ELECTROACOUSTIC OSCILLATIONS IN THE LEP SC. CAVITIES

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Abstract

The LEP superconducting cavities have been plagued by electroacoustic oscillations. Tests have been done to eliminate these by a special feed-back loop in the tuning circuit as well as a feed-forward path, but they could only be eliminated safely up to the design field by running the cavities close to tune neglecting beam-loading compensation. This technique proved successful during the first LEP2 test run at 70 GeV. The mechanism and essential parameters driving these oscillations have been analysed as well as the corresponding stronger loading of the power coupler.

1 OBSERVATIONS IN LEP

A strong modulation of the cavity RF voltage has been observed on some of the modules operating in LEP. In some dramatic cases the amplitude modulation is as high as about 50%, even at an average field below 4 MV/m. This effect, which was not observed during cavity testing prior to installation, manifests itself only when beam is present, and is clearly linked to beam intensity. It goes without saying that such a strong modulation appearing on one cavity of a unit (two modules driven by a common klystron) will impose a reduction of the operating field of all eight cavities of the unit, and jeopardise the future LEP2 operation [1].

The amplitude modulation of the RF voltage always corresponds to a phase modulation, as observed on the phase detector of the tuning loop, leading to the suspicion that a tune modulation of the cavity could be at the origin of the problem.

Analysis of the frequency spectra of the observed signals revealed a number of frequency lines in the vicinity of 100 Hz. Spectra taken with very low RF field in the cavities and without beam, also show peaks which can be attributed to an external excitation by cryogenics. The presence of mechanical excitation of the cavity from outside at precise frequencies does not explain, however, the other lines appearing in the spectrum when beam is present, which in some cases largely dominate. In the following we shall only consider the lines which *do not* correspond to an external excitation of the cavity by the cryogenic system.

2 EXPERIMENTAL OBSERVATIONS

During LEP operation with beam, the cavities are detuned to compensate the reactive part of beam loading in such a way that cavity voltage and forward power are in phase. In the case of LEP the detuning angle ϕ_z is always negative. Cavity detuning introduces a relation between small tune modulations and cavity voltage modulations, which could explain the observed coherence between phase and amplitude signals. In a LEP machine experiment, we changed the phase of the RF drive as compared to the beam, so as to put the cavity voltage and beam current in phase (bunches ride on the crest of the wave of that particular unit). The *modulations* were reduced by a large factor (> 20 dB) showing that cavity detuning (and not the presence of the beam) was responsible for the effect. This was confirmed by a counter experiment in the cavity test set-up where a cavity was deliberately detuned (± 45° offset in the phase detector of the tuning loop), the result being a strong phase and amplitude modulation (up to 80%) observed with a *negative* offset. We have checked that the negative offset corresponds to a cavity detuning of the *same sign as that induced by the LEP beam current*. Even with the tuning servo loop disabled, the modulation appeared when the (drifting) cavity tune wandered in a region of negative detuning, showing that this was not an effect due to the tuning loop.

The mechanical resonances of the cavity (at least those leading to a tune modulation) can be analysed in situ by exciting the cavity via the magnetostrictive tuner bars. A typical transfer function is displayed by the top curve in Fig. 1.
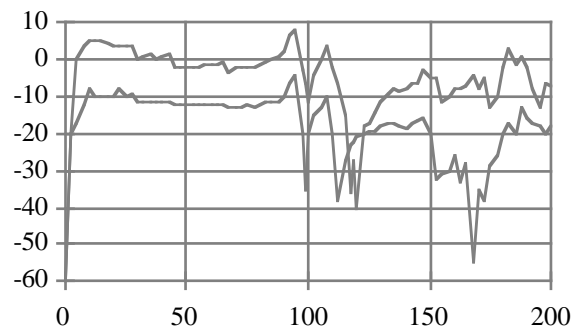

Fig. 1: Transfer functions [dB] versus frequency [Hz]:
• top: Magnetostrictive current -> phase
• bottom: Cavity voltage -> phase

It shows the amplitude ratio of cavity frequency modulation (measured on the tuner loop phase detector) and magnetostrictive current. The low-frequency part corresponds to the action of the servo tuner which keeps the cavity in tune against outside excitations. The two main mechanical resonances of the cavity (95 Hz and 107 Hz), already predicted by simulations [2], are observed, together with the weaker transverse resonances (30-40 Hz) and a more complicated response above 150 Hz.

The striking result of this analysis, made for a large number of cavities, is that the frequency of the modulation peak exactly corresponds to one of the two resonance peaks of that particular cavity. The spread of the two mechanical resonances, as observed on a dozen cavities is from 86 Hz (lowest peak) to 110 Hz (highest peak).

3 ANALYSIS

It is known that in high field superconducting cavities the resonance frequency of the cavity depends slightly upon the RF field. One mechanism is via the Lorentz force (radiation 'pressure') which deforms mechanically the cavity walls. There may be other effects, thermomechanical ones, in the helium bath for instance, linked to the cavity wall's dissipation.

We tried to measure this effect by deliberately modulating in amplitude the cavity field, through the klystron drive, and observing the corresponding cavity detuning on the tuner loop phase detector. The cavity must be on tune (no phase offset) and the klystron phase loop turned on. This ensures that the forward power to the cavity is amplitude-modulated only, without parasitic phase modulation.

The result is displayed in Fig. 1, bottom curve. Indeed there is a non-zero transfer function, from amplitude modulation to cavity tune, with peaks corresponding to the mechanical resonances of the cavity. The static detuning, as a function of field, has also been measured in a phase-locked loop configuration. The component proportional to V^2 ($\approx$ 35-70 Hz at 6 MV/m) corresponds approximately to the magnitude of the low-frequency part of the Fig. 1 curve. It can be observed that the magnitude of the transfer function increases with the average cavity field, as expected, and that in the Nyquist diagram the two circles corresponding to the two resonances around 100 Hz and the low-frequency part of the curve lie in two opposite half planes. This suggests an instability mechanism, not present (or controlled by the servo tuner) at low frequency (0-10 Hz), but appearing around 100 Hz where the transfer function is large (mechanical resonances) and its sign changed.

This type of oscillations has been examined already by [3][4]. We use here the transfer function between tune- and field amplitude modulation $G_{x,a}(s)$ as function of the Laplace parameter s [5] - depending on the detuning angle ϕ_z - and the response of the mechanical cavity-resonator, yielding a 4th order polynomial in s [6]. The real parts of the four complex solutions represent the growth rates, a positive real part corresponding to a self-exciting instability.

The only undetermined parameter in this polynomial, the mechanical attenuation Q_m, can be deduced to be about 20 from the mechanical transfer function in Fig. 1. The 'worst' of the four real parts - representing the dominant effect - has been plotted for different cavity

fields in Fig. 2. We see that with *negative* tuning angles $\phi_z = 0$ (automatically introduced by the tuning system when the beam current increases) for 2 MV/m there is (nearly) everywhere stability, for 4 MV/m already a large range is unstable and for 6 MV/m - the design field - there remains only a very small stable region close to $\phi_z = 0$.
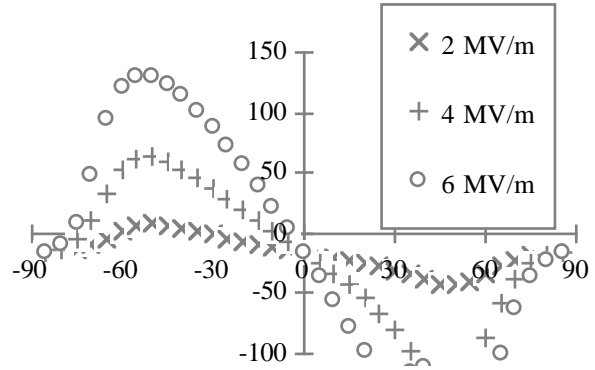

Fig. 2: Growth rates [s^{-1}] as function of ϕ_z[deg] for three different cavity field levels. The chosen parameters match the actual conditions of the LEP2 sc. cavities

4 CORRECTION

This instability is intrinsic to the cavity physical properties (mechanical, thermal); it could be suppressed by controlling the cavity voltage via the RF power generator (amplitude feedback, RF feedback). Unfortunately in the LEP case one klystron drives eight cavities and cannot be used to suppress the (incoherent) modulations of all cavities.

Another approach is to use the magnetostrictive tuner to provide a tune variation opposite to that naturally induced in the cavity. In this feedforward technique the cavity voltage modulation, properly filtered, is re-injected via the magnetostrictive current of the tuner (Fig. 3).

In an experiment made in the cavity test set-up a reduction by about 10 dB of the most dangerous peak was achieved, and the instability threshold pushed further up. Nonetheless this method is delicate (amplitude and phase control of the re-injected signal) and of limited efficiency: other instability frequencies appeared above 150 Hz when the field was raised. It implies that the two transfer functions of Fig. 1 are almost identical, which is not exactly the case.

For particularly dangerous mechanical resonances, one could use active damping by selective feedback around the resonance frequency. One or possibly several parallel feedback paths corresponding to the cavity resonances to be damped, would parallel the usual servo tuner electronics (Fig. 3). The expected gain, however can hardly be larger than about 10 dB (Fig. 1) because of the close vicinity of the two major mechanical resonances. This has been checked experimentally on a LEP2 cavity.
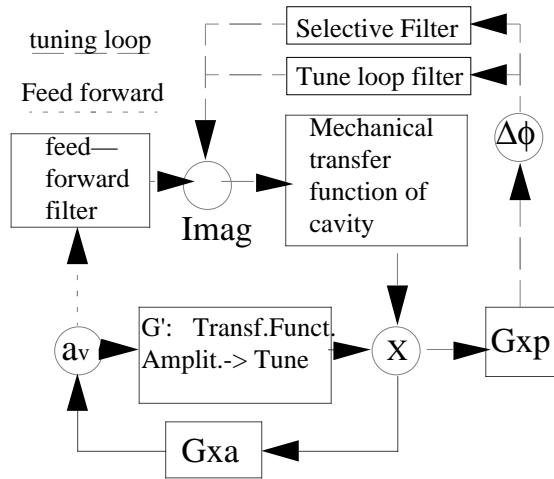
Fig. 3: Closed loop system block diagram and possible corrections (dotted/dashed lines)

The most radical solution, which would also minimise the effect on cavity voltage of external excitations, would be to run the cavities on tune ($\phi_z = 0$, $G_{Xa} = 0$). This can be done by offsetting the tuner phase discriminator by an angle ϕ_z. Indeed this has been tested in LEP. With no offset, the oscillations persist, with an offset of +20°, the instability disappeared completely. The price to pay is, however, an increased RF power for the same RF voltage. It also means that Robinson damping of the n = 0 mode disappears; this however can easily be restored if necessary by phase feedback.
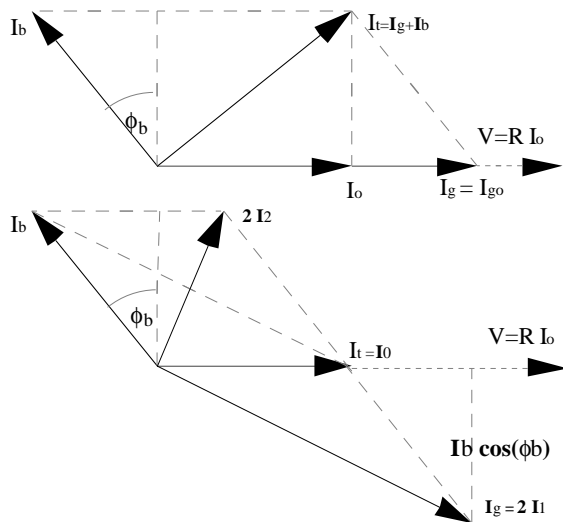

Fig. 4a,b: Vector diagram of cavity voltages and currents
• top: detuned (usual) case ; • bottom: cavity on tune

Figure 4a shows the usual vector diagram, where the cavity voltage V is the reference, I_b the RF component of the beam current, I_o the on tune current which produces V in the cavity ($I_o=V/R$), and I_g the generator current.

Usually, I_g is kept in phase with V by the action of the servo tuner to keep the power to a minimum

($I_g = I_{go}$). The total current vector I_t lies on the scaled admittance locus $(1/R + j\ x)\ V$ as in Fig. 4a.

If the cavity is kept in tune, I_t and V are in phase; in this case I_g is as in Fig. 4b. Simple geometric considerations show that in this case $I_g=I_{go}+jI_b\ \cos(\phi_b)$. The excess power ΔP is then - independent of the actual voltage - simply:

$$\Delta P = \tfrac{1}{8}\ R\ I_b^2\ \cos^2(\phi_b).$$

In the LEP2 case at maximum energy $\phi_b = 60°$, R = 460 MΩ (Qext$= 2\cdot10^6$, R/Q=232 Ω), and with I_b=10 mA d.c. (20 mA RF) we obtain ΔP=5.75 kW, which is fairly modest compared to the 100 kW delivered to the beam. However, the peak RF field in the main coupler increases if the cavity is run in tune, with beam. The forward (I_1) and reflected (I_2) wave currents in the coupler line (Z_o=R) are (Fig. 4b)

$$I_1 = 0.5\cdot(I_t - I_b);\qquad I_2 = 0.5\cdot(I_t + I_b)$$

The equivalent (local) coupler power (power which produces the same peak field)

$$P_{eq} = \tfrac{1}{2}Z_o(|I_1|\ +\ |I_2|)$$

is significantly larger in the detuned case ($P_{eq} = 1/8\ Z_o\ I_{go}^2$)

At injection $\phi_b = 0°$, V=1 MV per cavity and I_b=10 mA d.c. one obtains P_{eq}=92 kW and at 90 GeV, ϕ_b=60°, V=10 MV: P_{eq}=160 kW which is still acceptable by present couplers. A more detailed analysis and a proposal to avoid this drawback can be found in [7].

RUNNING EXPERIENCE

Practically it is complicated to keep a cavity on tune against strong beam loading. Therefore we have worked during the last LEP run (68/70 GeV/c) in 1995 with a *fixed* detuning *offset*. During injection the induced detuning is strong due to the then low cavity voltage and is not fully compensated by the fixed offset. However, as shown in Fig. 2, the instability develops only at higher cavity field levels so that the system remains stable. During ramping the cavity field rises approaching the unstable condition, but at the same time reducing the induced detuning correspondingly so that at higher fields the cavity is sufficiently close to tune to remain stable. During the whole 68/70 GeV-run (under operational conditions) we never encountered such cavity oscillations.

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