SIMULATION AND OPTIMIZATION OF THE PROJECT-X MAIN INJECTOR CAVITY*

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Abstract

Project-X, a proposed high intensity proton facility to support a world-leading program in neutrino and flavor physics at Fermilab, plans to use the existing FNAL recycler and main injector (MI) complex, but requires upgrading the MI RF system. Currently there are two proposed 53MHz RF cavity designs for 6 to 120GeV operation. One is a straight-line quarter wave resonant cavity and the other a tapered cavity. The electromagnetic (EM) simulations of the two cavity designs are carried out using SLAC finite element parallel code suite ACE3P. The EM simulation results show that the tapered cavity design has better RF performance than the straight one. The tapered cavity shape is chosen and optimized for the final design to meet the specified performance requirements for the Project-X. In this paper, the MI cavity simulation and optimization results are presented. Possible HOM dampers are investigated for damping the dangerous monopole modes.

MI CAVITY DESIGN

In order to provide at least 2MW of beam power at any energy over the range 60 - 120GeV for the Project-X, the current 30 years old main injector (MI) RF system in FNAL requires upgrading [1]. The new MI cavity RF parameters are listed in Table 1.

FNAL proposed two MI cavities for the Project-X as shown in Figure 1. They are single gap quarter wave coaxial structures made from copper with a characteristic impedance Z0=50Ω. The cavity I has a straight-line body, and the cavity II a tapered one. The MI cavity fast frequency tuning is achieved by using a perpendicular bias field on the ferrite tuner. The magnetic permeability of the low-loss ferrite cores can be changed in μr from 2.5 to 1.2 by applying a variable external magnetic field from 1.3 to 3kG to provide tuning of the cavity frequency within the desired range.

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 conical ceramic window also provides mechanical support for the inner conductor lever arm.

Even though the cavity II has the advantage over the cavity I in terms of its mechanical design, it is necessary to carry out RF simulations to determine which cavity has better performance for the Project-X. The electromagnetic (EM) simulations of the two designs are done using SLAC finite element parallel code suite ACE3P [2].

Table 1: MI Cavity Parameters

Parameter	Value	Units
R/Q	50	Ω
Q	10000	
Max. Voltage	240	kV
Harmonic number	588	
Frequency	52.617-53.104	MHz
Number of Cavities	20	

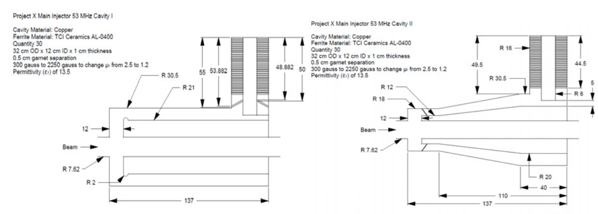

Figure 1: Sketches of the proposed MI cavity I (left) and II (right).

MI CAVITY SIMULATION

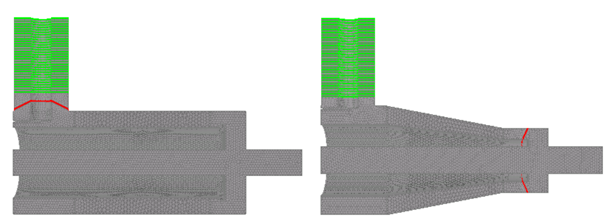

Figure 2: Simulating models of the MI cavity I (left) and II (right) including 30 ferrite cores (green) separated by 5 mm with εr=*13.5,* tan(δ)=0.0002, μr=2.5 ~ *1.2,* tan(δ)=0.0002, and a conical ceramic window (red) with εr=*12,* tan(δ)=0.0001, μr=1, tan(δ)=0.0001

The finite element (FE) meshes used for modeling the two proposed MI cavities are shown in Figure 2. Due to symmetry, only a half model cut at the symmetry plane is required for RF simulations. Tetrahedral elements with curved surfaces and second order basis functions are used. About 400k mesh elements are generated for both cavities to obtain converged results.

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Fundamental Mode

The fundamental mode RF parameters for the cavity I and II calculated by the Omega3P eigensolver code in ACE3P are listed in Table 2. Their field patterns are shown in Figure 3. It can be seen that the cavity II has a slightly higher R/Q and f that can be easily adjusted by changing the cavity coaxial line radius and length.

Table 2: Fundamental Mode RF Parameters

Tuner intrusion is 55mm.					
	μr	f(MHz)	Q0	R/Q (Ω)	Δf (KHz)
I	2.5	52.812	9613	51.23	584
	1.2	53.396	9457	56.68	
II	2.5	53.557	9679	56.95	539
	1.2	54.096	9529	61.30	

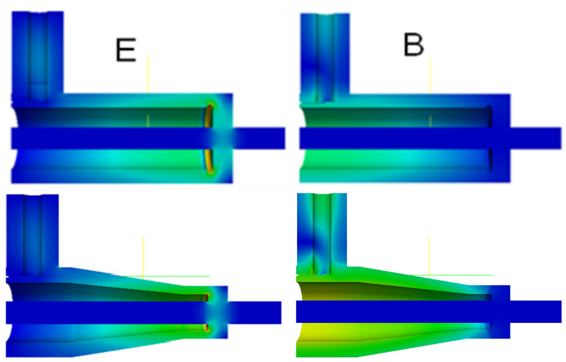

Figure 3: The fundamental mode E and B-field patterns for the cavity I (up) and II (low).

The tuning range versus the tuner intrusion for the cavity I and II is presented in Figure 4. For zero intrusion, the tuner center conductor is positioned at the cavity outer surface for both the cavity I and II, and the maximum intrusion is 85/95mm for the cavity I/II, respectively.

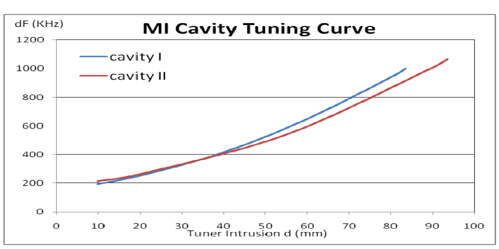

Figure 4: The tuning range vs. the tuner intrusion for the cavity I and II.

There is an extra mode around 60/70MHz existing due to the coupling of the cavity to the ferrite vessel in the cavity I/II. However, this mode will not affect the operating mode much because the mode separation is larger than the operating mode's bandwidth. The effect of the extra mode to the beam needs to be evaluated.

The MI cavity for the Project-X is designed to work at the accelerating gap voltage of 240kV. The calculated peak surface E-field is 7.4/12.2MV/m located at the accelerating gap with 20mm rounding in the cavity I/II. The calculated peak surface B-field located at the edge of the tuner loop is 37/31T in the cavity I/II. In reality, there is a certain rounding around the loop edges, and therefore the maximum peak surface B-field should be smaller than the value mentioned above. Most of the power loss happened on the cavity wall and a small portion in the ceramic window. The power dissipation in the ferrite cores is 39/28kW in the cavity I/II, respectively.

Higher-Order Mode (HOM)

There are two prominent monopole modes below 300MHz in the cavity I and II which may cause longitudinal coupled-bunch instability [3]. Their RF parameters are listed in Table 3, which show that the cavity I has stronger HOM modes' shunt impedances than the cavity II.

Table 3: Monopole Mode RF Parameters

Cavity	μr	f (MHz)	R/Q (Ω/cavity)	Q0	Rs (kΩ/cavity)
I	2.5	161.83	22.06	16580	366
		269.72	15.45	19973	309
	1.2	164.42	15.44	15310	236
		269.17	17.75	20026	355
II	2.5	166.51	19.34	14476	280
		279.17	11.84	18157	215
	1.2	169.25	12.70	14113	179
		279.07	12.13	18114	220

Dipole modes usually have less effect on the beam than monopole modes. However, the vertical dipole modes in the MI cavities are all off-center from the ferrite vessel axis. The field patterns of a vertical dipole mode in the cavity I and II are presented in Figure 5. These off-center dipole modes can be excited and generate transverse instability even the beam is on-axis. Their effects on the beam need to be evaluated in beam dynamic simulations.

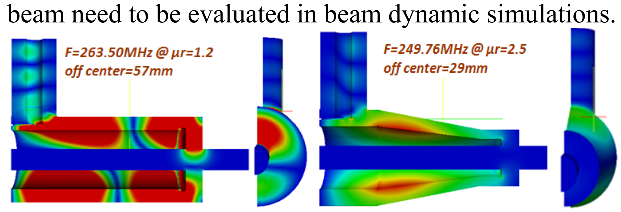

Figure 5: One of vertical dipole modes in the cavity I (left) and II (right).

Multipacting (MP) simulations are also carried out by the Track3P particle tracking code in ACE3P. The simulation results show that there are MP activities at low accelerating gap voltages in the cavity I and II [4].

In the present investigation, it is found that both the cavity I and II have similar fundamental mode performance, but the cavity II has smaller HOM shunt impedances than the cavity I. Therefore, the cavity II is chosen as the Project X MI cavity baseline design.

MI CAVITY OPTIMIZATION

Optimal 1MHz Tuning Range

The tuning range of 487KHz is required for 6 to 120GeV operation. However, the optimal design for the new MI cavity would be 1MHz tuning range [5].

In the original MI cavity II design, in order to achieve the tuning range of 1MHz, the tuner intrusion almost touches the cavity inner surface which can cause vacuum break down. The optimal cavity II design with 1MHz tuning range is achieved using a shorter tuner tank and a narrower tuner loop plus moving the tuner tank away from the rear end of the cavity. The tuning range as a function of the tuner intrusion in the original and optimal cavity II is plotted in Figure 6.

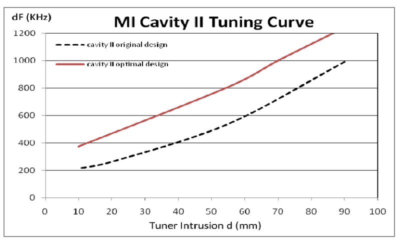

Figure 6: The tuning range vs. the tuner intrusion for the original and optimal cavity II.

The optimal cavity II design aiming for 1MHz tuning range will increase the power dissipation in the ferrite cores from 28kW in the original cavity II design to 50kW. The mode separation between the operating mode and the extra ferrite mode does not change significantly.

HOM Coupler Design

The two prominent monopole modes below 300MHz in the MI cavity II have to be heavily damped by HOM dampers. HOM coaxial damper with a large loop located at the rear end of the cavity can effectively damp HOM modes. Two mirrored HOM dampers with 45 degree orientation are adopted for damping both the monopole and dipole modes. In order to have a larger power capacity, the HOM damper is constructed within 2.3" coaxial line. The HOM loop is rounded to suppress MP activities at the HOM damper

Preliminary results show that the two dangerous monopole modes around 167MHz and 280MHz can be heavily damped with Qext 112 and 92, respectively. That means their shunt impedances can be reduced by two orders of magnitude. The dipole modes including the off-center ones also can be well damped with Qext around 200.

The HOM damper can couple to the fundamental mode and should be equipped with a fundamental mode filter. High-pass Chebyshev filters have been used in BNL 28 MHz normal conducting and 56 MHz superconducting cavity HOM damper designs for RHIC [6-7]. Higher element filters can provide a sharper rejection response at the fundamental frequency, and low attenuation at high-pass band. A 7-element high-pass filter constructed within 6" coaxial line is under investigated for the MI cavity HOM damper design. Preliminary results show that the filter can provide -80dB attenuation at 53MHz, while the attenuation above 100MHz drops to less than -7dB. Further optimization of the high-pass filter for the MI cavity is under way.

Figure 7 shows the MI cavity conceptual design including HOM dampers with high-pass filters and the input coupler. Finalizing the MI cavity II design to meet the Project-X requirements is ongoing.

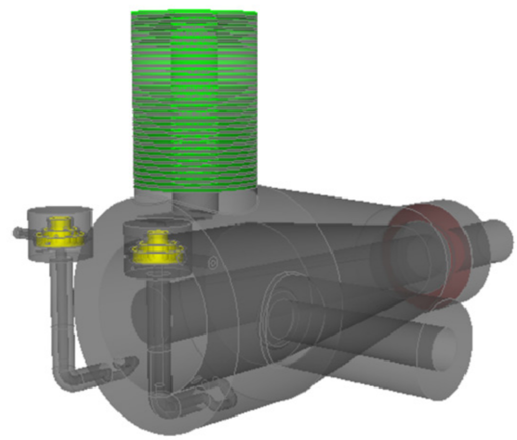

Figure 7: MI cavity conceptual design for the Project-X.

ACKNOWLEDGMENTS

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