity. It can be observed that around 41.0÷42.0 °C the growth rate reduces below the longitudinal radiation damping threshold.

To correlate the CBM oscillation to the driving impedance at different cavity temperatures, we measured the amplitude of the CBM on a spectrum analyzer. The excited CBM number 389 we are considering here will be present in the beam spectrum as a first order phase modulation sideband ($+f_s$) of the beam harmonic 821. To measure the relative amplitude variation of $+f_s$ at different cavity temperatures we simply took the beam spectrum signal from a capacitive button. The ring was filled with 432 uniform equally spaced bunches, for a total current of 150 mA. The amplitude of the harmonic at f_{RF} was equal to -19.0 dBm. In fig. 5a we can see the plot taken with the cavity tuned close to the critical temperature $T_{c1,389}$ of cavity S3. The amplitude of the +fs sideband at 949.5857 MHz is large. When the cavity temperature is changed to 42.5 °C the amplitude of the +fs sideband is reduced by 65.6 dBm, as it is shown in fig. 5b, in agreement with the prediction of fig. 4. Further changing the temperature makes the first order sideband completely disappear.

IV. CONCLUSIONS

The results obtained are consistent with the theoretical expectations. The significant reduction of LMBI obtained by temperature tuning of the RF cavities has allowed a satisfactory routine operation of the machine.

V. REFERENCES

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[2] M. Svandrlik et al., “Investigation of the HOM in the ELETTRA cavities”, in *Proceedings of the Fourth European Particle Acceleratore Conference*, London, U.K., June 1994, pp. 2134-2136.

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[4] M. Svandrlik et al., “Systematic RF cavities’ Temperature Tuning as a Cure for Multibunch Instabilities”, *Sincrotrone Trieste Internal Report*, ST/M-95/1.

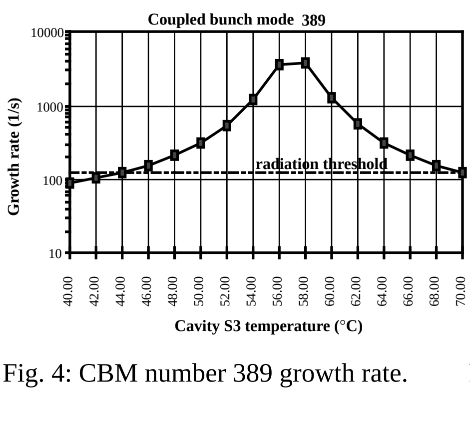

Fig. 4: CBM number 389 growth rate.

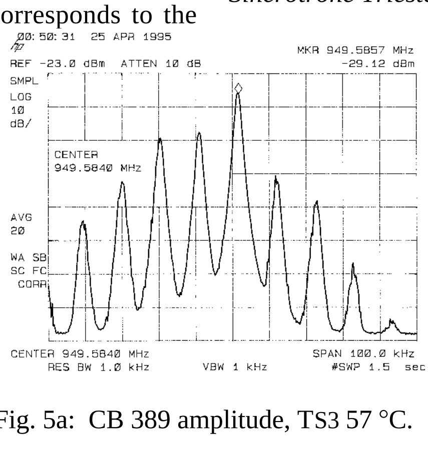

Fig. 5a: CB 389 amplitude, TS3 57 °C.

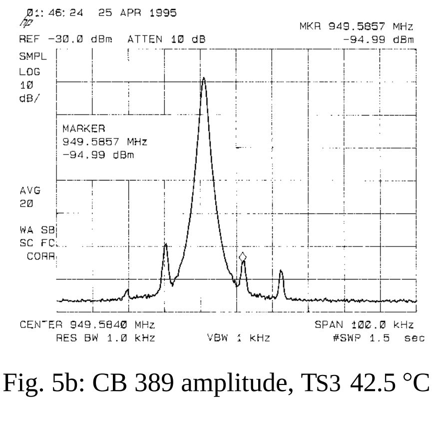

Fig. 5b: CB 389 amplitude, TS3 42.5 °C.