ELECTROACOUSTIC INSTABILITIES IN THE LEP2 SUPERCONDUCTING CAVITIES

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Abstract

Strong modulations (sometimes as high as 50%) of the accelerating voltage of the LEP2 superconducting cavities have been observed when the cavities are operated with beam. These modulations are shown to be the result of a closed loop instability which involves the mechanical resonances of the cavity, the sensitivity of cavity tune to RF field (e.g. radiation pressure effect) and the steady cavity detuning (which compensates the reactive part of beam loading). The instability depends only on intrinsic cavity and cryostat parameters, which unfortunately are now almost impossible to change; its threshold (inversely proportional to the square of the accelerating voltage and to the beam current) very severely limits the cavity performance in LEP2 conditions. Various methods for curing or alleviating the problem are considered, the only realistic one being to avoid cavity detuning, at the expense of a (modest) increase in RF power.

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 cavities of the unit, and jeopardize the future LEP2 operation.

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. Two examples show very sharp peaks with largely variable amplitudes from cavity to cavity, but the same frequencies. These peaks are coherent from one cavity to another, some even from one module to another, suggesting a common mechanical excitation of all cavities.

Indeed we observed mechanical vibration on the two modules examined using accelerometers fixed either on the helium inlet pipe or on the waveguide. The spectra, taken without RF field in the cavities and without beam, show a relatively broad band centred at around 93 Hz, but also a very narrow peak at 98.1 Hz. If the helium inlet valve is fully opened or the cryostat is completely filled with liquid He, these vibrations disappear completely. In conclusion, part of the spectrum can be attributed to an external excitation, which is linked to the cryogenic conditions of the cavity.

The presence of mechanical excitation of the cavity at precise frequencies does not explain, however, the other lines present in the spectrum, 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. Observations in the test string

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. 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

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experiment, we changed the phase of the RF drive (the "station phase") 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 offest 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. 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 [1], 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).

Note also that for the cavities examined, the frequency of the external excitation (cryogenic) did not coincide with any mechanical resonance of the cavity. If this were to happen larger modulations resulting from the external excitations would be expected.

3. Analysis

It is known that in high field superconducting cavities the resonance frequency of the cavity depends slightly upon the RF field [2, 3]. 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.

Any amplitude modulation in the cavity leads to a tune modulation, as observed, which, in turn gives an amplitude modulation of the cavity voltage, *provided the cavity is detuned*. If the

overall loop gain is larger than unity (this has been checked using the measured curve of Fig. 1 and the calculated transfer function for a detuned cavity) the system is unstable and results in a strong modulation of the cavity voltage, only limited by the losses in the system and non-linearities.

Figure 2 shows a block diagram of the closed loop system. Using the notations of [4]:

$x = \Delta\omega/\sigma$ — relative cavity detuning; σ — half cavity bandwidth

ϕ_z — cavity detuning angle; $a_v = \Delta V/V$,

the transfer functions G_{xp} (detuning $\rightarrow$ phase) and G_{xa} (detuning $\rightarrow$ amplitude) are given by:

$$G_{xp} = \frac{\sigma^2 + \sigma s}{s^2 + 2\sigma s + \sigma^2(1 + \tan^2\phi_z)}, \quad G_{xa} = \frac{-\sigma^2 \tan\phi_z}{s^2 + 2\sigma s + \sigma^2(1 + \tan^2\phi_z)} \quad .$$

From the measured $\Delta\phi$, one can evaluate x, and therefore G' (transfer function amplitude modulation $\rightarrow$ tune) and finally the open loop gain.

$G_{xa}(s = 0)$ has a maximum ($G_{xa} = 0.5$) for a 45° detuning (worst case situation). The magnitude of G_{xa} as a function of frequency shows a rather flat response up to about $s = j\sigma$ followed by a smooth roll-off. For LEP2 cavities we have the unfortunate situation that ϕ_z is of the order of 45° (max. gain) and $\sigma \cong 2\pi \times 100$ Hz very close to the mechanical resonances of the cavity.

If we assume that the detuning x is a square function of the cavity voltage (Lorentz force effect, thermal effects) we find the instability threshold inversely proportional to V^2:

$$G' = \frac{\delta x}{a_v} \approx \frac{V\Delta V}{\frac{\Delta V}{V}} \approx V^2$$

and also to first order, inversely proportional to the beam current through G_{xa} and $\tan\phi_z = (RI_b/V)\cos\phi_b$ (R = cavity shunt resistance, I_b: RF component of the beam current).

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 (possibly 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 bars (Fig. 2). In an experiment made in the cavity test set-up a reduction by about 10 dB of the most dangerous peak of G' 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 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. 2). 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.

The most radical solution, which would also minimize the effect on cavity voltage of external excitations (cryogenics, for instance), 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 on LEP. 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 be restored if necessary by phase feedback.

Figure 3 shows the usual vector diagram, where the cavity voltage $\vec{V}$ is the reference, $\vec{I}_b$ the RF component of the beam current, $\vec{I}_0$ the on tune current which produces $\vec{V}$ in the cavity ($I_0 = V/R$), and $\vec{I}_g$ the generator current. Usually, $\vec{I}_g$ is kept in phase with $\vec{V}$ by the action of the servo tuner to keep the power to a minimum ($I_g = I_{g0}$). The total current vector $\vec{I}_t = \vec{I}_b + \vec{I}_g$ lies on the scaled admittance locus $\left(\frac{1}{R} + jx\right) \cdot \vec{V}$ as in Fig. 3a. If the cavity is kept in tune $\vec{I}_t$ and $\vec{V}$ are in phase; in this case $\vec{I}_g$ is as in Fig. 3b. Simple geometric considerations show that in this case $\vec{I}_g = \vec{I}_{g0} + j\vec{I}_b \cos \phi_b$. The excess power ΔP is then simply

$$\Delta P = \frac{1}{8} I_b^2 \cos^2 \phi_b R \quad ,$$

independent of the actual voltage.

In the LEP2 case at maximum energy $\phi_b = 60°$, R = 460 MΩ ($Q_{ext} = 2 \cdot 10^6$), and with $I_b = 10$ mA d.c. (20 mA RF) we obtain $\Delta P = 5.75$ 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 ($\vec{I}_1$) and reflected ($\vec{I}_2$) wave currents in the coupler line ($Z_0 = R$) are displayed in Fig. 3b.

$$\vec{I}_1 = \frac{1}{2}\left(\vec{I}_t - \vec{I}_b\right) \qquad \vec{I}_2 = \frac{1}{2}\left(\vec{I}_t + \vec{I}_b\right).$$

The equivalent coupler power (power which produces the same peak field): $P_{eq} = \frac{1}{2} Z_0 \left(|I_1| + |I_2|\right)^2$ is significantly larger than in the detuned case $\left(P_{eq} = \frac{1}{8} Z_0 I_{g_0}^2\right)$.

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, $\phi_b = 60°$, V = 10 MV: $P_{eq} = 160$ kW which is at the limit of the present performance of the couplers.

References

1. J. Genest, in LEP200 Working Group, Minutes of the Meeting held on 29 May 1991
2. M. Karliner et al., Vibrations of the Walls of a Cavity Resonator under Ponderomotive Forces in the Presence of Feedback, Soviet Physics, Technical Physics, Vol. 14, No. 8, Feb. 1970
3. P.H. Ceperley, Ponderomotive Oscillations in a Superconducting Helical Resonator, Internat. Conf. on Multiple-Charged Heavy Ion Sources and Accelerating Systems, Gallinburg, Tenn., USA, 25-28 October 1971
4. F. Pedersen, Beam-loading Effects in the CERN Booster, MPS/Int.BR/75-6 and Proc. 1975 Particle Accel. Conf., Washington D.C.
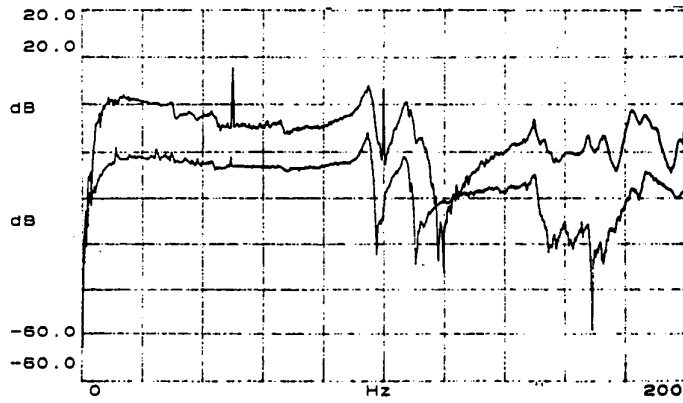
Fig. 1.   Transfer functions: Magnetostrictive current → phase (top)
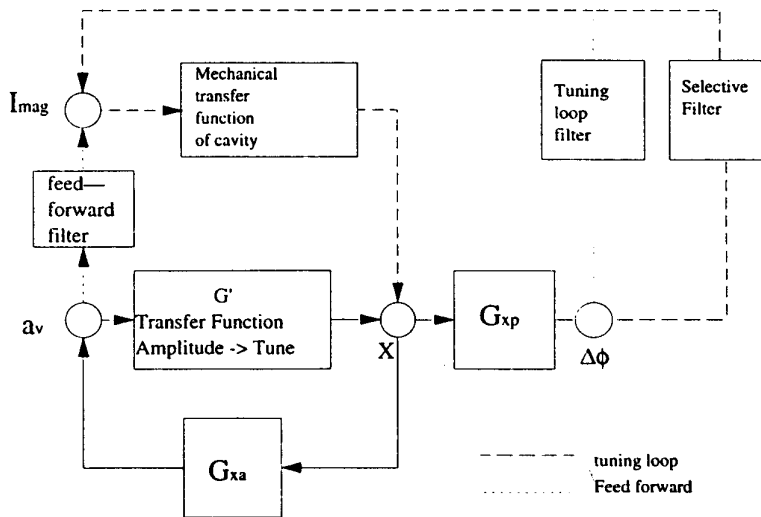Cavity voltage → phase (bottom)

Fig. 2.   Closed loop system block diagram and possible corrections (dotted lines)
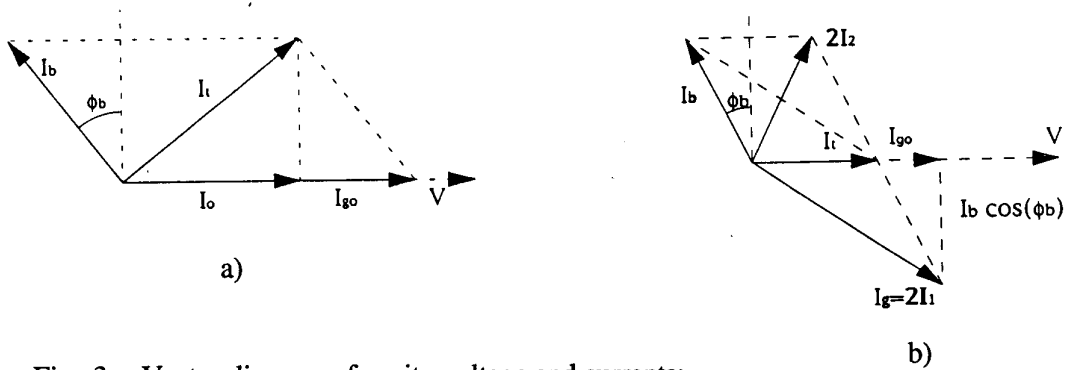

a)

b)

Fig. 3.   Vector diagram of cavity voltage and currents:
a) detuned cavity (usual case); b) on tune cavity

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