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FERMILAB 500-GEV MAIN ACCELERATOR RF CAVITY 128-MHZ MODE DAMPER

Q. A. Kerns and H. W. Miller
Fermi National Accelerator Laboratory*
Batavia, IL 60510

Summary

The Fermilab 500-GeV main accelerating system has been operating for a year now with the aid of 128-MHz mode dampers. Such dampers proved to be necessary to achieve stable operation and a reasonably smooth slow spill at intensities of ~2×10^{13} protons per pulse, and furthermore are low-cost and reliable. This paper describes the approach used to identify troublesome modes, mentions something about the observed beam blow-up without dampers, and outlines the steps taken to design and install suitable dampers on eighteen main ring cavities. Spectrum analyzer pictures help illustrate the performance.

Introduction

Accelerating cavities in the Fermilab main accelerator have a number of higher order modes which can lead to longitudinal beam instabilities.[1] The instability growth time is related to the rf gap impedance and appropriate exciting component of beam current.[2] Control of the instability growth can sometimes be accomplished electronically in the low-level circuits of the accelerator, but in any case the magnitude of the problem is reduced by damping the offending modes in the cavity. Both approaches, low-level control and high-level damping, have been used at Fermilab. This paper describes the high-level mode damper used in the main ring cavities. Most modes above 150 MHz were damped in the original cavity design by selective end wall ferrites.[3] The known remaining frequencies that excite longitudinal instabilities, at machine intensities up to 2.5×10^{13} protons per pulse, reside in a range from 112 to 132 MHz. This paper describes the mode damper used on the main ring cavities to cover this range of frequencies.

Method of Determining Strength of Beam-Excited Modes

The main-ring rf cavities tune their 52.813 to 53.104 MHz fundamental mode by adjusting dc current in loop coupled ferrite tuners. Many of the cavity higher order modes are also tuned with ferrite bias current. The frequency and voltage distribution of a mode in the cavity is thereby a function of cavity geometry, ferrite bias current and rf power level (via cavity temperature).

Our mode damper was developed on a spare main ring cavity that could be driven and measured independently of machine operation. To measure the array of modes, a 300Ω Zo-current probe bidirectionally matched to a 50Ω system, was constructed to fit across the gap. The probe was then inserted across the cavity gap and connected to test instruments, Fig. 1. RF frequency was swept and the transmitted signal viewed on a spectrum analyzer.

Figure 2 shows a typical transmitted signal at one ferrite bias current. The absorbtion of the signal indicates the modes coupled to the gap. Broad nulls in the transmitted signal indicate strong coupling to the gap (coupling is a function of both the modal Q and voltage distribution within the cavity). Repeating the

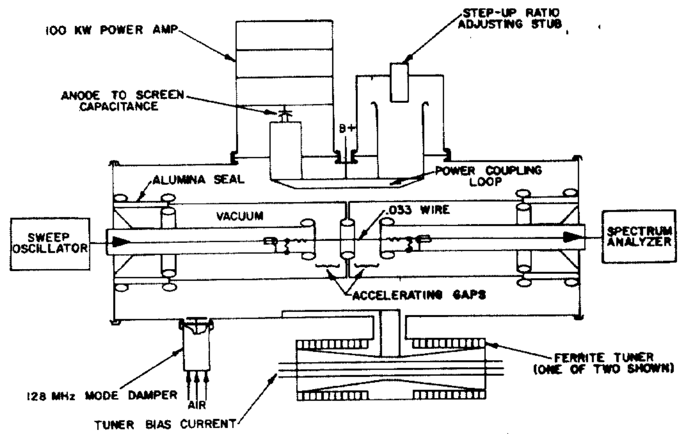
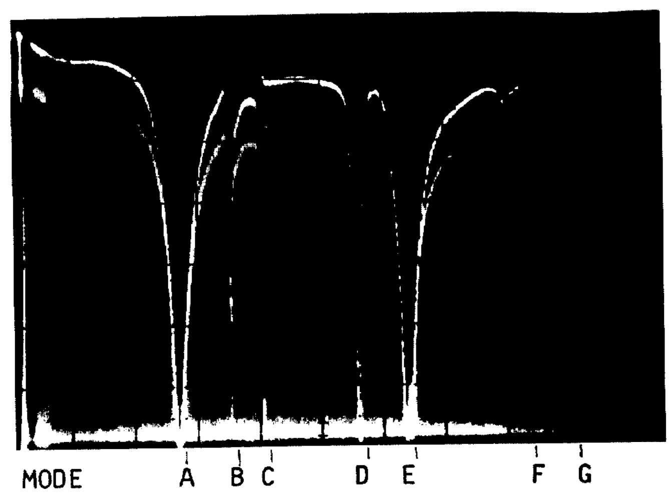


Fig. 1. Cavity and test circuit.



Horiz: 20 MHz/Div.
Center Line: 100 MHz
Tuner Bias: 500 Amperes

Fig. 2. Spectrum analyzer response in test circuit (Fig. 1).

measurement at a number of ferrite bias currents covering the operating range of the cavity, we mapped out the cavity resonant frequencies and the relative strength with which each mode couples to the gap.

Figure 3 is the map of the fundamental and next 18 cavity modes versus bias current. Accelerator operation requires bias current from ≈40 to ≈1800 amperes. Modes that are suspected to couple strongly to the beam, based on the width of the probed resonance, are indicated by an asterisk.

Before we had the data of Fig. 3, there were observations of beam blow-up at intensities approaching 2×10^{13} ppp in the main accelerator, accompanied by the buildup of a spurious signal in main-ring rf cavities. The result was a longitudinal oscillation of every-third-bunch in the accelerator. Coincident with the beam instability, a spectrum analyzer monitoring

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Frequency MHz

Bias I Mode	A*	B	C	D	E	F	G	H	I*	J	K	L	M	N	O	P	Q	R	S
0	52.60*	71	80	83	125*	140		223	231		252	300	317		341		355*	375*	394
100	52.86*	71	80	93	126*	162		223	231		252	300	317		341		355	375	394
250	53.03*	71	80	103	127*	164	180	223											
500	53.15*	71	80	112*	128*	166	180	223	231		252	300	317		341		356	375	394
1000	53.25*	71	80	120*	132*	168	180	223											
1500	53.29*	71	80	122*	135	170	182	223	231	244	252	300	317	336	341	352	360	375	394

Fig. 3. Cavity modes as a function of ferrite bias current.

the cavity voltage showed a strong ~128 MHz component. Experimentation in shifting cavity cooling water temperature, hence ferrite bias current and the exact modal frequency allowed us to "dodge" the resonance and eliminate beam blow-up. The "128 MHz" cavity mode was, therefore, strongly implicated in causing the instability and accordingly the first to be damped. As shown in Fig. 3, modes D & E both strongly couple to the gap and overlap for a range of frequencies as ferrite bias current tunes from 0 to 1500A. The indicated range of potentially strong interaction guided us to fabricate a damper that would overlap the frequency range from 112 MHz to 132 MHz.

Description of the Mode Damper

We followed these guidelines in designing the mode damper:

1. The design must not add rf leakage.
2. Necessary modifications to the cavities had to be made in situ.
3. Modification to the cavity, once started, had to be completed within an 8-hour shift.
4. The damper must strongly couple out power at the designed mode, but extract little power at the fundamental.
5. Any necessary tuning of the device must be done in a test area. The damper should be easily attached to the cavity without requiring retuning.
6. The damper must not lower the voltage capability of the cavity by unwanted side effects such as increased sparking, overheating, excess power loss or restricted tuning range of the fundamental.

Our damper is mounted with quick-disconnect Marmon clamps to flanges which were welded onto the rf cavities on accelerator maintenance days. Because the cavities will work with blank-off plates over the damping ports, the dampers were added as they were made. Figure 4 shows the MRRF accelerating cavities with mode dampers installed. A spare flange, which provides for additional damping capability should the need arise, presently serves as a convenient access port. This has turned out to be handy for cleaning ceramics, mopping of water spills, etc.

The damper mounting ports are positioned along the cavity side wall at the 128-MHz mode voltage maximum. Energy is capacitively coupled from the cavity into the damper. Figure 5 is a view of the damper showing the portion that plugs into the cavity. Visible are the capacitive disc which couples electrostatically to the intermediate cylinder of the cavity, half of the Marmon flange which mates with the cavity flange, a perforated partition which carries the side wall current of the cavity while allowing cooling air to flow into the

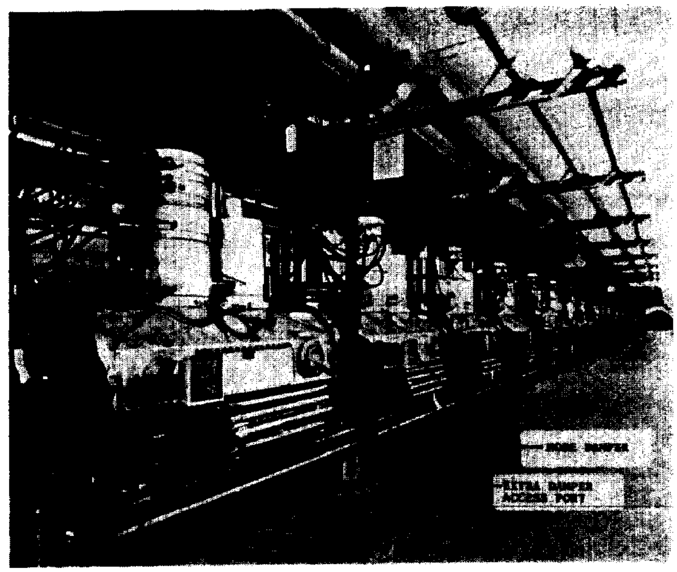

Fig. 4. Main ring rf accelerating cavities.

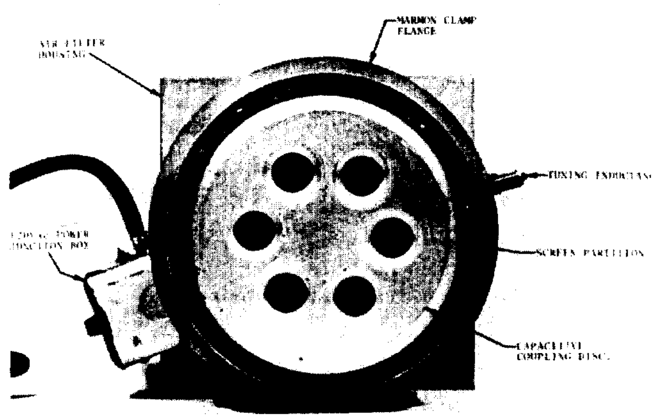

Fig. 5. View of damper from cavity port.

cavity, an inductive tuning adjustment, an air filter holder and the 120-volt power connection to the blower. Air flow eliminates a potential pocket of stagnant air on the inner surface of the disc.

An electrical representation of the damper as mounted on cavity is shown in Fig. 6. The damper disc couples to the cavity intermediate cylinder by C_c=1.5pf. The sum capacitance $C_c+C_p+\frac{C_d}{n^2}$ is tuned to parallel resonance at 128 MHz. We can choose R_p at will because R_d transforms into an R_p via n^2. One finds the maximum damping of the 128 MHz mode occurs for $R_p=X_{C_c}=1052\Omega$

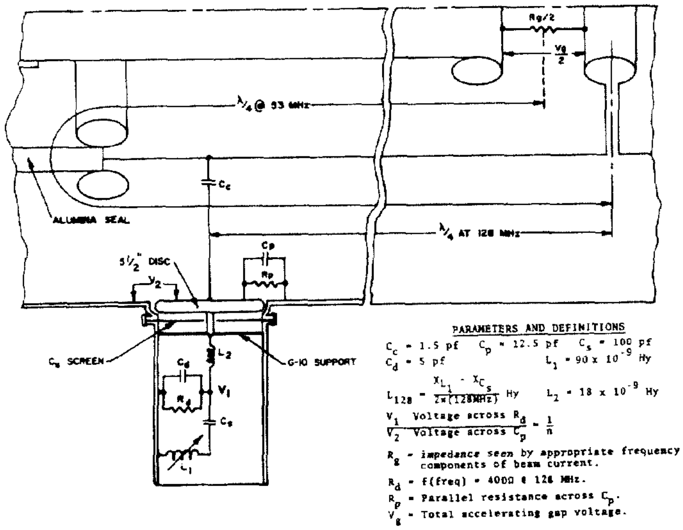

Fig. 6. Illustrative electrical circuit of 128 MHz mode damper on 1/4 section of cavity.

where; X_{C_c} *is the reactance of the coupling* C_c *at 128 MHz.* R_p is the parallel resistance of the circuit at resonance. A lower value of R_p is reflected across C_p as a compromise to extend the damping bandwidth.

R_d is mounted as near the disc as possible to provide maximum damping bandwidth. Capacitor C_s and L_1 is a series resonant trap at the fundamental operating frequency which minimizes 53 MHz rf voltage at V_1. R_d is made of 6 parallel 3.9K, 2-watt carbon resistors. Their resistance, which is a strong function of frequency, provides R_d=400Ω at 128 MHz and a C_d which is nearly independent of frequency. Since the series circuit L_1+C_s is inductive of value $L_{128}=75\times10^{-9}$Hy, and the voltage $\frac{V_2}{V_1}$=75+18/75=1.24 at 128 MHz, R_d is reflected across C_p as 615Ω. In actual practice L_2 is the self inductance of the disc plus a 1" diameter rod which mounts the disc on the G-10 support. Spacers between the disc and rod allow adjustment of C_p. This, coupled with the tuning of L_1, provides the necessary freedom to simultaneously tune the parallel mode to 128 MHz and the series trap (which carries 18A) to minimum V_1 at 53.1MHz.

We find the damping bandwidth as follows. Estimating the parallel tuned circuit reactance by:

$$X_L = 2\pi f_L = 2\pi \times 128 \times 10^6 \times 93 \times 10^{-9} = 74.8\Omega$$

$$Q = \frac{R_p}{X_p} = 8.22 = \frac{f}{\Delta f}$$

$$\Delta f = 15.57 = \text{B.W.}$$

Thus, the 3db points are 120 and 136 MHz.

The damper parts are cooled by a fan which blows axially from the rear of the damper. Air exits in a number of cavity locations. The net damper 53 MHz loss is ≈18 watts for the electronic components exclusive of the copper screen and capacitor disc which dissipate ≈100 watts induced by direct side wall cavity currents. As an added attraction, the fan air flow is sufficient to displace heated air in the cavity which otherwise collects just above the ceramic insulators and corona rolls and causes rf sparking.

Results

Operating experience with the fan on has shown an increase in cavity sparking threshold of >5% and a significant decrease in the number of cavity arcs per day.

Typically Q=1524 for nondamped cavity and Q=60.8 for a damped cavity at 128 MHz.

A spectrum analyzer display of cavity gap voltage is shown in Fig. 7 with: a) no mode damper; b) mode damper installed; and c) with the mode damper on but with the bunch spreader off. (The bunch spreader is an electronic method of decreasing the amplitudes of higher order beam frequency components by spreading the bunch in phase space after the transition energy in the machine.) The cavity was accelerating beam from 8 GeV to 400 GeV at an intensity of 1 x 10^{13} protons per pulse. The photographs are time exposures over one complete machine cycle to show the responses to beam current of all the resonances in the displayed band.

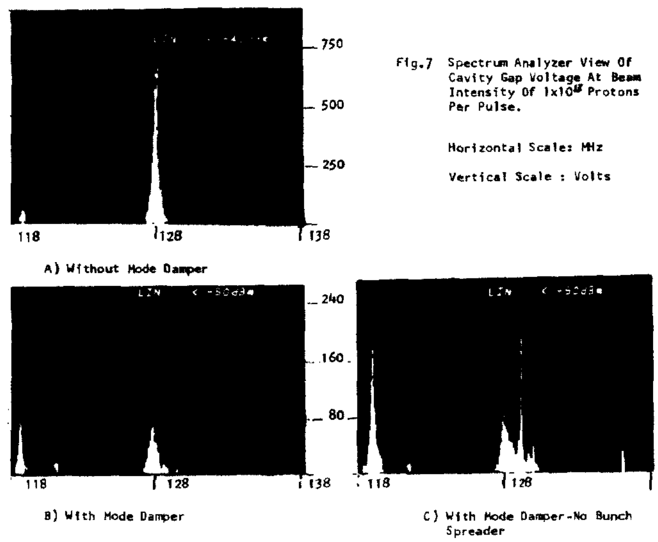

Fig.7 Spectrum Analyzer View Of Cavity Gap Voltage At Beam Intensity Of 1×10^{13} Protons Per Pulse.

Horizontal Scale: MHz

Vertical Scale : Volts

Comparing Fig. 7 A)&B), the improvement is at least a factor of 10 with the damper installed. Fig. 7 C) demonstrates the desirability of using electric low-level circuits to increase the spread of the beam in phase space and hence reduce the Fourier components that excite the cavity higher order modes.

Cost including parts, machine work and installation totaled $425 per cavity.

Acknowledgement

We are delighted to acknowledge that Rae Stiening as Head of the Main Ring Group, first clearly pinpointed the 128 MHz problem, and kept us busy at its solution.

References

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