Higher Order Mode Damping Studies on the PEP-II B-Factory RF Cavity*

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Abstract

We describe studies of the higher-order-mode (HOM) properties of the prototype 476 MHz RF cavity for the proposed PEP-II B-Factory and a waveguide damping scheme to reduce possible HOM-driven coupled-bunch beam instability growth. Numerical studies include modelling of the HOM spectrum using MAFIA and ARGUS, and calculation of the loaded Q's of the damped modes using data from these codes and the Kroll-Yu method [1]. We discuss briefly the experimental investigations of the modes, which will be made in a full-size low-power test cavity (figure 1), using probes, wire excitation and bead perturbation methods.

1. INTRODUCTION

Higher Order Modes in accelerator RF cavities can give rise to the growth of longitudinal and transverse beam oscillations in storage rings. In machines with high currents, short bunches or low emittance these growth rates may exceed the natural damping rates of the beam causing beam blow up. This can be countered by de-Q-ing those HOMs which have significant impedances and/or by the use of feedback systems to damp beam motion. If the number of troublesome HOMs is small it is sometimes possible to tune the HOM frequencies operationally (e.g.: by changing the cavity water temperature), so that they do not drive coupled-bunch instability modes. In some machines HOMs have been damped by using tuned antennas (for a few modes), or broadband filters in the drive waveguide [2], but these techniques have not been proven at high levels of beam current, such as those proposed to get the required luminosity for the PEP-II B-Factory [3], (Table 1).

If nothing is done the high beam currents needed in PEP-II will result in very high coupled-bunch instability growth rates. The large number of bunches and therefore coupled-bunch modes possible, due to the size of the ring, means it will be impossible to tune all of the HOMs to "safe" frequencies. A broad-band damping scheme is therefore being developed for the RF cavity [4] which should reduce the coupled-bunch instability growth rate to the point where bunch motion can be controlled by an economically feasible feedback system [3,5], with a minimum loss of fundamental-mode performance.

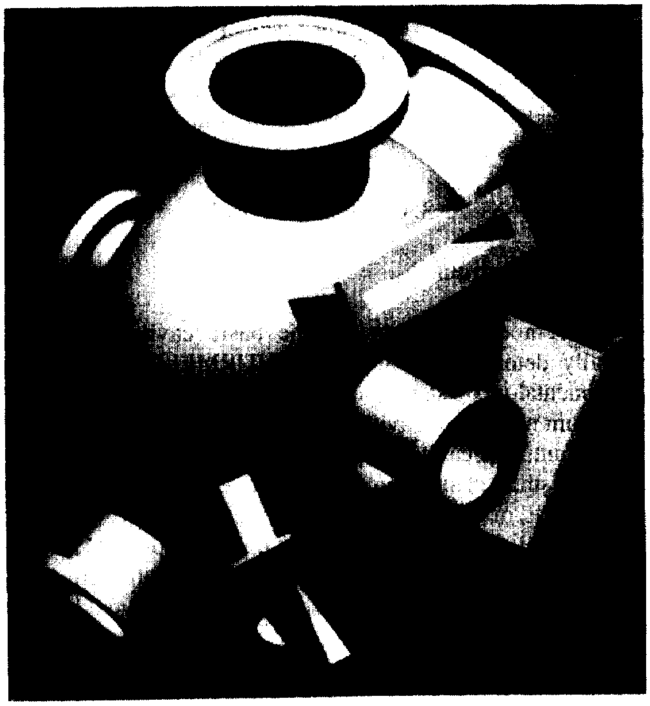

Figure 1. Low-Power test prototype of PEP-II RF cavity. The damping waveguides are attached to the three rectangular ports emerging from the cavity body. The large circular ports at the top of the cavity are the two alternative locations being considered for the main RF drive coupler.

Table 1: PEP-II RF system parameters
(including the effect of the 5% gap in the beam)

PARAMETER	HER	LER
RF frequency (MHz)	476	
Beam current (A)	1.55	2.25
Number of bunches	1658	
Number of cavities	20	10
Shunt Impedance R_s (MΩ) [a]	3.5	
Gap Voltage (MV)	0.93	0.95
Accelerating gradient (MV/m)	4.2	4.3
Wall loss/cavity (kW)	122	129
Coupling factor without beam (β)	3.5	3.9
Unloaded Q of cavity[b]	~31000	

[a] $R_s = V^2/2P$
[b] with ports, at 40°C

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2. DAMPING SCHEME

The damping scheme being developed uses waveguides coupled directly to the cavity body (fig 1.) to extract the power from all HOMs. The waveguides are sized to have a cut-off frequency between the fundamental mode (476 MHz), and the first HOM (685 MHz), and are located to couple strongly to the worst longitudinal HOM (TM011, 764 MHz), without missing any other modes. The opening into the cavity may be narrower than the waveguide, forming an iris, and the size may be optimized to give the best trade-off between HOM coupling and loss of fundamental-mode Impedance.

Other waveguide damping schemes have been proposed using larger apertures on or near the cavity equator [6,7] but these do not couple as well to the strongest HOMs and result in too much degradation of fundamental-mode performance to be used in this case.

3. CALCULATIONS

3.1. HOM spectrum

The mode spectrum for the basic cavity shape was initially determined using the 2D URMEL code [8]. The fundamental-mode shunt impedance was maximized so that the minimum number of cavities need be used. It may be possible to fine tune the cavity shape to reduce particular HOMs, for example small changes in the nose-cone separation affect the impedance of the TM011 mode more strongly than the fundamental mode. The locations of the magnetic field zeros of all the other modes below the beam pipe cut-off were found and the damping waveguides placed so that none would remain trapped.

3.2. MAFIA/Kroll-Yu damping analysis

Initial attempts to calculate the effectiveness of the waveguide damping scheme were made using the MAFIA 3D code [9]. A pillbox cavity used for previous HOM studies was fitted with waveguides, located where the magnetic field of the TM011 mode was maximum. MAFIA was used to calculate the resonant frequencies of the structure with the waveguides shorted at different lengths. The Kroll-Yu method was then used to calculate the loaded Q's of the pillbox structure [10] and these were compared with experimental measurements made on the model [11]. The results agreed well so MAFIA models were made for the PEP-II RF cavity with waveguides, which predicted very low Q's for the troublesome modes, well within the requirements of the proposed feedback system.

3.3. ARGUS/Kroll-Yu damping analysis

Further refinement of the calculations required a larger number of mesh points and more modes, so the simulations were continued using the ARGUS code [12], on the NERSC CRAY 2 at Lawrence Livermore National Lab. Half of the cavity was modelled, using a magnetic wall boundary condition at the symmetry plane, (H_{normal} and $E_{parallel}$ are continuous, $H_{parallel}$ and $E_{normal} = 0$). This precluded finding the TE011 mode but it theoretically has zero longitudinal impedance. One waveguide was modelled easily, parallel to the plane of symmetry but the other was constructed by building slices in the +z direction, appropriately offset in the x and y directions. The height and width of this waveguide were adjusted by carefully examining the cross sections of the mesh and comparing with the other waveguide, and by looking at the decay of the fundamental-mode fields along its length. The presence of the third waveguide was implied by symmetry.

Two sets of calculations were performed, in the first the three waveguides were 25 cm wide and 2.54 cm high, and entered the cavity through irises of the same height but 21.3 cm wide, the dimensions to which the low-power test cavity is being built. The data points from the ARGUS runs were fitted to the theoretical curves of the Kroll-Yu method, (figure 2), and the results again showed damping of the troublesome HOMs to within the capabilities of the proposed feedback system, Table 2.

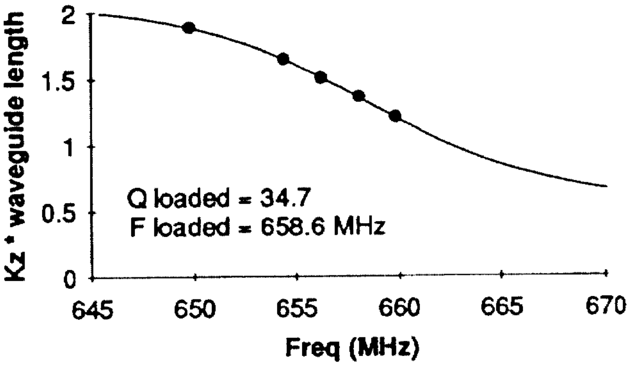

Figure 2. Phase vs Frequency plot showing theoretical curve and ARGUS data used to find loaded Q for the TE111 mode by Kroll-Yu method.

The second set of calculations used waveguides and irises with the same widths but with the height doubled to 5.08 cm. In this case the HOMs are loaded further still, again with a tolerable loss of fundamental-mode performance. This design could be used to give a greater margin of safety if desired.

Table 2: Damping of prototype cavity by three waveguides.

	No Waveguides			3 wg+1"iris		3 wg+2"iris	
mode	Freq	Q_0	RT^2	Freq	Q_L	Freq	Q_L
mono	(MHz)		(MΩ)	(MHz)		(MHz)	
TM010	486	44031	4.98	481	41922	477	42274
TM011	764	36082	1.54	743	42	726	11
TM020	1004	40685	0.011	1008	221	1009	160
dipole			(MΩ/m)*				
TE 111	676	58780	0.001	665	51	659	35
TM110	789	67842	20.6	790	239	792	146

* $R/k(r)^2$ (where R the Shunt Imp. @ radius r =0.03969 m)

4. LOW-POWER TEST CAVITY MEASUREMENTS

4.1. Measurement techniques

The PEP-II low-power test cavity is being made by electro-forming on an aluminum mandrel. The test model has two alternative locations for the RF drive port so that the effect on the HOM fields from this perturbation can be observed and an appropriate coupler position chosen for the high-power cavity design. Plugs will be used to blank off the ports when not required so that comparisons will be possible between, for example, the loaded Q with one or the other (or neither) of the RF drive ports open.

Various techniques are available to study the HOMs in RF cavities, including excitation by probes and wires to observe frequency response and perturbation by small objects to map field quantities. Several of these techniques will be used to assess the damping of the HOMs in the low power test cavity.

4.2. Excitation by probes

Small electric or magnetic probes (antennas or loops) can be used to excite the cavity to find the mode frequencies and Q's. With care it is possible to selectively excite monopole, dipole and higher order families of modes independently using multiple probes, which makes mode identification easier [11]. This method does not measure the shunt impedance directly but if the R/Q is known from calculations and is assumed constant then it is possible to use the measured loaded Q to estimate the impedance of the damped cavity.

4.3. Excitation by a wire

Using a wire to excite the cavity as in other impedance measurements [13] should allow the impedances and Q's to be found directly. However unless the wire impedance is very high the cavity response is strongly loaded by its presence. It should be possible to compensate for this loading in the analysis but in practice it becomes difficult to terminate the wires well and the large frequency shifts make mode identification hard at higher frequencies.

4.4. Perturbation by beads

By pulling small metal or dielectric objects through the cavity and recording the shift in resonant frequency it is possible to get the field distributions and R/Qs of the modes by Slater's method [14]. By making the measurements on the beam axis and recording the Qs at the same time, the impedance of the mode can be calculated. If several objects are used (for example to map both E and H fields), and many measurements are made, this can become a time consuming operation. An automated bead puller is being constructed and a dedicated data-acquisition program will be used to make sets of measurements in the PEP-II low-power test cavity. Taking data both on and off the beam axis will help to identify the HOMs and quantify the effects of the damping scheme.

5. CONCLUSIONS

Studies so far indicate that the waveguide damping scheme, while targeted on the worst HOM, is sufficiently effective for all other modes that coupled-bunch instabilities can be controlled by a reasonable feedback system. At the same time the reduction of fundamental-mode impedance and Q has been kept to a minimum, which may be vital in applications where many normal-conducting cavities are used.

The low-power test cavity will be used to verify the calculations and look at the effect of the location of the RF drive port, tuner and other apertures. The numerical models will continue to be refined to include these features and provide information on the thermal loading which will influence the design of a high-power prototype cavity.

Studies are in progress to design and test the waveguide loads that will be required to operate in vacuum and provide a good termination over a wide frequency range.

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