A VERSATILE RF CAVITY MODE DAMPER

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Abstract

The ferrite tuned KAON booster synchrotron cavity is coaxial with the beam and operates from 46 to 61 MHz. Higher order modes can be strongly damped by including one or more 50 Ω resistors shunted by a 250 MHz annular slot cavity within the acceleration cavity. The parameters are chosen so that the resistance dissipates a tolerable amount of power at the acceleration frequency. Immediately above the acceleration frequency, the damping shunt resistance decreases rapidly, approximately as the inverse fourth power of the frequency. Both calculation and measurement have shown very strong damping of all modes between the fundamental and 1,000 MHz.

Introduction

The rf cavity is an essential component of any synchrotron, providing the accelerating voltage. It is also an object of concern because it can excite beam instabilities, which, in turn, can limit the beam current. For example, the fundamental (accelerating) cavity mode is involved with the Robinson instability [1]. Historically, various feedback techniques as well as external damping have been used to raise the current limit imposed by this instability. In addition to the fundamental mode, higher order cavity modes are unavoidably present. They can also cause beam-current-limiting instabilities. These are usually longitudinal coupled-bunch oscillations [2]. The exact, quantitative details of these various possible instabilities and their damping mechanisms are complicated and dependent on a myriad of machine details and parameters. In spite of advanced planning, some of these may have to be dealt with during the commissioning process of any new accelerator. It is therefore desirable to strongly suppress higher order cavity modes. An rf cavity mode damper is proposed here which has several desirable properties. It is a general purpose mode damper, applicable to many cavities. It damps all modes which couple to the accelerating gap, and its parameters can be adjusted to suppress the higher order modes much more strongly than the fundamental mode, which is needed for beam acceleration.

Description

The mode damper consists of an annular-slot resonant cavity which is close to the accelerating gap and coaxial with the beam. The damper cavity is heavily loaded by one or more rf power resistors connected across its entrance slot. In this location, the displacement current flowing across the accelerating gap must also flow through the damper. A practical realization of this design is shown in Fig. 1.

At low frequencies, the power dissipated in the resistor(s) increases as the fourth power of the frequency, assuming a fixed voltage across the accelerating gap. Under these conditions, the displacement current across the accelerating gap is proportional to the frequency. Most of that current will flow through the (inductive) damper cavity, whose reactance is proportional to frequency, in the low frequency limit. Thus, the voltage across the damping resistor is proportional to the frequency squared, and the power dissipated is proportional to the fourth power of the frequency. Hence, the equivalent damping resistance appearing in parallel with the shunt resistance of the accelerating cavity at the accelerating gap decreases as the inverse fourth power of the frequency. It is this fact that allows the damper to load the fundamental mode relatively lightly and the higher order modes heavily. A more complete analysis is given below.

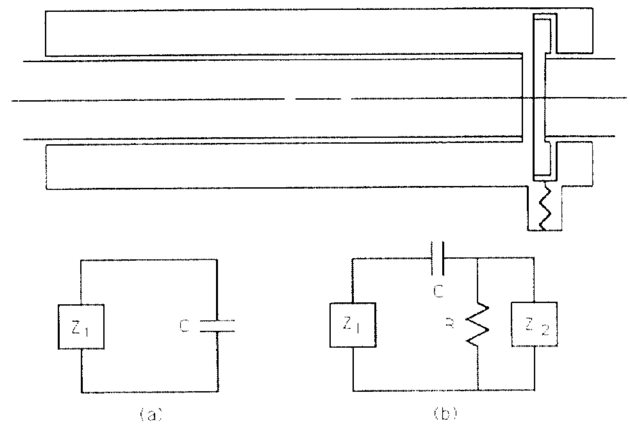

Fig. 1. A quarter wavelength coaxial line cavity with a mode damper cavity added. Its equivalent circuits are given with, (b) and without, (a) the damper. Z_1 is the impedance of a short-circuited copper coaxial line with radii of 9.0 and 17.5 cm, and length 105 cm. C is the accelerating gap capacitance of 18 pF. The resonant frequency is 59 MHz. Z_2 is the impedance of the annular slot cavity, and R is its loading resistor.

The Equivalent Circuit

A useful analysis of this mode damper can be achieved by using a combination of two cavities and circuit elements. The utility of the mode damper is demonstrated by calculating its effect on the normal modes of the quarter wave resonator shown in Fig. 1. Without the mode damper, the complex impedance presented to the beam at the gap is:

$$Z = \frac{Z_1 \times Z_c}{Z_1 + Z_c}, \tag{1}$$

where Z_1 is the impedance of the quarter wave resonator, and Z_c is the impedance of the beam gap capacitance. The absolute value of Z is ploted as a function of frequency in Fig. 2a.

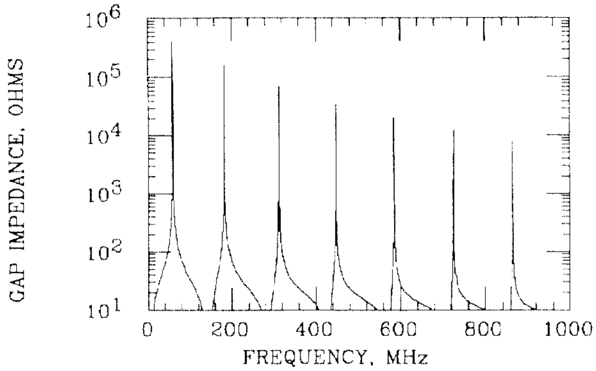

Fig. 2a. The impedance (absolute value) presented to the beam by the cavity defined in Fig. 1a.

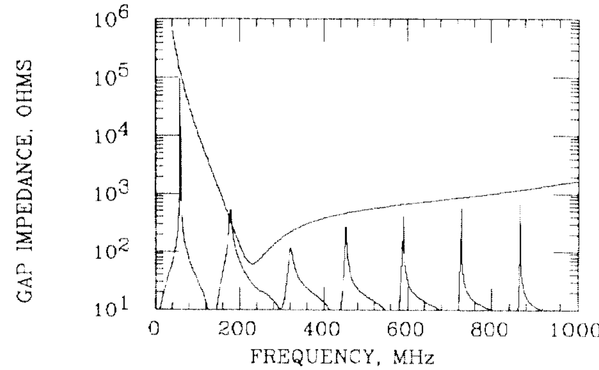

Fig. 2b. The impedance of the same cavity, but with the mode damper added, as calculated with Eq. (2). The smoother curve is the damping resistance calculated with Eq. (4).

The equivalent circuit of the complete cavity and mode damper is given in Fig. 1b. The impedance presented to the beam becomes:

$$Z = \frac{Z_t \times Z_c}{Z_t + Z_c}, \qquad (2)$$

where:

$$Z_t = Z_1 + \frac{R \times Z_2}{R + Z_2},$$

and Z_2 is the impedance of the damper cavity. The calculation of Z_2 as a function of frequency presents a minor problem. A computer program, such as SUPERFISH [3], may be necessary to accurately determine the cavity parameters, but such a program is awkward to use in designing the mode damper. For purposes of damper design, the procedure adopted here is to approximate the damper cavity by two sections of coaxial transmission line terminated in a short- circuit, which provides an analytical expression for Z_2. This approximation has been compared with SUPERFISH solutions, and has been found to give the resonant frequencies with an accuracy of 10 to 20%. The coaxial cavity model dimensions can be adjusted to tailor the mode damper's properties. After the damper has been designed, the actual cavity dimensions which will produce the desired resonant frequencies and R/Q can then be refined by use of SUPERFISH. The absolute value of the calculated gap impedance of the quarter wave cavity with the mode damper added is given in Fig. 2b.

A Useful Damping Resistance Expression

An approximate expression for the equivalent damping resistance appearing across the cavity gap is useful when choosing the damper parameters. Referring to the circuit in Fig. 1b, the elements in series with Z_1 have an impedance Z_g, which can be resolved into an ideal capacitance in parallel with a damping resistance, R_d, where:

$$Z_g = Z_c + \frac{R \times Z_2}{R + Z_2}, \qquad (3)$$

and:

$$R_d = 1/real(1/Z_g). \qquad (4)$$

This resistance, R_d, is close to the damping resistance appearing at the gap if the voltage across the damper is small compared to the voltage across the gap, which is normally the case. The expression for R_d is of value because it allows the exploration of damping resistance as a function of frequency for various parameter choices, without having to consider the rest of the cavity. The value of damping resistance found with this expression is ploted in Fig. 2b. It is seen to be in good, but not perfect, agreement with the more accurate results of the previous section.

Optimizing the Damper Parameters

The important damper parameters are: the gap capacitance, C, the loading resistance, R, and the slot cavity parameters. The relevant slot cavity parameters are: f_1, the frequency of the lowest resonance (high-impedance), the corresponding R/Q, and f_2, the frequency of the lowest low-impedance resonance.

The capacitance, C, is that part of the gap capacitance which feeds current to the mode damper. Increasing C increases the loading of the main cavity at all frequencies. Some adjustment of C is possible by varying the location of the entrance slot to the damper cavity, or by making the cavity end wall more, or less, cup shaped, as is illustrated in Fig. 1.

In the present application, the loading resistance, R, has been assumed to be one or more standard coaxial 50 Ω, 5 kw water cooled rf power resistors. These resistors provide a rugged, low inductance installation. For the KAON booster synchrotron, it is anticipated that about 5 kw of fundamental power would be dissipated in this resistance, which will increase the Robinson stability.

The effects of the damper cavity parameters are illustrated in Fig. 3. The lowest resonant frequency of the cavity, f_1, produces the minimum at 249 MHz. There the slot cavity impedance is a maximum, and most of the current across the gap reactance, X_c, must go through the resistance, R, so the damping resistance at the minimum is approximately:

$$R_d = \frac{X_c^2}{R}. \qquad (5)$$

As expected, the width of this minimum is determined by Q_1, the loaded Q of the damper cavity, which is the quotient of R and the R/Q value of the cavity at this resonance.

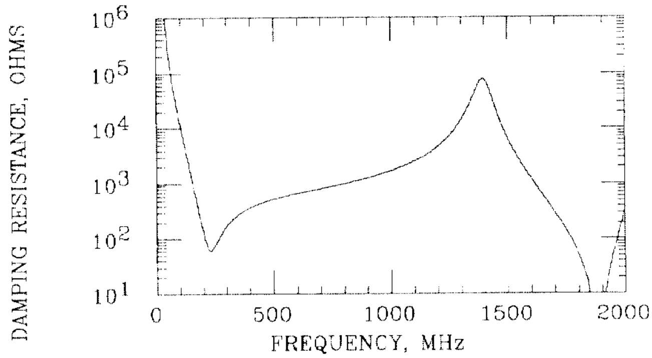

Fig. 3. Damping resistance at the gap calculated with Eq. (4). The effects of the "parallel" resonance at 249 MHz and the "series" resonance at 1393 MHz are clearly seen.

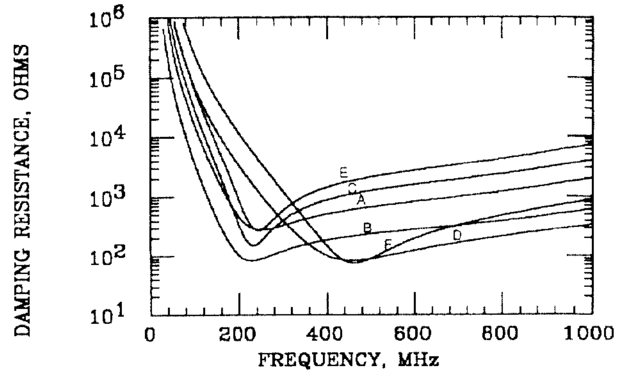

Fig. 4. The effective damping resistance appearing at the acceleration gap as a function of frequency for various choices of damper parameters, which are listed in Table 1.

If the damper cavity was just a uniform coaxial line, short-circuited at the end, there would be a second resonance at $f_2 = 2f_1$, at which the short at the end of the line would produce a voltage null at the damping resistor. At this frequency the damper becomes ineffective. By changing the shape of the cavity, the frequency at which this second resonance occurs can be pushed much higher than twice f_1. In Fig. 3, that resonance occurs at 1393 MHz, or $5.6f_1$. For an actual cavity, f_2 can be determined by using SUPERFISH with the Neumann boundary condition imposed at the entrance slot, which corresponds to zero voltage across the entrance.

The effects of changing various damper parameters are shown in Fig. 4. The parameters themselves are listed in Table 1. The changes considered include doubling: the gap capacitance, C; the damper resistance, R; the resonant frequency, f_1; and the loaded Q of the cavity, Q_1.

Table 1.

The damper parameters for the curves A–E in Fig. 4. Curve G parameters apply to Figs. 2 and 3. Parameter values significantly different from those of curve A are printed in boldface type.

Curve	C (pF)	R (Ohms)	f_1 (MHz)	Q_1	f_2 (MHz)
A	8	25	249	1.5	1393
B	**16**	25	249	1.5	1393
C	8	**50**	249	**3.0**	1393
D	8	25	**498**	1.5	1545
E	8	25	249	**3.1**	1393
F	8	25	**498**	**2.8**	1535
G	**18**	25	249	**3.1**	1393

Prototype Tests

As a preliminary test of the ideas presented here, a non-optimized version of this mode damper was installed in the LAMPF/TRIUMF prototype booster cavity [4]. Design compromises were required to fit it into the existing cavity; however, the tests verified that it was possible to damp all modes up to at least 1,000 MHz, and that it was possible to damp the higher order modes much more strongly than the fundamental mode.

Discussion

The effectiveness of the higher order mode damper described here is illustrated by Fig. 2. It is broad range, effectively damping higher order modes up to 20 times the fundamental frequency. It couples directly to current flowing to the acceleration gap, and thus is expected to damp most modes which can affect the longitudinal motion of the beam. It discriminates in favor of the fundamental mode by use of a fourth power dependence on frequency, rather than by the use of tuned circuits. This is an advantage for synchrotron cavities which must be rapidly tuned over a substantial frequency range. The mode damper absorbs power at the fundamental frequency; however, appreciable higher order mode damping can be achieved with modest power consumption. The mode damper is simple and rugged.

Acknowledgements

We wish to thank J. E. Griffin, C. C. Friedrichs, H. A. Thiessen, and L. S. Walling for stimulating discussions of higher order mode dampers. One of us (WRS) wishes to thank TRIUMF and Los Alamos National Laboratory for their hospitality and support during his sabbatical leave year.

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