

# Higher Order Mode Damping in Kaon Factory RF Cavities

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## Summary

Proposed designs for Kaon factory accelerators require that the rf cavities support beam currents on the order of several amperes. The beam current has Fourier components at all multiples of the rf frequency. Empty rf buckets produce additional components at all multiples of the revolution frequency. If a Fourier component of the beam coincides with the resonant frequency of a higher order mode of the cavity, which is inevitable if the cavity has a large frequency swing, significant excitation of this mode can occur. The induced voltage may then excite coupled bunch mode instabilities. Effective means are required to damp higher order modes without significantly affecting the fundamental mode. A mode damping scheme based on coupled transmission lines has been investigated and is reported.

## Introduction

A major problem to be overcome for the proposed Kaon factory rf cavities is the excitation of higher order modes by the large beam currents. The modes that are of most concern have resonant frequencies that extend to 1 GHz. The magnitude of the voltage that is excited for a particular mode is directly related to its shunt impedance. It is desired to reduce the shunt impedances of these modes to less than 1000 ohms.

The types of rf cavities under investigation can be considered as sections of TEM transmission lines with the accelerating mode being the fundamental TEM resonance. The technique investigated in this paper to attenuate higher order modes is to introduce into the cavity a separate damping transmission line that is terminated at one end by a resistive load. The geometry of the damping line is selected so that the voltage induced at the resistor by the magnetic and electric coupling cancel at the fundamental frequency resulting in no attenuation. At the frequencies of the higher order modes the induced voltage at the resistor will probably not be zero and these modes will be attenuated. A simple quarter wavelength stripline resonator with the damping transmission line at the high voltage gap is shown in Figure 1. The damping line is terminated by a resistive load at the gap and a short circuit at an appropriate distance from the gap.

Coupled transmission line theory was used to analyse this method of mode damping. When two lengths of transmission line are placed sufficiently close such that their fields interact the lines are said to be coupled. There are two distinct modes of propagation and it is necessary to consider the coupled section as a four port network.

### Analysis of Coupled line Mode Damper

At the resonant frequency of the fundamental mode it will be assumed that the length  $d$  of the coupled section is small compared to the wavelength. This allows this section to be represented by a differential length of coupled transmission line.<sup>1</sup> The equivalent lumped circuit for the four port network is shown in Figure 2. The coupled line is characterized by capacitances  $C_{11}, C_{22}, C_M$  and inductances  $L_{11}, L_{22}, L_M$  whose values are expressed per unit length. The coupling between the two transmission lines is provided by the

capacitance  $C_M$  and the inductance  $L_M$ . The voltages across the coupled inductors  $L_{11}$  and  $L_{22}$  are related to their respective currents by

$$\begin{aligned} V_{L1} &= j\omega d(L_{11}I_{L1} + L_M I_{L2}) \\ V_{L2} &= j\omega d(L_M I_{L1} + L_{22}I_{L2}) \end{aligned}$$

The equivalent circuit for the stripline resonator is shown in Figure 3. The accelerating gap is at port 1. Ports 2 and 3 are terminated by the damping resistor and short circuit, respectively. The section of the resonator that is not coupled to the damping line is represented by the susceptance  $jB_r$  and is connected to port 4.

Imposing the condition that the voltage at the damping resistor is zero at the resonant frequency of the fundamental mode and with port 3 shorted the voltages  $V_1, V_4$  and the currents  $I_1, I_{L1}, I_{L2}$  are related by

$$G \begin{bmatrix} I_1 \\ V_1 \\ V_4 \\ I_{L1} \\ I_{L2} \end{bmatrix} = \vec{0}$$

where the matrix  $G$  is given by

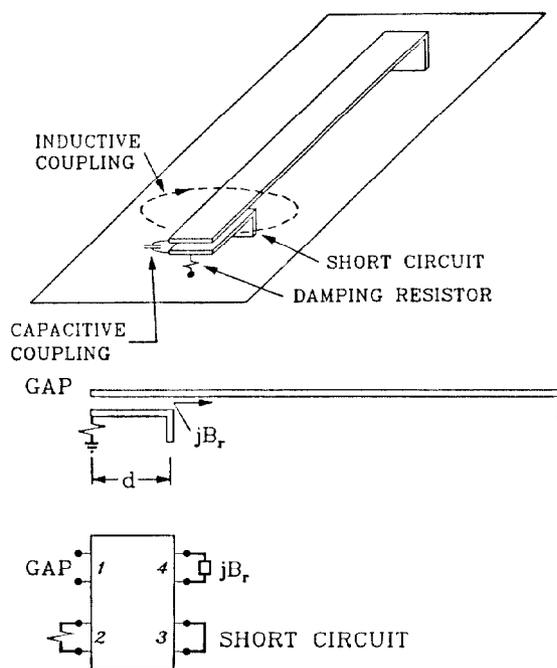


Figure 1 Stripline resonator with coupled line higher order mode damper

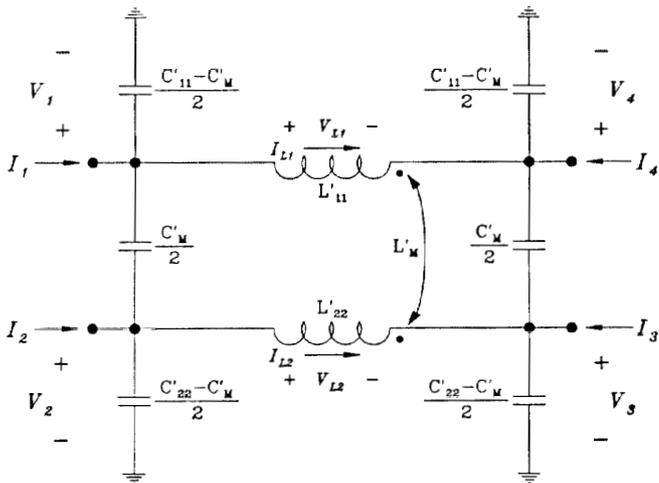


Figure 2 Four port representation of coupled section of resonator  
 $C'_{11} = C_{11}d$ , etc.

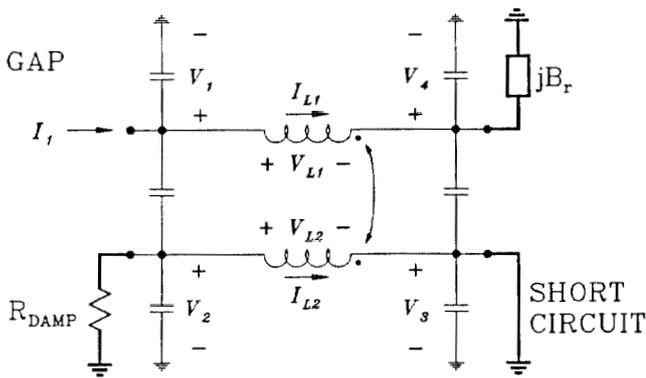


Figure 3 Equivalent circuit for resonator

$$G = \begin{bmatrix} 1 & -j\omega C_{11}d/2 & 0 & 1 & 0 \\ 0 & 0 & -jB_r - j\omega C_{11}d/2 & 1 & 0 \\ 0 & -j\omega C_M d/2 & 0 & 0 & 1 \\ 0 & -1 & 1 & j\omega L_M d & j\omega L_M d \\ 0 & 0 & 0 & j\omega L_M d & j\omega L_{22}d \end{bmatrix}$$

Setting the determinant  $G$  equal to zero allows determination of the length of the coupling section. The propagation constant  $\beta$  is defined as

$$\beta = \frac{\omega}{v} = \frac{2\pi \times \text{frequency}}{v}$$

The symbol  $v$  represents the velocity of propagation in the medium. Setting the determinant of  $G$  equal to zero and retaining only first order terms in  $\beta d$  yields the result

$$\beta d = \frac{-B_r}{vC_{11}}$$

### Design and measurement of stripline resonator

A simple stripline resonator was constructed in a rectangular copper box as shown in Figure 4. In this example the higher order mode damper consisted of symmetric coupled transmission lines. The two modes of propagation are identified as the even mode and the odd mode with each having their corresponding characteristic impedances. The capacitances per unit length for the two modes are given by<sup>2</sup>

$$C_e = 2\epsilon_o \left[ \frac{w/b}{1-s/b} + \eta_e \right]$$

$$C_o = 2\epsilon_o \left[ \frac{w/b}{1-s/b} + \frac{w}{s} + \eta_o \right]$$

where

$$\eta_e = 0.4413 + \frac{1}{\pi} \left[ \ln \left( \frac{1}{1-s/b} + \frac{1}{b/s-1} \ln \frac{b}{s} \right) \right]$$

$$\eta_o = \frac{b}{s} (\eta_e - 0.4413)$$

the capacitance  $C_{11}$  is given by

$$C_{11} = \frac{1}{2}(C_o + C_e)$$

the characteristic impedance of the single conductor stripline is

$$Z_o = \frac{376(b^2 - s^2)}{4wb} = 77.4 \Omega$$

the susceptance  $B_r$  is given by

$$B_r = -\frac{1}{Z_s} \cot \beta d_r$$

the physical dimensions chosen for the stripline resonator are

$$w = 5.08 \text{ cm}$$

$$b = 4.32 \text{ cm}$$

$$s = 0.76 \text{ cm}$$

$$d_r = 30.10 \text{ cm}$$

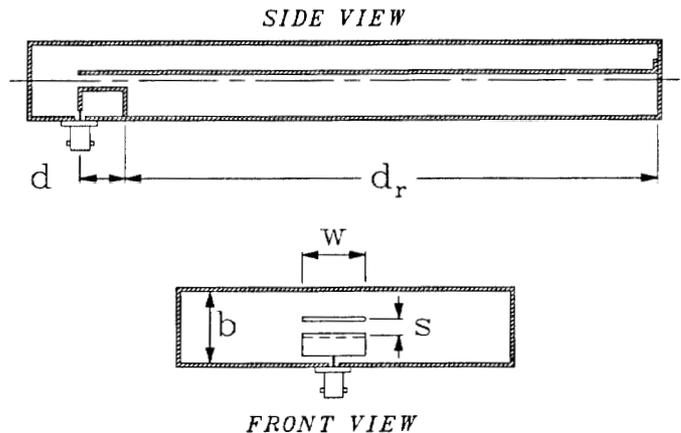


Figure 4 Simple stripline resonator

using these values yields

$$\begin{aligned}
 C_o &= 161.4 \text{ pF/m} \\
 C_e &= 36.3 \text{ pF/m} \\
 C_{11} &= 98.9 \text{ pF/m} \\
 d &= 4.06 \text{ cm}
 \end{aligned}$$

Measurement of the gap voltage as a function of frequency comparing the cases of the damping line resistively terminated and open circuited (no damping) is shown in Figure 5. The quality factor of the fundamental mode is 0.91 of its value with no damping. The majority of the higher order modes in this frequency range are significantly attenuated. For non TEM modes which are predominant at frequencies above 1.5 GHz this mode damping scheme appears to be less effective.

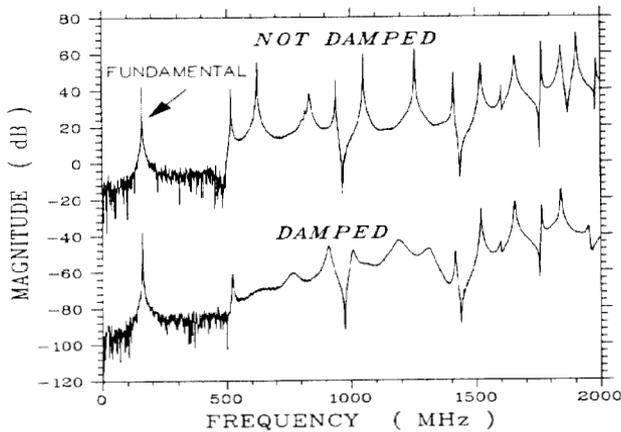


Figure 5 Measurements of stripline resonator

#### LANL/TRIUMF main ring cavity

At LANL a one half scale model of the proposed LANL/TRIUMF main ring cavity has been built. A cross section of the coaxial structure is shown in Figure 6.

The cavity consists of two sections, a beam leg which is on axis with the beam and a tuner leg situated at 90 degrees which contains

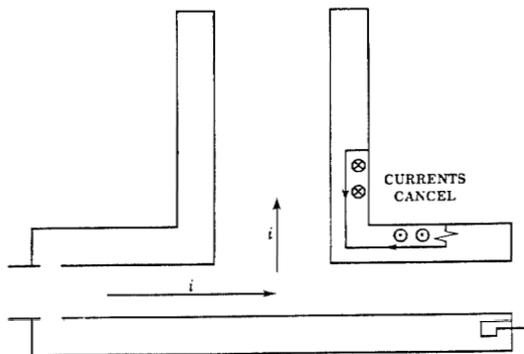


Figure 6 LANL/TRIUMF main ring cavity

$f_r$ (MHz)	$Q_o$	$Q_{damp}/Q_o$
107	1540	0.94
150	936	0.81
264	1804	0.07
307	1916	0.47
361	1803	-
473	4427	0.00
556	6360	0.31
578	6105	0.00
606	3752	0.00
619	1225	0.00

Table 1

the ferrite tuner. The higher order mode damper is formed through coupling of the damper transmission line to both the beam leg and the tuner leg. At the fundamental frequency each leg induces a voltage in the the damper line but the voltages are opposite in phase. By proper selection of the damper line geometry it should be possible to achieve a balance so that at the fundamental frequency no net voltage is induced at the damping resistor. For the higher order modes the induced voltages are not in general equal and energy will be absorbed in the damping resistor. Preliminary measurements have been done on the effectiveness of this technique and the results are shown in Table 1. The fundamental mode is not greatly affected while the majority of the remaining modes in this frequency range are significantly attenuated. Higher order mode damping work is continuing utilizing this technique.

#### Conclusions

A higher order mode damping scheme using coupled transmission lines has been investigated. Theoretical analysis and measurement indicate that it is effective for damping higher order TEM modes without significantly affecting the fundamental mode.

#### References

- [1] Lawrence N. Dworsky "Modern Transmission Line Theory and Applications" John Wiley and Sons
- [2] Harlan Howe, Jr. "Stripline Circuit Design" Artech House Inc.