Higher Order Mode Suppression In Accelerators

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ABSTRACT

The frequencies and techniques of RF cavities in present and future accelerators span a wide range. A correspondingly broad spectrum of mode damping measures has evolved and is described and commented.

1. Introduction

If one plots the beam impedance of an accelerator against frequency one finds below the beamtube cutoff frequency a number of resonances. These can be traced back to the presence of cavities in the beamtube, especially the RF cavities, and how to reduce the impedance at these resonances is the subject of this talk.

2. Damping by propagating modes

The observation that impedance resonances disappear above the beamtube cutoff gave rise to a damping approach of apparently great simplicity. One tries to put the cavity between beamtubes of such a big diameter that *all modes*, except the fundamental one, become propagating[1,2].

Evidently, to keep the tube size manageable, this can only be done at high enough *fundamental mode* (FM) frequencies. But even there are pitfalls. If one widens the iris diameter of a π-mode cavity (cell length $\lambda/2$) the frequency of the first higher mode TE_{111} falls and it 'refuses' to propagate. A way out of this dilemma has only been found recently, at least for monocell cavities.

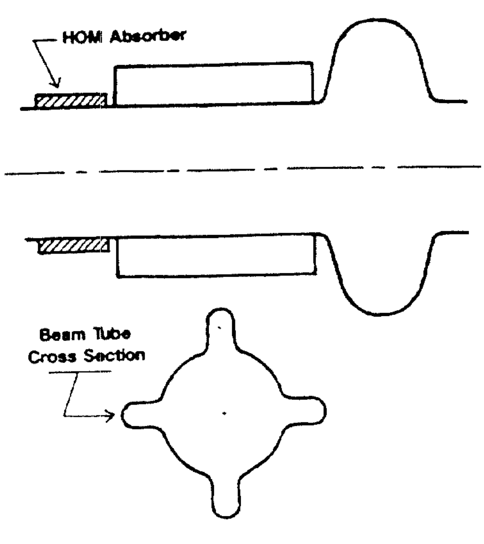


Fig. 1 SC B-factory cavity.

Making the cell length smaller than $\lambda/2$ moves the TE_{111} frequency up and forming four ridges into the beam tube [3] brings the cutoff frequency for dipol modes down so that propagation can be obtained. A consequence of the wide iris aperture inherent to this approach is a reduced coupling impedance (R/Q) for *all* modes, very welcome for the *higher modes* (HM) but only affordable for the FM if the cavity is made *superconducting* (SC) as in the Cornell University proposal [4] for a 500 MHz B-factory cavity, illustrated in **fig.1** .

To absorb the propagating HM, vacuum compatible ferrite tiles [5] bonded to the beam tube wall are foreseen. HM loaded Q values of the order 50 are obtained. A HM power of several kilowatts has to be removed. Therefore a low heat resistance bond between ferrite and beam tube wall is of prime importance. Alternative lossy materials with high thermal conductivity and in a ceramic form, compatible with UHV, have been developed at CEBAF[1]. Work on this problem is still going on. Such cavities, which couple via large apertures to guides of appropriate cutoff frequency, are often called *single mode cavities*.

Projects with copper cavities employing nose cones to enhance the fundamental mode R/Q attach these guides to the equatorial region. A proposal discussed in ref.[6] forsees square shaped guides evenly distributed around the circumference.

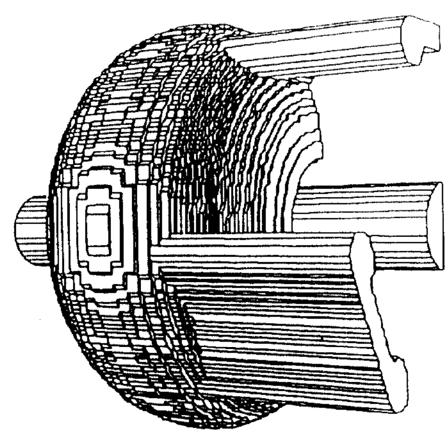


Fig. 2 Copper B-factory cavity.

Also the B-factory project at SLAC uses this concept of cavity damping but employs ridged waveguides taking advantage of there reduced size. **Fig. 2** shows the MAFIA code boundary of cavity and guides. Loaded Qs smaller 30 shall be realized [7]

[1] I.E. Campisi et al. , this conference.

3. Coupling slots

The use of guides is certainly the simplest solution to the problem of suppressing coupling to the FM but the transversal size required to propagate all HM is important and a length several times bigger is needed to sufficiently cut off FM transfer. Other technical constraints often demand more compact constructions. In this context coupling slots must be mentioned.

If parallel to the FM wall currents, coupling apertures of this form do not magnetically transfer FM energy and communicating to secondary volumes which contain RF absorbers a damping effect on only the higher order dipole modes can be obtained. The EPA 19MHz cavity of CERN uses slots backed by ferrite absorbers as part of the HM damping scheme [8]. A 1 GHz 'slotted cavity' has been studied at DESY[9]. Very interesting combinations of slots and waveguides are examined to achieve damping of travelling wave structures for future TeV linear colliders. Radial slots in the iris don't interact with the FM but couple strongly to the most troublesome TM_{110} modes. The excited slot waves flow into ridged waveguides which radially prolong the slots. But also guides radially attached to the structure cells are examined.[10,11,12].

4. Resonant coupling

Damping of a mode can be enhanced if the secondary volume is made *resonant* at the mode's frequency. If the secondary resonator has a quality factor Q (set by amount and position of the damping material) and its coupling factor to the mode resonance is k, then the damping of the mode, as characterised by its external Q, can be calculated.

$$Q_{ex} = \frac{1}{k^2}\,\frac{1}{Q} \qquad (1)$$

This formula is valid for $k\,Q < 1$; for $k\,Q >> 1$ mode splitting with $\Delta f = k\,f$ occurs and can be used to determine k either experimentally or with the help of a computer code like MAFIA which admits only boundaries and volumes without losses.

5. Use of transmission lines

Also with slot coupling wavelength determines the dimensions of secondary resonators. A step to more compactness, as required especially for HM dampers of SC cavities, needs a change to transmission lines as wave guiding elements.

Since lines have a zero cutoff frequency their transverse dimensions can be made as small as compatible with other requirements, as for instance the presence of a filter, tuned to suppress FM coupling.

HM dampers based on lines take two forms. The coupling element proper may be either a probe or a loop. Both are complementary, in coupling to electric and magnetic fields respectively, but a loop has also electric field sensitivity. Because of its simpler action we will now analyze a probe coupler in some detail. In its simplest, primitive form it is just a coaxial line, matched at its far end, and ending at or near to the cavity in an open circuit which forms the probe. In **fig. 3** it runs down to the beamtube to let the cavity proper unobstructed. This facilitates reaching high gradients in SC cavities and corresponds to the "beamtube coupler" scheme of the superconducting 4-cell LEP and HERA cavities.

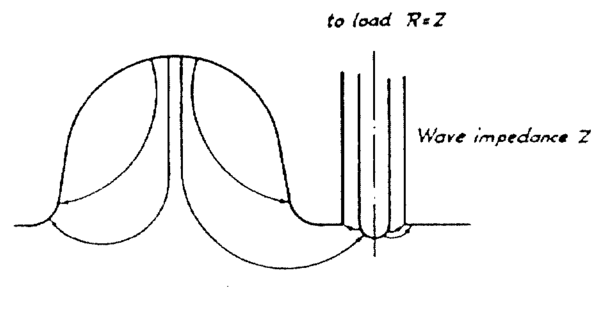


Fig. 3 A primitive probe coupler.

5.1 *Filter considerations*

For a 50 Ohm line of 100mm diameter and the LEP cavity measurements have shown that coupling to the TM_{011} mode (HM with the highest R/Q) is 7-times stronger than to the FM, i.e. if one wants to load the HM to an Q_{ex} of 15000 then, without a filter, the FM would have a Q_{ex} of 100000.

As a consequence, at an accelerating gradient of 5MV/m (8.6MV gap voltage) the FM power picked up (R/Q = 230Ω) would be :

$$P = V^2 / (2\, Q_{ex}\, R/Q) = 1.6\ MW$$

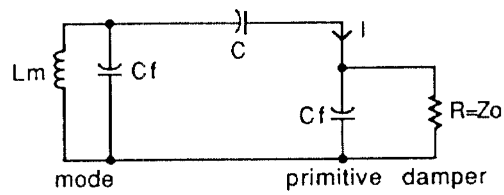
This is the power incident on a filter inserted to suppress FM coupling. By comparison, the HM power in LEP at 2 x 3mA beam current is minute, of the order 100 W. It is worthwhile to make the FM leakage through the filter even smaller, not bigger than 20W. Then thin flexible coaxial cables suffice to transport HM- plus FM leakage power out of the cryostat.

The filter and all coupler parts in front of it, however, have to be dimensioned and cooled to withstand the currents and voltages engendered by the incident FM power. Cavity construction standards are required, SC surfaces and liquid helium cooling, or water cooling if copper is the construction material.

5.2 *Resonator approach with lines*

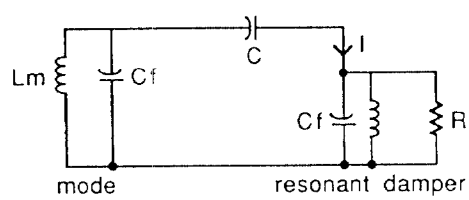
To alleviate the demands on the filter, the earlier mentioned method of resonant coupling is a valuable tool. Then a given mode damping specification can be realized with less probe area and hence smaller FM pick up.

We arrive at this concept quite logically. Around the probe tip unavoidably a fringe field exists which stores electric field energy. We can represent it by a capacitor C_f in parallel to the input resistance $R=Z_0$ of the matched line and may model coupling to a mode field by the circuit below



C_f and L_m represent a mode resonance with frequency ω and C the small proportion of the mode field which impinges on the probe tip.

C_f obviously reduces the damping effect of R in bypassing part of the coupling current I . However, the full damping potential can be realized if we compensate C_f by an inductance.



It is now worthwile to increase the input resistance R of the line. At least as long as $R << X = 1/(\omega C)$. If this condition holds, then formula (1) can be obtained by simple algebra :

$$Qex = (\omega Cf)\frac{X^2}{R} = 1/(k^2 Q)$$

$$k = C/C_f \ ; \ Q = \omega C_f R$$

6. A tuned antenna mode damper

Both, transformation to higher input resistance and reactance compensation can be combined if one uses line transformer techniques: The basic probe coupler is a $\lambda/4$-resonator. **Fig. 4** shows as example the dampers of the SPS 100 MHz cavities [13] .

The load resistor connects to the central conductor (the antenna) at some distance from the closed end of the resonator to set the coupler's Q. A FM filter is not required for three reasons: The lowest HM of these strongly reentrant cavities are at 3-times the FM frequency, the bandwidth of these couplers is small (since the HM come in clusters) and positioned near the cavity equator they see little FM E-field.

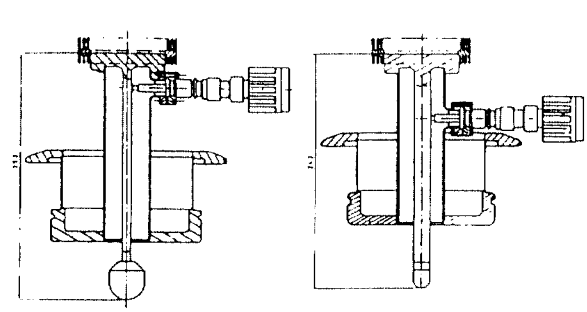


Fig. 4 Tuned antennas as mode dampers.

7. Multi-resonance couplers

For beam-tube couplers of present-day SC cavities with their large iris opening the situation is different. They have to cover a frequency span from 1.3- to 4-times the FM frequency and need a filter.The use of resonant coupling does not appear to be worthwhile.

But an inspection of the mode spectrum of the CERN and DESY cavities reveals that the harmful modes come grouped together at 1.4-, 1.9- and 3.4-times the FM frequency.In response to this, couplers with three resonances were developed.

Take the tuned antenna of **fig.4** as starting point. Connect inner and outer conductor near the probe tip by a post (a shunt inductor). Together with the second post in the back of the coupler (from the load connection point to the short circuit plane) a two post approximation to a ridged waveguide structure is formed which, due to its dispersion, reduces the frequency distance between the first and the second $\lambda/4$ resonance. In addition, replace the galvanic connection to the load by a capacitive one. As discussed in reference[14] the first resonance then splits into two.

To reject the FM a series resonator electrically parallel to the back post may be employed. This is the scheme of the HM dampers used at DESY [15]. Through the two posts the coupler is easy to cool and the ridged guide feature gives a prefiltering of the FM. The coupler is welded to the beamtube. **Fig. 5** gives an outline.

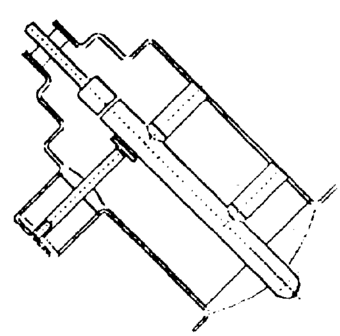


Fig. 5 Outline of the DESY HM coupler.

To ease the sputtering of cavities, the CERN version of this coupler had to be demountable. Therefore here the connection between the first advanced post and the external conductor is not galvanic but via a capacitive gap. A series resonator is formed which, correctly tuned, shunts the picked up FM displacement current to mass. Hence, anywhere to the rear, a dismounting flange sees only the much weaker HM currents.

Up to here we discussed interaction with FM E-fields. But in its advanced position the filter inductor also functions as H-field coupling loop.A geometry worked out in a collaboration between CERN and SACLAY[16] and sketched in **fig. 6** emphasizes this feature to enhance magnetic coupling to the TE_{111} modes.

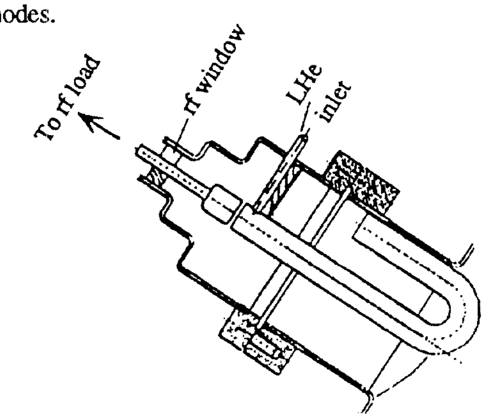


Fig. 6 Schematic of a demountable beamtube coupler.

The loop orientation is perpendicular to the cavity axis to avoid H-field coupling to the FM. However, in turning the loop away from this position, errors in FM filter tuning can be compensated.

The transfer curve of **fig. 7** has been produced in feeding a small probe, brought near to the coupler's front end, from a tracking generator, with a spectrum analyser connected to the coupler's output (replacing the load resistor). This kind of measurement exhibits a damper's E-field sensitivity. We see a notch at the FM frequency and the three resonances with their alignement on the mode spectrum. Replacing the probe by a small loop the H-field sensitivity can be measured.

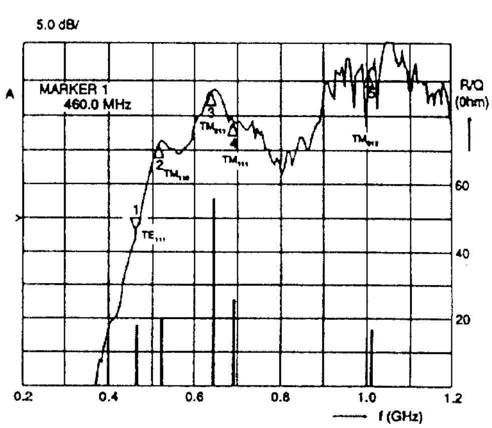


Fig. 7 Transfer curve of the LEP cavity damper.

With two such dampers, one on each beamtube, all harmful modes of the LEP cavity have Q values below 15000. In DESY, adding a third high Q coupler tuned to the TM_{011} frequency, this mode's Q is reduced to below 600.

8. Loop couplers

Reactance compensation is the key also to efficient H-field coupling.A loop formed from a conductor of 1cm diameter and 10cm length has at 500MHz a reactance $X = \omega L_s$ of about 150Ω. For a given flux through the loop, compensation by a series capacitor will increase the power dissipation in a connected 50Ω load by a factor ten. We now have a resonant loop with Q=X/R. Smaller load resistors give more damping but at the expense of coupler bandwidth.

Compensation at a higher frequency can be combined with notch filter action at the lower FM frequency if an additional inductor is connected parallel to the compensating capacitor to form a wavetrap. If we represent the induced loop voltage by a voltage generator then a circuit representation of such a damper takes the form of **fig. 8** .

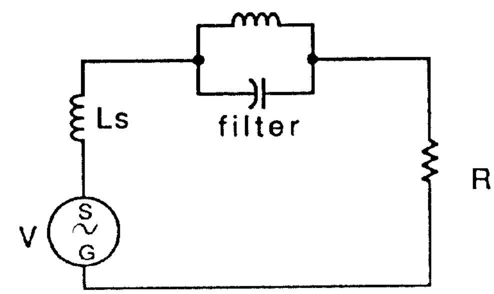


Fig. 8 Circuit diagram of resonant loop with notchfilter.

Discussions of damper constructions which follow this approach are in references[17,18,19]. **Fig. 9** shows as an example the 'HM suppressor' of the SPS 200MHz cavity.

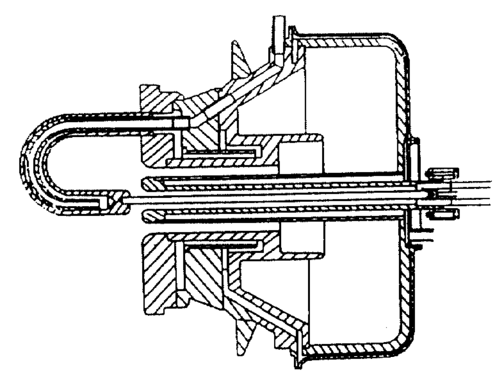


Fig. 9 Resonant loop damper of 200 MHz cavity.

9. Directional couplers as dampers

A directional coupler extracts the travelling wave components from a standing wave. Hence, if one moves such a coupler over a standing wave pattern, its damping action does not change. Located at an E-field zero it couples to the H-field, and at a H-field zero to the E-field.

A simple way to realize such a desirable damper behavior is to connect a loop to a waveguiding device with two transmission modes, as for instance a two wire screened transmission line. If each wire is independently and properly terminated to mass(the screen) then E-field coupling will excite the even (and H-field coupling the odd) mode and no interference between the two kinds of coupling can occur.

A damper proposal worked out for the 200 MHz SPS cavities connects the loop to the two ridges of a double ridged waveguide, terminated by vacuum compatible ferrite absorbers.In this way also FM filtering is obtained.[19]

10. Damping of 50 MHz KAON-Factory cavities

For these high intensity machines very effective HM damping is required in a broad frequency range. One development line [20] puts the dissipative element in series with the accelerating gap. As indicated in the equivalent circuit diagram of **fig.10** damping resistors are integrated into a parallel resonator, tuned to 240MHz. At the FM frequency most of the gap current is bypassed through the resonator's inductance.

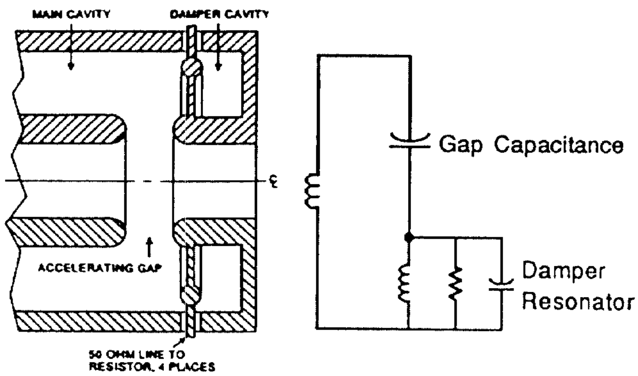


Fig.10 Damper resonator in series with acc. gap.

All HM which create voltage across the gap and hence interact with the beam are well damped. The concept is successful since in coaxial resonators the distance between FM and first HM is sufficiently big.

A second approach[21] belongs to the category of probe coupling with the specialty that FM suppression is not by a filter but by compensating at the FM electric coupling by an admixture of magnetic coupling.

11. The use of codes for Q estimations

Codes wich solve Maxwell's equations within lossy boundaries are not yet available. But codes like SUPERFISH or MAFIA can be used to make meaningful damping estimations.

One can for example "measure" the open circuit voltage and the short circuit current of a loop (or a probe). This gives sufficient information to calculate power flow into any, i.e. also a lossy, termination.[22]

A second method goes back to Slater and has recently been coupled to MAFIA as described in [23]. A damper guide, normally terminated, is left open and the frequency shift for different guide lengths calculated. From this information Q can be extracted.

12. Conclusions

Adequate structure damping is a key parameter for the success of all present day frontier accelerator projects, from factories to TeV colliders. In response intense development work is under way. The results obtained so far allow the conclusion that damping requirements can be met.

12. References

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