Coupled Transmission Line Higher Order Mode Damper

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Abstract

The proposed design for the KAON factory requires 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 there is a large frequency swing during the acceleration cycle, significant excitation of this mode can occur. The induced voltage may then excite coupled bunched mode instabilities. It is necessary to reduce the shunt resistances of higher order modes to less than 1000 ohm without significantly affecting the fundamental mode. This paper describes an effective mode damping scheme using coupled transmission lines. Results of signal level measurements of such a mode damper installed in the LAMPF prototype rf booster cavity are reported.

Introduction

A higher order mode damping scheme is required to attenuate the shunt impedances of all higher order modes up to 1 GHz to less than 1000 ohm without significantly affecting the fundamental mode. A mode damper based on coupled transmission lines has been previously described[1]. This type of mode damper, shown in Figure 1, has been modified with the addition of a capacitive ring terminated into a resistive load, at the accelerating gap. The additional capacitance provides more effective attenuation of higher order modes. An inductive strap is attached to the ring and extends into the rear of the cavity, coupling into the magnetic field. The strap is capacitively terminated to ground. The fundamental mode is isolated from the damping effect of the capacitive ring by arranging the geometry of the damper such that for the fundamental mode the electric coupling, which arising mostly from the capacitive ring, is cancelled by the magnetic flux coupled in from the inductive strap which results in no power being dissipated in the resistor. For higher order modes it would be expected that the electric and magnetic coupling would not cancel and these would be attenuated.

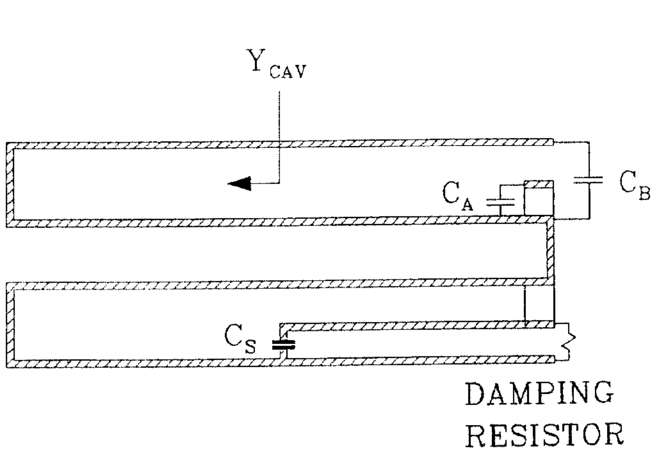

Figure 1: Coupled transmission line higher order mode damper

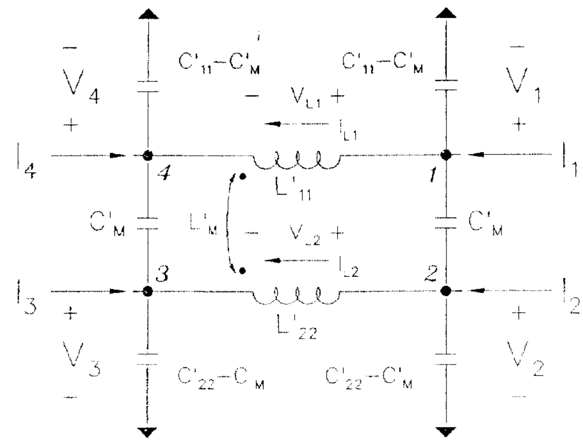

Figure 2: Lumped element representation of coupled transmission lines

Theory

To analyse this type of mode damper use is made of coupled transmission line theory. The section of coupled lines represents a four port network whose lumped equivalent circuit is shown in Figure 2. Values for the capacitances and inductances for this network can be determined from

$$\begin{aligned} C'_{ii} &= \frac{C_{ii}}{\beta}\tan\frac{\beta d}{2} \\ C'_M &= \frac{C_M}{\beta}\tan\frac{\beta d}{2} \\ L'_{ii} &= \frac{L_{ii}}{\beta}\sin\beta d \\ L'_M &= \frac{L_M}{\beta}\sin\beta d \end{aligned} \tag{1}$$

The inductances L_{ii}, L_M and capacitances C_{ii}, C_M are the values per unit length and are determined from the geometry. If the coupled lines are in a medium that is homogeneous and isotropic the following relations are valid

$$\begin{aligned} \text{coupling} = k = \frac{C_M}{\sqrt{C_{11}C_{22}}} &= \frac{L_M}{\sqrt{L_{11}L_{22}}} \\ \text{velocity of propagation} = v &= \frac{1}{\sqrt{C_{ii}L_{ii}(1-k^2)}} \end{aligned} \tag{2}$$

The equivalent lumped transmission line circuit for the damper and cavity is shown in Figure 3. Node 1 is the accelerating gap, the damping resistor is connected to node 2 and at node 3 a capacitance C_s is introduced which will be referred to as the strap termination capacitance. At node 4 the admittance $Y_{cav} = G_{cav} + jB_{cav}$ represents the remainder of the cavity. The capacitance C_A represents the capacitance between the ring and the inner conductor. The tip capacitance C_B represents the capacitance from the inner conductor to ground. The cavity plus damper is resonant when the susceptance at node 1 is zero. To prevent attenuation of the fundamental mode the voltage across the damping resistor must be zero at the resonant frequency. These two conditions are satisfied through correct selection of Y_{cav} and C_S . It will be assumed for the following analysis that $G_{cav} = 0$. Applying KCL (Kirchhoff's Current Law) at the four nodes yields

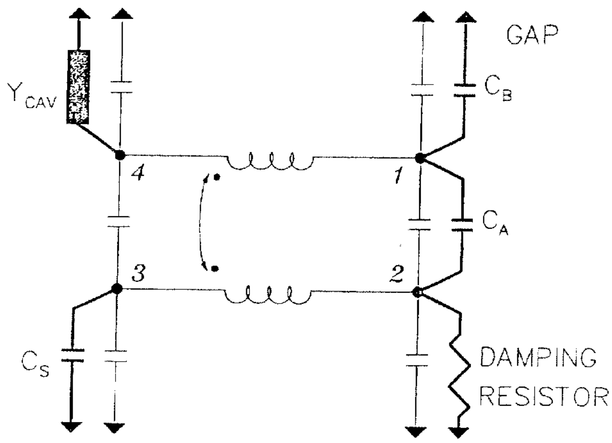

Figure 3: Lumped element representation of mode damper in cavity

$$
\begin{aligned}
\text{Node 1 :} \quad I_S &= s(C_A + C_B + C'_{11})V_1 + I_{L1} \\
\text{Node 2 :} \quad 0 &= -s(C_A + C'_M)V_1 + I_{L2} \\
\text{Node 3 :} \quad 0 &= s(C'_{22} + C_S)V_3 - sC'_M V_4 - I_{L2} \\
\text{Node 4 :} \quad 0 &= -I_{L1} - sC'_M V_3 + (sC'_{11} + Y_{cav})V_4 \qquad (3)
\end{aligned}
$$

The relations for the coupled coils are

$$
\begin{aligned}
V_1 - V_4 &= sL'_{11}I_{L1} + sL'_M I_{L2} \\
-V_3 &= sL'_M I_{L1} + sL'_{22}I_{L2} \qquad (4)
\end{aligned}
$$

To simplify the analysis the following approximation for the KCL relation at node 4 is made

$$I_{L1} \approx V_4(sC'_{11} + Y_{cav}) \qquad (5)$$

The above equations are solved to obtain the required admittance $Y_{cav} = jB_{cav}$ and strap termination capacitance C_S .

$$B_{cav} = \omega C'_{11} + \left\{ \omega L_{11} - \frac{1 + \omega^2 L'_M (C_A + C'_M)}{\omega(C_A + C_B + C'_{11}}\right\}^{-1} \qquad (6)$$

$$C_S = -C'_{22} + \frac{\xi - \omega C'_M(\omega C'_{11} + B_{cav})^{-1}}{\omega^2(L'_{22}\xi - L'_M)} \qquad (7)$$

where

$$\xi = \frac{I_{L2}}{I_{L1}} = -\frac{C_A + C'_M}{C_A + C_B + C'_{11}} \qquad (8)$$

A computer program has been written to analyse the simple coaxial line cavity plus damper shown in Figure 1 with the accelerating gap driven by a current source. The voltage on the capacitive ring as a function of frequency for the case where $C_B = 0$ and $1/C_S = 0$ (short circuit) is shown in Figure 4. The voltage peaks at the resonant frequency of the cavity and shows a sharp dip at a frequency lower than that of the cavity. The significance of the dip is that this is the frequency for which the electric coupling from the capacitive ring and magnetic coupling from the inductive strap cancel. When the damper is properly "tuned" the frequency of this dip coincides with the resonant frequency of the cavity. This condition was achieved by adjusting the strap termination capacity C_S. The correct value for the strap termination capacity is given by equation 7 and the value for B_{cav} from equation 6. It was assumed that the tip capacity C_B was zero and that the damping resistor was 50Ω. The frequency response from 0 MHz to 1 GHz for the cases of load off and load on is shown in Figure 5. Comparing the two plots shows that the damper is very effective in attenuating the shunt resistances of higher order mode up to 1 GHz to less than 1000 Ω.

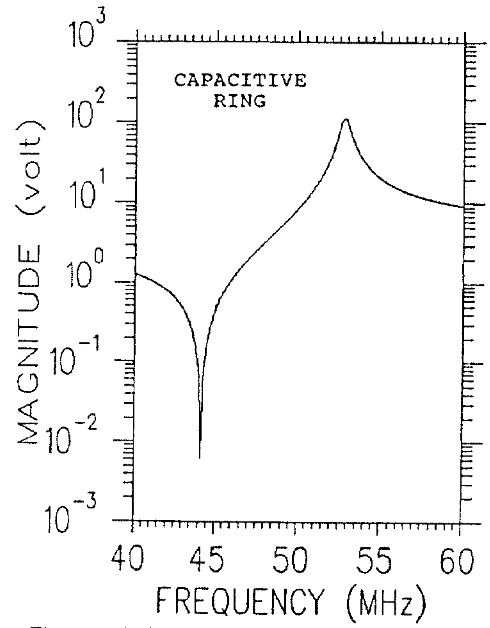

Figure 4: Voltage response on capacitive ring

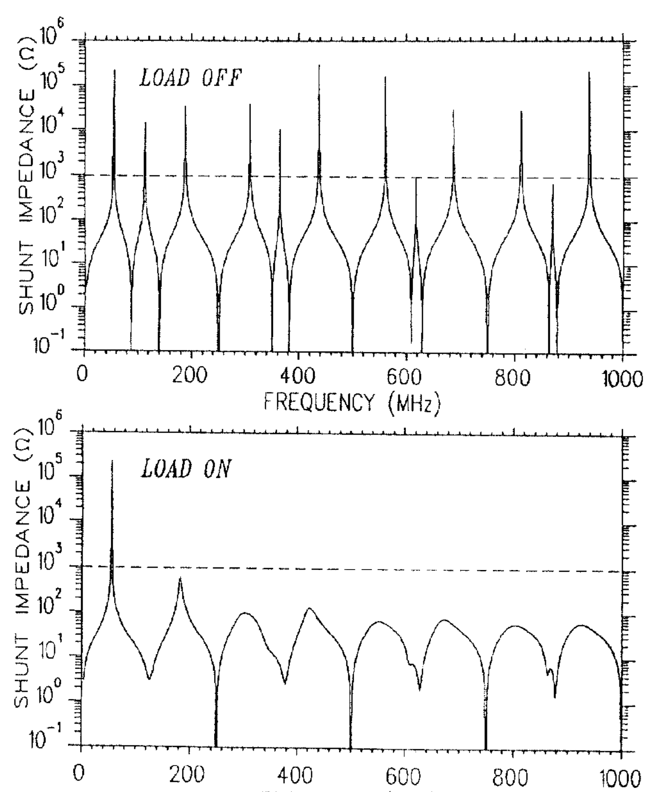

Figure 5: Shunt impedance of cavity with damping resistor off and on

Coupled line damper in LAMPF prototype cavity

A coupled line higher order mode damper was constructed and placed in the LAMPF prototype booster cavity as shown in Figure 6 . The radius of the capacitive ring was 4cm greater than that of the inner conductor. It's length was 5 cm and provided a calculated capacitance of approximately 8 pF. Four BNC type bulkhead adaptors were mounted on the the outside of the cavity, 90 degrees apart. This allowed different combinations of damping resistors to be tried. The center conductors of the bulkhead adaptors were attached to the capacitive ring with low inductance connections. For the purpose of clarity the inductive strap was shown to be at the bottom of the cavity in Figure 6. In practice two inductive straps were used and were positioned on opposite sides of the cavity. The straps extend toward the rear of the cavity and terminate at two ports already existing in the cavity. The straps were constructed from .9525 cm copper tubing. The strap termination capacitance was realized by inserting .127 mm Kapton spacers between the flange of the port and a plate solder on to the inductive strap as shown in Figure 7. This provided capacitances in the order of several hundred pF. Adjusting the tension on the nylon screws that positioned the plates over the ports provided the adjustment necessary to achieve the required tune. The introduction of the mode damper lowered the fundamental frequency by approximately 4 MHz but did not adversely affect the tuning range. The shunt impedance was measured using the "wire" technique[2] that is commonly used in longitudinal coupling impedance measurements. The real part of the cavity shunt impedance as a function of frequency with the loads off and loads on are shown in Figures 8 . As is evident from the plots the shunt resistances of the higher order modes up 1 GHz were reduced to less than 1000 Ω. It should be noted that there were some modes around 600 MHz and 800 MHz that were not affected by the mode damper. These were dealt with separately by installing coupling loops terminated into 50 Ω near the the accelerating gap and in the lower vertical section of the cavity which contains the coupling capacitor.

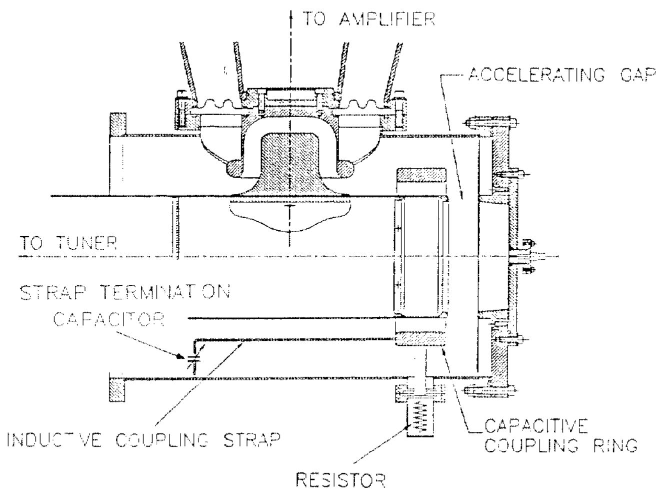

Figure 6: Coupled transmission line damper in LAMPF prototype booster cavity

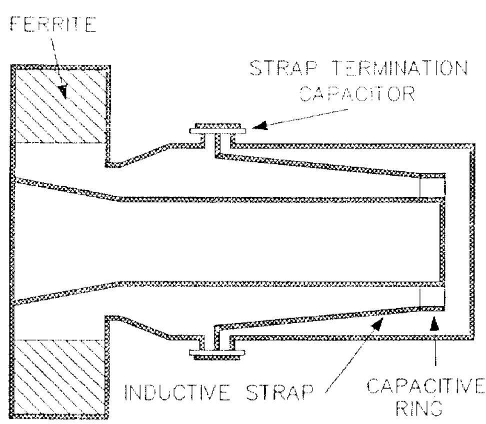

Figure 7: Cross section of LAMPF cavity showing strap termination capacitance

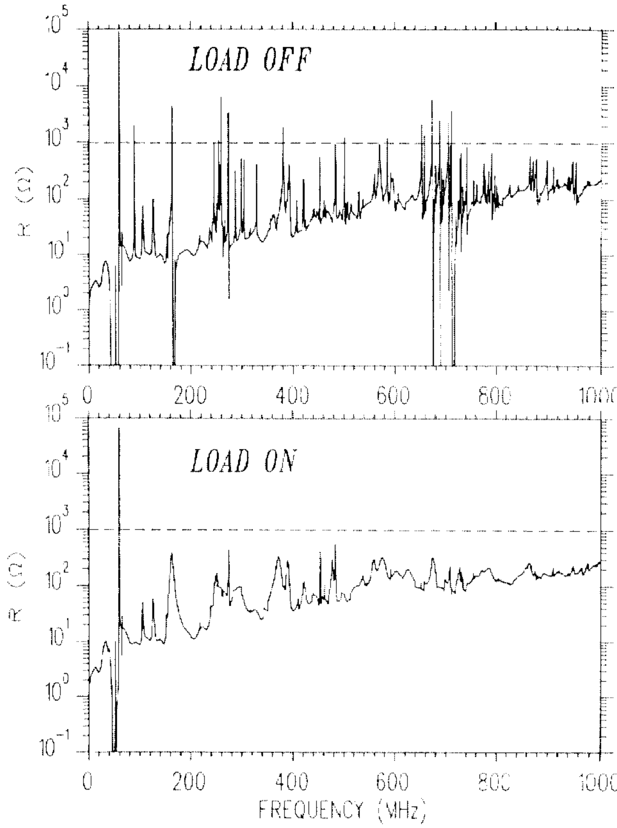

Figure 8: Shunt resistance of LAMPF cavity with damping resistors on and off

Summary

A mode damping scheme based on coupled transmission lines has been investigated theoretically and experimentally on the LAMPF prototype booster cavity. The measurements on the LAMPF prototype cavity demonstrated that except for some troublesome modes around 600 MHz and 800 MHz that this mode damper was successful in reducing the shunt impedances of all higher order modes up to 1 GHz to less than 1000 ohm.

References

[1] T. Enegren, R.L. Poirier, J. Griffin, L. Walling, H.A. Thiessen and W.R. Smythe., " Higher Order Mode Damper in KAON Factory RF Cavities", Proceedings of the 1989 IEEE Particle Accelerator Conference, March 20-23, 1989, Chicago, P196

[2] H. Hahn and F. Pederson "On Coaxial Wire Measurements of the Longitudinal Coupling Impedance", Brookhaven National Laboratory report BNL-50870, April 1978