

Measurements of Higher Order Modes in 3rd Harmonic RF Cavity at Fermilab

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Abstract

We have measured the R_s/Q for several higher order modes of the modified CERN 159MHz RF cavity up to 1.5GHz using bead-pull as well as stretched-wire methods. The data have been compared with the predictions of 2D code URMEL. Attempts have been made to investigate coupled-bunch instabilities that can arise from higher order modes of the cavity with the beam-on conditions. No resonances of the third harmonic cavity below 800 MHz were found to give rise to any noticeable beam instability.

I. INTRODUCTION

Recently a focus-free transition crossing rf system has been implemented at Fermilab Main Ring (MR) to reduce the beam loss and emittance growth related to the transition crossing. The details of the principle of this technique, associated hardware and software are described elsewhere¹. One of the main components of this system is a modified CERN RF cavity (sometimes called a third harmonic rf cavity) which has unloaded Q of about 36000 for its fundamental mode (at 159MHz). Predictions made using 2D rf cavity code URMEL² for this cavity structure suggested that there should be many higher order modes with considerably large values below 1.5 GHz. Hence one of our primary concerns was a coupled bunch instability of the beam that would be induced by the third harmonic rf cavity if it is used in the beam along with other MR 53 MHz rf cavities. Before installation of the third harmonic rf cavity in the MR a study of the cavity shunt impedance (R_s) was made. The measurements have been made by two independent methods which are outlined later and carried out under two different conditions viz, with tuner unbiased and biased. After installation of the third harmonic rf cavity in the Main Ring, studies have been performed with the beam.

Here we report our bench measurements of R_s/Q for third harmonic rf cavity higher order modes below 800MHz and a search for coupled bunch MR beam instabilities due to these cavity modes.

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II. MEASUREMENTS OF THE SHUNT IMPEDANCE OF THE CAVITY MODES

In the past, mainly two different methods have been suggested^{3,4} to measure shunt impedance of the resonances of an rf cavity : 1) field perturbation method and 2) wire measurements. The principles of measurement for these two methods have been outlined below. In practice both of these methods have merits and demerits.

A. Bead-Pull Method

The R_s/Q of an rf cavity resonance is related to the shift in its resonance frequency $\frac{\delta f}{f}$ arising from a conducting sphere placed in the magnetic field-free region of the cavity and is given by³,

$$\frac{R_s}{Q} = \frac{1}{2\pi f_0} \left\{ \int_L \sqrt{\frac{\delta f}{f} \frac{4}{3\epsilon_0 \delta v_M}} dz \right\}^2 \quad (1)$$

where f_0 is the resonance frequency of a cavity mode. Q is determined for the unperturbed resonance. L is the length of the cavity. δv_M is the volume of the conducting sphere, ϵ_0 is permittivity of free space. $\frac{\delta f}{f}$ is obtained by measuring the phase shift of the transmitted signal from the cavity due to the perturbing object. If the phase of the unperturbed cavity mode is set to zero then the frequency shift is related to phase shift ϕ by⁵,

$$\frac{\delta f}{f} = \frac{1}{2Q} \tan \delta \phi \quad (2)$$

Thus in an R_s/Q measurement the phase shift ϕ is measured as a function of the position of a conducting metallic bead along the axis of the cavity and used to determine the integrand of Eq. 1.

In our measurements a copper spherical bead of volume 0.113cm^3 was attached to a nylon thread and was pulled along the axis of the third harmonic rf cavity. The motion of the bead was controlled using an automated motor system⁶. The velocity of the bead was about $3.54 \pm 0.30\text{cm/s}$ and synchronized with a network analyzer sweep time. Sitting on a particular resonance of the cavity,

magnitude of the S_{21} phase ϕ was measured with a zero frequency span on a HP8753C 300kHz-3GHz Network Analyzer. The cavity was excited with a very weak signal. The data were digitized to evaluate the integrand in eq. (1). The results of the measurements are tabulated in Table I. One of the limits of the bead-pull measurements is that it can be used only for strong resonances.

B. Stretched-Wire Measurement

In this technique a situation quite similar to beam-on conditions is generated by inserting a thin wire along the axis of the cavity and sending wide band-width high frequency TEM signals through one of the ports. To reduce the reflection due to step transition from 50 Ω transmission line connection to the beam pipe, a matching resistor of an appropriate value is introduced in series with the wire at both ends. Then the impedance of the cavity mode can be obtained⁴ by measuring the amplitude of the scattering parameter $S_{21}=(1+0.01R_s)^{-1}$ which depends on the reflected signal at port 1 and the transmitted signal at port 2 of the stretched-wire insert system. In order to remove the effects arising due to attenuation of the cables and to correct for the path length, measurements have to be done with a reference device. Thus the shunt impedance of a cavity mode is given by⁴,

$$R_s = 2R_o \left(\frac{1}{S_{21dev}} - \frac{1}{S_{21ref}} \right) \quad (3)$$

where $R_o = 50\Omega$. The quantities S_{21dev} and S_{21ref} are measured for the device under test and the reference device. A critical survey of the wire measurements of impedance has been done earlier⁷.

In the case of the third harmonic rf cavity the beam pipe radius with the copper sleeves¹ was 4.0in dia and each sleeves shrink-fitted had a slant starting at about 2in from the nosecones. The acceleration gap was about 4.33in. A stretched-wire system was designed with a 10 mil wire and length of 8.5 in. The wire was supported using two .25in dia G10 rods. The characteristic impedance of the beam pipe with the wire was 359 Ω . Two matching resistors of 300 Ω were used in series with the wire one at each end. A 50 Ω matching for the SMA connector was obtained by using four 220 Ω resistors in parallel and symmetrically placed at both ends of the wire. An aluminium cylinder of 4.0in inner dia and about 14.0in length with one of its end slanted to tight fit to the sleeves-slant was used as a reference device.

Using the network analyzer S_{21} calibration measurements were made with the test device. Then the wire assembly was slid in between the acceleration gap of the cavity without disconnecting the cables. The R_s/Q determined by this method for resonances below 800 MHz are compared with the bead-pull measurements in Table I. The higher order modes of the cavity up to 1.5 GHz are shown in Fig.1.

Table I. A comparison of R_s/Q of third harmonic rf cavity resonances measured* using bead-pull and stretched-wire. The measurements were done for loaded cavity (with a ferrite tuner and power amplifier coupling loop).

Tuner Bias (Amp)	f_o (MHz)	Bead-pull R_s/Q (Ω)	Wire R_s/Q (Ω)	URMEL [†] R_s/Q (Ω)
0.0	159.095	255	457	179
	419.920	30	56	11.5
	561.285	44	8	20
	721.007	4.9	132 §	2.
	776.836	16.2	6.22	7
300	159.040	315	318	
	419.618	29	51	
	561.265	56	8.27	
	721.020	4.5	119 §	
	776.762	7.0	5.47	

* The statistical error in R_s/Q for bead-pull measurements was about 10%.

† URMEL calculations were made for unloaded cavity.

§ The large value of R_s/Q value for this resonance is coming from errors in Q measurements.

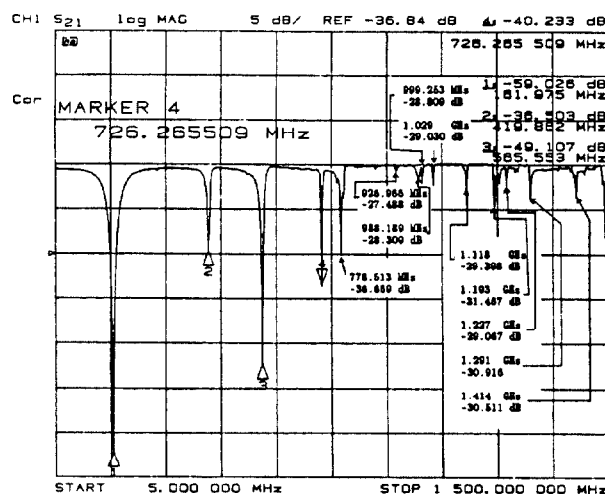


Fig.1. S_{21} stretched wire measurements for third harmonic rf cavity. For high Q resonances a frequency shift by few MHz is seen.

The R_s/Q measured by these two methods are considerably different for tuner unbiased and biased. In the case of wire measurements, the observed cavity Q- values are lowered because of the presence of the conducting wire along

the axis of the cavity. Also a large amount of resonance frequency shift is observed. Hence the present measurements had a large systematic error. A recent⁷ similar wire study on a simple pill-box cavity also found to show similar results; 1-2% frequency shift and measured R_s/Q differed by about 20-30% from the analytical solutions. However, the wire-measurements offers a nice technique to simulate beam on conditions during the bench tests. Our measurements with bead-pull had small errors and were reproducible within about 10%.

III. BEAM-ON STUDIES OF THE THIRD HARMONIC RF CAVITY

Ideally one would like to damp all unwanted modes of a cavity to reduce the coupling of the beam with cavity modes which causes beam instability. Here we have investigated the effects of higher order modes of the third harmonic rf cavity on the MR beam. The measurements were carried out in two steps. First, each of the beam-excited cavity modes up to 1.0 GHz were identified using a spectrum analyzer. Here the beam signals were observed using one of the gap monitors of the third harmonic rf cavity. The pattern of the beam excited resonances were similar to the one shown in Fig.1. Then, sitting on a resonance the growth of amplitude of a mode corresponding to the one detected in the cavity was monitored as a function of acceleration cycle time. The beam signals from a 2GHz resistive wall pickup system were used for this measurement. During this time the spectrum analyzer was triggered on the accelerator clock event at the beginning of the acceleration cycle. This was repeated for each resonance given in Table I for two different beam intensities viz., 0.9×10^{10} ppb and 2.0×10^{10} ppb. We found no modes that show considerable growth indicating none of the third harmonic rf cavity higher order resonances have significant effects on the MR beam during normal operation at these intensities.

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