SECOND HARMONIC CAVITY DESIGN FOR PROJECT X MAIN INJECTOR*

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Abstract

In order to accelerate the proposed beam intensity for Project X at FNAL, the current Main Injector (MI) RF system will be required upgrading the 53 MHz first harmonic RF system and adding 106 MHz second harmonic cavities to meet the MI requirements for Project X. The new first harmonic RF cavity design is a single gap quarter wave coaxial resonator with a perpendicular biased ferrite tuner. The second harmonic RF cavity baseline design is similar to the fundamental one and scaled down from it. The RF simulations and shape optimizations on the first and second harmonic cavities are carried out to obtain the optimal performance which meets Project X requirements. The results are discussed and presented in this paper.

INTRODUCTION

The proposed Project X at FNAL is an intensity frontier machine that will provide at least 2 MW of beam power at any energy over the range 60 – 120 GeV to a neutrino production target for supporting long-baseline neutrino experiments [1]. The existing Recycler/Main Injector (MI) complex will be used for Project X; however, the current 30 years old RF system needs to be upgraded and new second harmonic cavities are required to meet Project X requirements [2].

The new 53 MHz MI cavity design is a ferrite tuned quarter wave coaxial resonator, which is based on the SSC LEB cavity with a modified tuner tank design [3]. This new design has a lower R/Q (~50Ω) for solving longitudinal beam instability and transient beam loading effects with fewer cavities running at higher voltage. The magnetic permeability of the low-loss ferrite cores can be changed from 2.5 to 1.2 by applying a variable external magnetic field from 1.3 to 3 kG to provide the desired tuning range from 52.617 to 53.104 MHz. FNAL has proposed two MI cavities for Project X as shown in Figure 1. The cavity I has a straight-line body, and the cavity II a tapered one. The cavity II requires only a single vacuum ceramic, and hence the tuner, driver, and HOM dampers will be at atmospheric pressure for easy installation and repair. The RF simulations also show that the cavity II has less high-order mode impedances than the cavity I [4]. However, the electric fields in the ceramic window in the cavity II can reach at a few MV/m at the peak accelerating voltage of 240 kV, thus limiting the use of the cavity II for Project X. Therefore, the cavity I design is selected for Project X MI cavity.

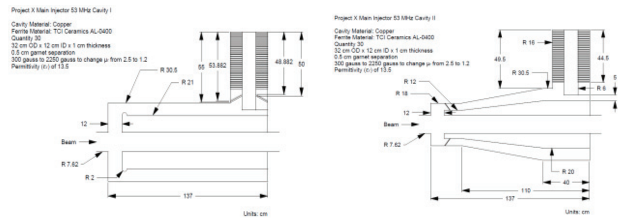

Figure 1: Sketches of the proposed MI cavity I (left) and II (right).

Meanwhile, using a 106 MHz second harmonic RF system can reduce the peak longitudinal beam density and produce a more uniform beam distribution for Project X. The 106 MHz MI cavity could be similar to the fundamental including the use of perpendicular biased tuner arrangement.

In this paper, the 53 MHz and 106 MHz cavity simulations are performed using the parallel finite element EM code suite ACE3P developed at SLAC [5]. The simulation results are presented and discussed in the following sections.

53 MHz MI CAVITY SIMULATIONS

The original 53 MHz MI cavity I design as shown in Figure 1 has a low R/Q of ~50 Ω. The R/Q is defined using the accelerator definition ($R/Q=V_{acc}^2/\omega U$, $V_{acc}=V_{gap}$), and thus it is twice larger than the circuit definition [2,3]. Recently, we decide to increase the cavity R/Q from 50 to 70 Ω in order to reduce its power loss on the cavity wall. By achieving this, the outer radius of the 53 MHz cavity is increased from 305 mm to 340 mm. Therefore, the cavity length needs to be adjusted to get the frequency tuning range right. The dependence of the cavity frequency on the cavity length with different tuner intrusions is plotted in Figure 2. The simulation results show that the cavity length should be around 1345 mm in order to obtain the desired cavity frequency tuning range.

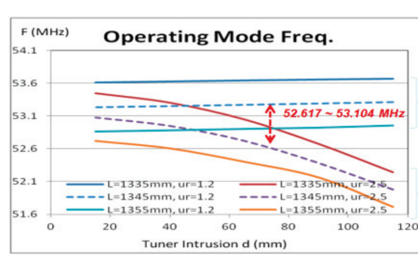

Figure 2: The cavity frequency dependence on the cavity length.

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When the magnetic permeability u_r of the ferrite cores is small, the operating mode frequency will not change significantly as the tuner intrusion changes. However, at a large magnetic permeability such as u_r=2.5, the operating mode frequency is strongly disturbed and largely reduced at a large tuner intrusion. The dependence is similar for the operating mode shunt impedance as shown in Figure 3.

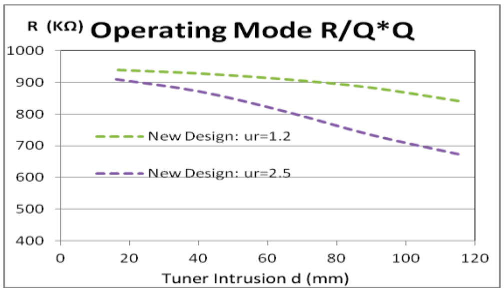


Figure 3: The cavity shunt impedance dependence on the tuner intrusion.

The tuning range versus the tuner intrusion for the current cavity design is presented in Figure 4. For zero intrusion, the tuner center conductor is positioned at the cavity outer surface, and the maximum intrusion of 120 mm in the current cavity design is larger than in the original cavity design, indicating the current cavity design can achieve a larger tuning range than the original one.

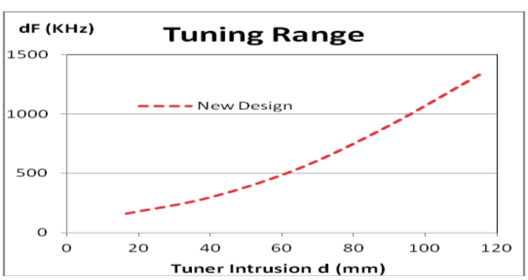


Figure 4: The cavity tuning curve.

Fundamental Mode

The fundamental mode RF parameters for the current 53 MHz cavity design calculated using the Omega3P eigensolver code in ACE3P are listed in Table 1.

Table 1: Fundamental Mode RF Parameters

Tuner intrusion d=75mm @ Vacc=240kV		Ur=1.2	Ur=2.5
New Design	R/Q (Ω)	72.87	62.98
	Q0	12244	12023
	F (MHz)	**53.3047**	**52.6152**
	Max. Es (MV/m)	7.3	7.3
	Max. Hs (kA/m)	12.5	30.5
	P(kW) on the wall	64	76
	P(kW) in the ferrite	6	42
	P(kW) in the ceramic	0.2	0.6

We will plan to use an accelerating voltage of 120 kV instead 240 kV at u_r=2.5. The power loss in the ferrite cores would be reduced to 10 kW and the tuner tank will need 10 gpm of water cooling on the cooling plates for the ferrite, which is achievable.

Higher-Order Mode (HOM)

The monopole modes in the MI cavity will cause longitudinal coupled-bunch instability, and dangerous monopole modes have to be damped by a HOM damper [4]. The frequency spectrum of the monopole modes below 400 MHz is shown in Figure 5. The first monopole mode is the operating mode having a largest R/Q. Due to the coupling between the tuner tank and the cavity, there is an extra mode around 60 to 70 MHz. Fortunately, this mode is out of the operating mode bandwidth, and thus will not be driven by the operating mode. However, it might be excited by the beam and its effect on the beam needs to be further evaluated.

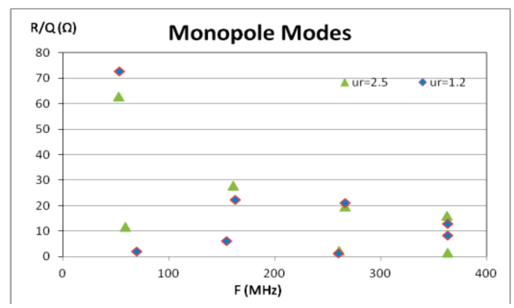
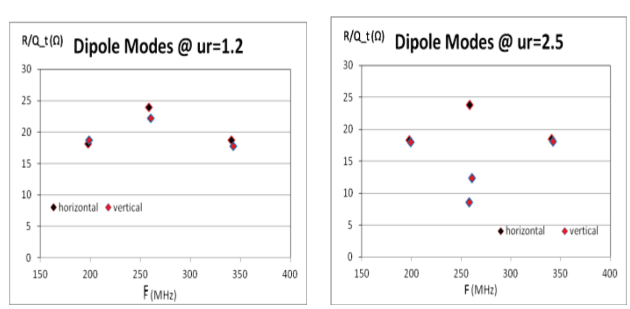


Figure 5: The monopole modes frequency spectrum with the tuner intrusion of 75 mm.

The frequency spectrum of the dipole modes in the current cavity design is presented in Figure 6. Usually the dipole modes have less effect on the beam than the monopole modes. However, the vertical dipole modes in the MI cavities are all off center along the ferrite vessel. The field pattern of a vertical dipole mode in the cavity is presented in Figure 7. These off-center dipole modes can be excited and generate transverse instability even when the beam is on axis. Their effects on the beam need to be evaluated in beam dynamic simulations.



(a) (b)

Figure 6: The dipole modes frequency spectrum at $\mathbf{u}_r$=1.2 (a) and $\mathbf{u}_r$=2.5 (b) with the tuner intrusion of 75 mm.

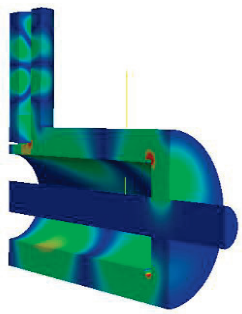


Figure 7: One of the vertical dipole modes in the cavity.

106 MHz MI CAVITY BASELINE DESIGN

The 106 MHz MI cavity RF specifications are listed in Table 2 [6]. The current 53 MHz MI cavity is scaled down as its baseline design. Therefore, the 106 MHz cavity would have an R/Q of ~ 70 Ω instead of 50 Ω.

Table 2: 106 MHz MI Cavity RF Specifications

Harmonic Number	1176	
Frequency Min	105.234	MHz
Frequency Max	106.208	MHz
Design Frequency Sweep	2	MHz
Acceleration Ramp Slope	240	GeV/s
Number of Accelerating Cavities	6	
Cavity R/Q (accelerator definition)	50	Ω
Q	4000	
Maximum Cavity Accelerating Voltage	240	kV/Cavity

Since the beam aperture is decided by the magnet bend and the beam energy in the MI complex, the beam aperture of 76.2 mm in the current 53 MHz cavity design is kept in the 106 MHz MI cavity baseline design. The 106 MHz MI cavity scaled down from the 53 MHz MI cavity is shown in Figure 8. The frequency and R/Q dependences on the tuner intrusion are plotted in Figure 9 and 10.

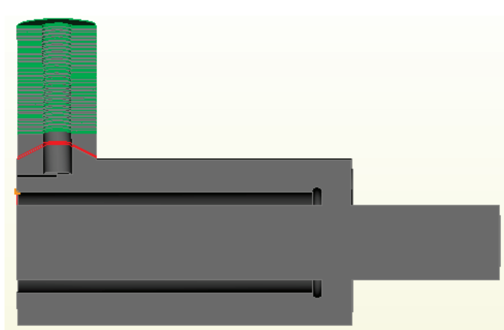


Figure 8: 106MHz MI cavity baseline design.

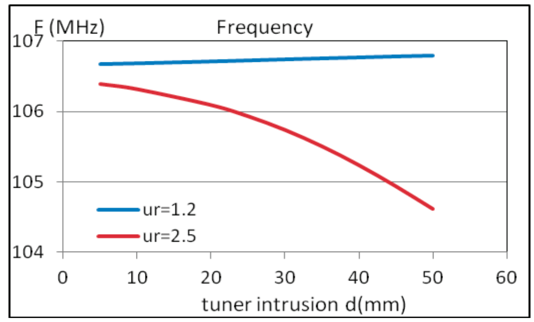


Figure 9: The 106MHz MI cavity frequency dependence on the tuner intrusion.

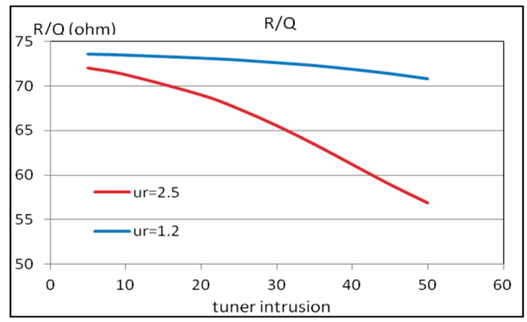


Figure 10: The 106MHz MI cavity R/Q dependence on the tuner intrusion.

In the current 106 MHz MI cavity baseline design, it is hard to put cooling channels in the narrow space between the inner and outer conductors. Therefore, the 106 MHz cavity baseline design needs to be further optimized. Meanwhile, we also have been looking for other solutions for the 106 MHz MI cavity design.

ACKNOWLEDGMENTS

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