A SIMPLE HIGHER ORDER MODE DAMPING SYSTEM FOR THE PETRA II CAVITIES

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Abstract

Higher order mode (HOM) dampers are required for the 50 MHz PETRA II ring rf cavities. The damping system must reduce the shunt impedance of higher order modes to less than 5000 ohms. Shunt impedance calculations with URMEL suggest that some cavity modes will require up to 17 dB of damping. A simple loop coupled filter system based on a shorted half-wave coaxial line meets most requirements up to 300 MHz. Design calculations, and the results of cold model tests are presented.

Introduction

The bunched, relativistic high current proton beam in the PETRA II accelerator ring will excite rf modes in all beam line cavities in proportion to the mode shunt impedance and the Fourier component of the beam at the mode frequency. The two 50 MHz acceleration cavities in the ring have many higher frequency, higher order modes with appreciable beam shunt impedances. Beam generated higher order mode cavity fields remove increasing amounts of energy from the circulating beam and can excite both transverse and longitudinal beam oscillations and instabilities. Such modes must be heavily damped and their influence on beam quality minimized. Calculations[1] indicate that the ring will be absolutely stable (i.e., instabilities will not be possible) if the shunt impedance of all higher order modes is less than 5000 Ω. Thus this was set as a goal for the mode damper design.

RF properties of the PETRA II acceleration cavities were calculated using the URMEL code[2] at DESY and theoretical estimates were made of various mode frequencies, shunt impedances, Q and (R/Q) values. Low power measurements were done on the cavities to establish the true mode spectrum and identify mode properties.

A mode damping system based on a loop coupled external filter system was devised which has negligible effect on the cavity fundamental, can be adjusted to strongly attenuate a few individual modes and has some damping effect on most other modes.

The PETRA II Cavity Mode Structure

The PETRA II rf cavity, shown schematically in Fig. 1, can be conceptually viewed as two folded coaxial quarter wave lines, the open line ends facing each other to form the accelerating gap. This configuration would leave the intermediate cylinder (which forms the outer conductor of the inner coaxial line) physically unsupported. In practise it could be supported either by dielectric material or by metal supports located at the cavity mid-point. A single metal support post was chosen for the PETRA II cavities, to simplify mechanical design. The post has very little effect on the acceleration modes, but a strong perturbing influence on most other modes.

The TEM mode fields on the two folded coaxial lines are distorted where the lines face each other across the accelerating gap. Because the cavity is reflection symmetric about the midplane, longitudinal electric fields formed across the gap are either bucking (essentially zero shunt impedance) or accelerating (Fig. 2). Many modes which would be possible on a single coaxial resonator are eliminated by the midplane symmetry. The modes may also be differentiated according to their azimuthal symmetry: those with no azimuthal variation (m=0, "monopole" modes) can induce longitudinal bunch instabilities, while those with a single cycle of azimuthal variation (m=1, dipole modes) can induce transverse instabilities. As the lower cutoff frequency for the m=1 modes in the inner coaxial line is ≈ 310 MHz, the shunt impedances of m=1 modes below this frequency are low.

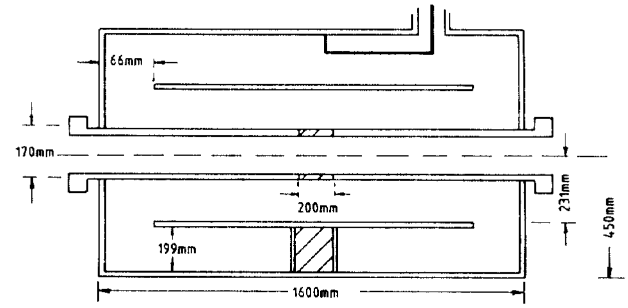

Fig. 1 A schematic diagram of the PETRA II cavity showing the folded back-to-back coaxial line geometry, the intermediate cylinder support post and the location of the HOM damper coupling loop.

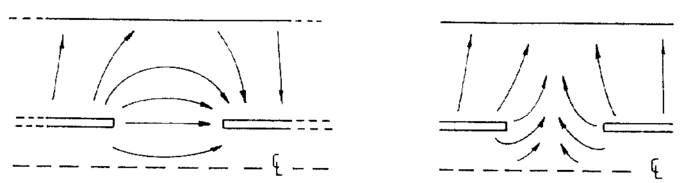

Fig. 2 Schematic representation of the electric fields at the acceleration gap for accelerating and bucking modes for a cavity symmetric about the midplane.

Cavity mode spectrum and gap field symmetries of individual modes measured using an electric field probe in the accelerating gap and a magnetic probe drive loop in the outer cylinder are given in Tables I and II. The mode associated with the loop coupled, ferrite loaded frequency tuning system[3] (57 MHz) was seen, but has low shunt impedance since most of its stored energy is in the external tuner cavity. Bucking modes have low shunt impedances and need no damping. Results of URMEL calculations for monopole and dipole modes in an axially symmetric cavity without support post are given in Tables III and IV. The large theoretical shunt impedance of the 127 MHz accelerating mode indicates it will require very strong damping, the other modes certainly being less important because of the smaller beam Fourier components at higher frequencies.

A comparison of measured and calculated mode frequencies shows that bucking modes are strongly perturbed by the post. Measurements show that lower

Table I

Measured Properties of the PETRA II Cavity
Monopole Modes at High Tuner Bias Field

Freq. (MHz)	Gap Field Symmetry	Q (undamped)	Q (6 Ω damped)	Damped Shunt Impedance (kΩ)
34	buck.	3100	3100	0
52	accel.	6200	5700	665
57	accel.	2800	2480	0
100	buck.	6300	600	0
127	accel.	11690	<100	<7
155	buck.	2260	1970	0
164	buck.	1500	<100	0
198	buck.	7600	6000	0
199	accel.	11800	11800	?
208	buck.	1300	1190	0
226	buck.	3500	3500	0
229	buck.	1000	?	0
231	accel.	1500	?	<26?
251	accel.	2080	<600	<20?
250	buck.	740	740	0
267	accel.	1400	<130	<5?
277	buck.	3600	1380	0
289	buck.	2680	690	0
292	buck.	580	1670	0
298	accel.	1170	990	<35?
301	accel.	5380	5000	190

Table II

Measured Properties of the PETRA II Cavity
Dipole Modes at High Tuner Bias

Freq. (MHz)	Gap Field Symmetry	Q (undamped)	Q_D (6 Ω damped)	Q_D/Q_{URMEL}
325	buck.	10800	2700	0.065
357	accel.	7000	7900	0.18
362	buck.	2260	2200	0.05
436	buck.	835	1200	0.027
478	accel.	10800	8380	0.17

Table III

URMEL Calculations of PETRA II
Monopole (m=0) Mode Properties

Freq. (MHz)	Gap Field Symmetry	Shunt Impedance (MΩ)	Q (pure copper)
52.04	accel.	2.1	18 000
96.44	buck.	0.008	19 700
126.5	accel.	1.57	23 000
171	buck.	0.013	31 200
228	accel.	0.65	36 900
288	buck.	0.039	35 300
303	accel.	1.3	34 200

Table IV

URMEL Calculations of PETRA II
Diple (m=1) Mode Properties

Freq. (MHz)	Gap Field Symmetry	(R/Q)* (ohms)	Q (pure copper)
156	buck.	$7 * 10^{-4}$	33 k
197	accel.	0.04	31 k
243	buck.	0.03	34 k
292	accel.	0.43	39 k
328	buck.	4.9	41 k
358	buck.	2.0	45 k
359	accel.	12.5	43 k
426	accel.	3.0	50 k
438	buck.	3.9	45 k
481	accel.	12	48 k

$$\left(\frac{R}{Q}\right)^{*} = \frac{R(r_o)}{Q}\,\frac{1}{k^2 r_o^2}, \quad k = \frac{2\pi}{\lambda}$$

where λ is the wavelength and r_o the radial position with respect to the cavity symmetry axis.

frequency bucking modes are of mixed TE and TM mode configurations. The lowest mode appears to be a hybrid where the post may be viewed as inductor coupled across the intermediate cylinder to outer wall capacitance (Fig. 1). This mode has large radial electric fields on the wall opposite the post, and large magnetic fields around the post.

Design of a Broad Band "Notched" Mode Damper

The main requirements of a mode damping system are (1) that it adequately reduces the Q of required high order modes and (2) that it does not appreciably affect the Q of the fundamental. A loop coupled system with these properties is shown diagramatically in Fig. 3(a). The operating principle is simple - the external length of shorted line forms a half wave resonator at the fundamental frequency and reflects its short back to the exact location of the resistor, thus shorting out the resistor. At other frequencies the coaxial line reflects a finite reactance in parallel with the resistor position, leaving the resistor as a lossy element in the HOM loop circuit. The disadvantage of this system is that at exact integer multiples of the fundamental frequency the resistor is again shorted out and no damping occurs. However, the URMEL calculations showed no accelerating modes near these multiples.

A theoretical analysis with the equivalent circuit shown in Fig. 3(b) was done to predict the reduction in Q of both the higher order modes and the fundamental as a function of system parameters. Component values of the equivalent circuit for the main cavity were determined by SUPERFISH calculations. The impedance of the loop and the values of the coupling constant were determined from model measurements. The external coaxial line was represented with the standard expression for the impedance of a shorted low loss transmission line.

The analysis showed that the reduction in Q of the fundamental mode (52 MHz) was minimal (< 15%) if the Q of the external shorted coaxial line was 500 or more. The Q reduction of a specific higher order mode could be varied by adjusting both the loop structure resonant frequency and the damping resistor value (Fig. 4).

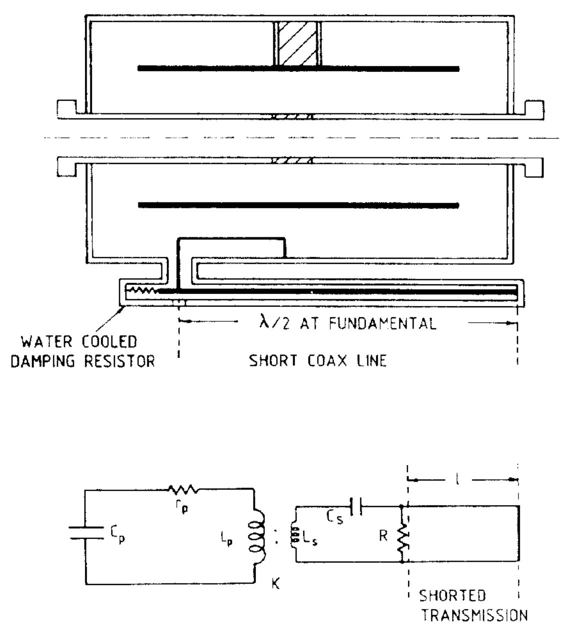

Fig. 3 (a) Pictorial representation of and (b) equivalent circuit representation of the main cavity, coupling loop, HOM load resistor and shorted coaxial line.

The mechanical design of the system involved only a determination of the required physical dimensions of the coupling loop and the choice of a coaxial line type. The quality factor of the external coaxial resonator Q_x is a function of the attenuation constant, α, and the propagation constant, β, of the coaxial cable - $Q_x = \beta(\text{radians/m})/2\alpha(\text{nepers/m})$. The published attenuation constant for Andrews HJ7-50A-1-5/8" air dielectric copper coaxial line ($\alpha = 0.48 * 10^{-2}$ dB/m $= 1.1 * 10^{-3}$ nepers/m) yields a Q_x of just over 500 at 50 MHz. A commercially available water cooled coaxial resistor was used as a load. The exact length of the $\lambda/2$ shorted coaxial line was determined experimentally by making small changes in line length and carefully measuring the Q of the cavity fundamental mode.

Measured Characteristics of the Damped Cavity System

The reduction in Q of the fundamental mode was measured over the full operating frequency range (51.5 - 52.0 MHz) for both 6 Ω and 50 Ω damping resistors. The effective Q reflected by the HOM system into the main cavity over this frequency range was 65 000. The power loss at 100 kV accelerating gap voltage on the external coaxial line is 0.66 kW, making some minimal cooling of the coaxial line necessary. The damping of the fundamental Q is, as predicted, quite acceptably small.

The measured Q values of all modes up to 300 MHz, without and with the damping resistor are shown in Table I. Most modes are strongly damped, but some remain uninfluenced and a few at high frequencies appear to have increased Q values. This latter effect appears related to high frequency modes in the loop and damping line itself. Several monopole accelerating modes cannot be clearly associated with URMEL monopole modes, in particular those at 199, 251 and 267 MHz.

The accelerating mode at 199 MHz is not predicted by the code, and may result from the breakdown of exact midplane symmetry producing a weak mode. The shunt impedance of this mode should be small, and careful tuning should reduce it to any required value.

The damped shunt impedances given in Table I, were estimated using the measured damped Q and the shunt impedance and Q calculated for an axially symmetric cavity without intermediate cylinder support. The value for the 127 MHz mode is < 7 kΩ, and could be decreased by careful tuning of the loop resonant frequency. The uncertain estimates for the higher frequency modes are based on a conservative theoretical estimate of Q = 35 000 and shunt impedance of 1.2 MΩ.

The adequacy of the overall broadband damping will be determined during accelerator operation. If it is shown that the damping of the 231 MHz accelerating mode is not adequate, then a second damping system could be added with a loop tuned to resonance at this frequency. It seems clear however, as one might have predicted, that a separate high frequency mode damping system will be required for modes above 300 MHz.

Acknowledgments

The authors would like to thank K.C.D. Chan, presently of Los Alamos National Laboratories, for performing the URMEL calculations.

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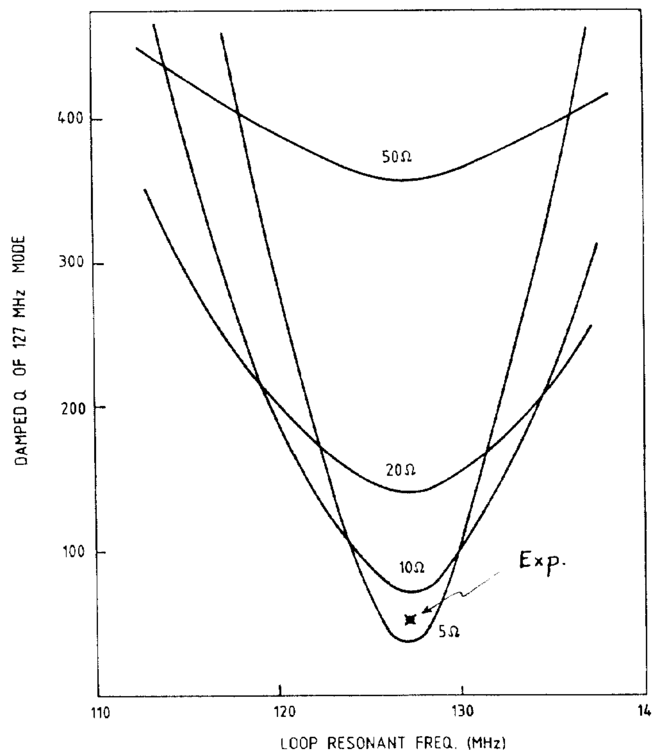

Fig. 4 Theoretical Q values for the 127 MHz mode, using the damping system model from Fig. 3 with a selection of damping resistor values. The experimentally determined optimum value with a 6 Ω load resistor is shown.