RF Simulations and Analysis for the Project-X Main Injector Cavity

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Outline

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- Omega3P for cavity RF simulation
- Track3P for cavity MP simulation

3. MI Cavity RF Simulation Using Omeag3P

- Mesh Convergence Study
- Operating Mode RF Parameters
- Tuning Range vs. Tuner Coupling
- Maximum Surface E/B-Fields
- Power Distributions
- Monopole HOMs
- Dipole HOMs

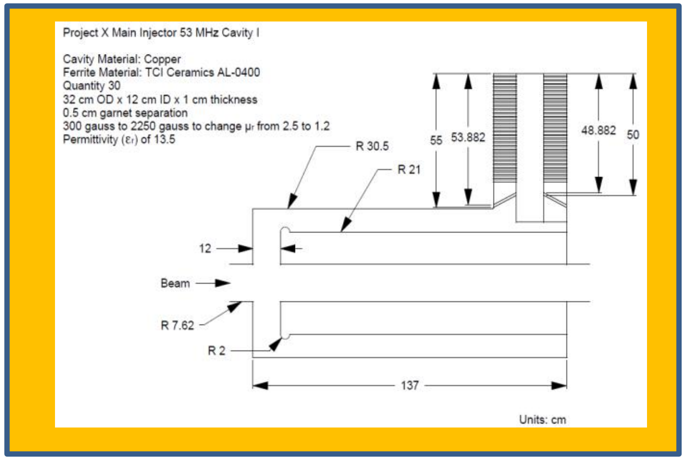
4. MI Cavity MP Simulation Using Track3P

- MP Locations
- MP Barriers
- MP Trajectories

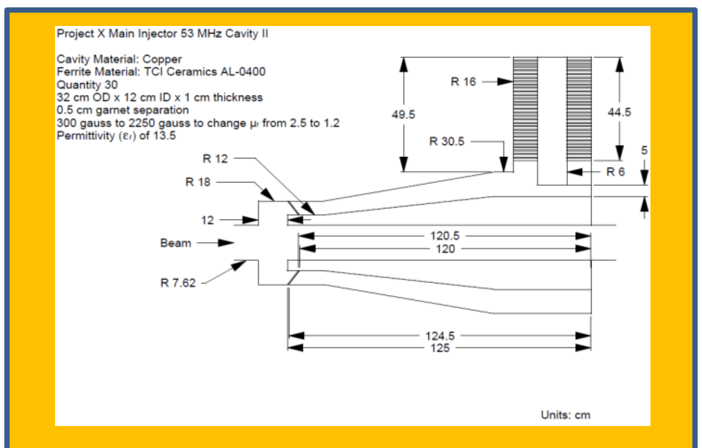
5. Summary

1. Main Injector Cavity for Project-X

Cavity-1: 120GeV Cavity



Cavity-2: 6GeV Cavity



MI Cavity RF Specification

Parameter	Value	Units
R/Q	50	Ω
Q	10000	
Max. Voltage	240	kV
Harmonic number	588	
Frequency	52.8114-53.104	MHz
Number of Cavities	20	

- ***Low R/Q to solve the longitudinal beam instability & transient beam loading effects with fewer cavities running at higher voltage.***
- ***FNAL & SLAC signed a MOU to perform the new MI cavity simulation and optimization to meet the requirements for Project-X.***

2. Parallel Finite Element EM Code Suite ACE3P

SLAC has developed the conformal, higher-order, C++/MPI-based parallel EM code suite ACE3P for high-fidelity modeling of large, complex accelerator structures.

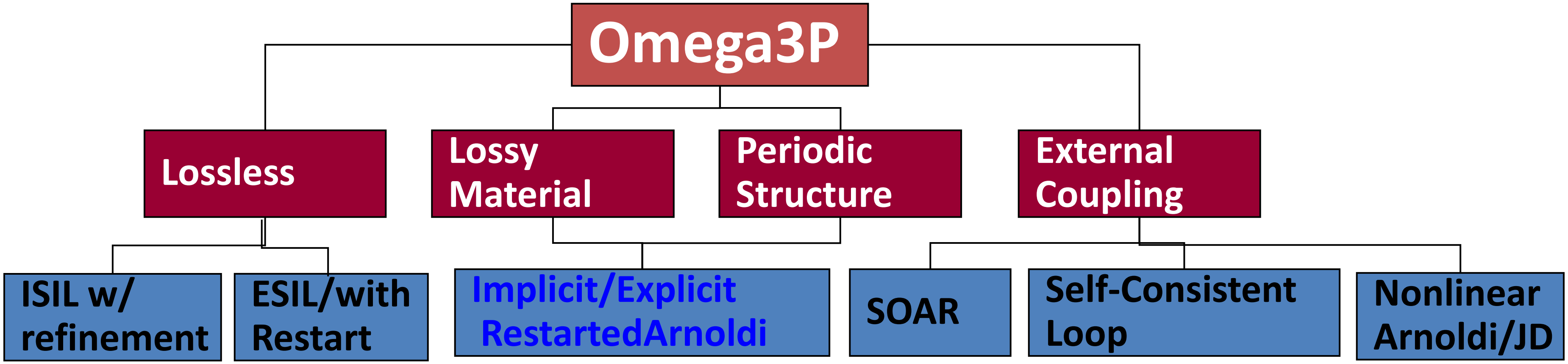
ACE3P: Parallel Finite Element EM Code Suite

(Advanced Computational Electromagnetics, 3D, Parallel)

	ACE3P Modules	– Accelerator Physics Application
***Frequency Domain*:**	Omega3P	– Eigensolver (nonlinear, damping)
	S3P	– S-Parameter
***Time Domain*:**	T3P	– Transients & Wakefields
	Pic3P	– EM Particle-In-Cell (self-consistent)
***Particle Tracking*:**	Track3P	– Dark Current and Multipacting
***Multi-Physics*:**	TEM3P	– EM-Thermal-Mechanical
***Visualization*:**	ParaView	– Meshes, Fields and Particles

Goal is the virtual prototyping of accelerator structures.

2.1 Omega3P for Cavity RF Simulation



Krylov Subspace Methods

Domain-specific preconditioners

WSMP

MUMPS

SuperLU_Dist

Different solver options have different performance dynamics.

2.2 Track3P for Cavity MP Simulation

- **Track3P provides accurate and efficient MP simulation**
  - *High-resolution EM fields:*
    Load RF and external fields from other ACE3P modules, such as Omega3P, S3P and T3P
  - *High-fidelity geometry representation:*
    2nd order curved surface built in the FEM allows realistic modeling of particle emission on cavity wall
  - *Realistic SEY curve:*
    Obtain MP maps using accurate SEY curves provided by experiments
  - *Versatile postprocessing:*
    Identify onset of MP through various parameter scans

Launch Electrons
- **Energy, angle**
- **RF field, location, phase, …**

↓

Track Particles in EM fields
- **Determine impact positions**
- **Generate secondary electrons**
- **Continue tracking for a specified number of RF cycles**

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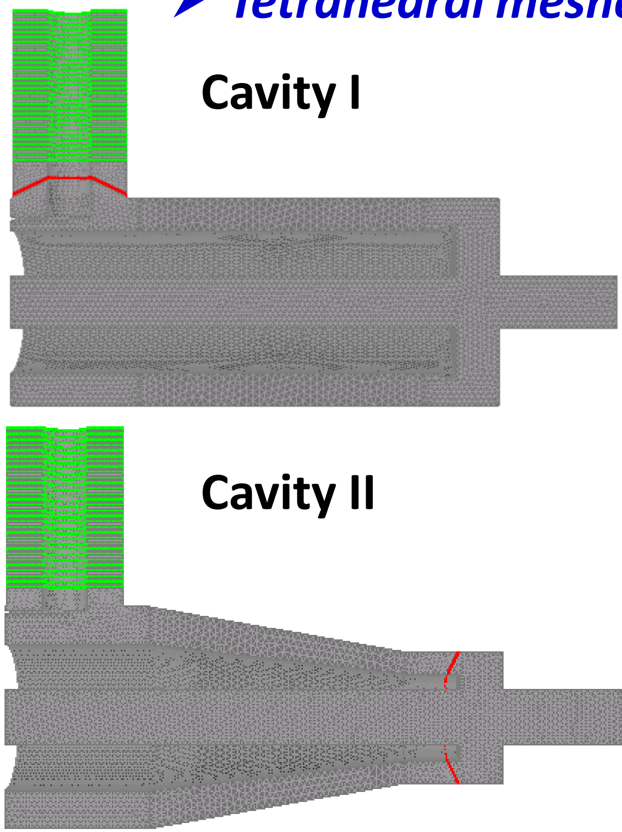
Postprocessing
- **Determine "resonant" trajectories**
- **Construct MP susceptible zone**

3. MI Cavity RF Simulation Using Omega3P

Meshed Computational Models

- ***Tetrahedral meshes with 2nd order curved surfaces***



Half model cut at symmetry plane

30 ferrite cores with 5mm separation:

$\varepsilon r=13.5$, $\tan(\delta)=0.0002$,

$\mu r=1.2 \sim 2.5$, $\tan(\delta)=0.0002$

Ceramic window:

$\varepsilon r=12$, $\tan(\delta)=0.0001$,

$\mu r=1$, $\tan(\delta)=0.0001$

Copper coated wall:

$\sigma=5.8e7 s/m$

3.1 Mesh Convergence Study

MI Cavity I

Tuner intrusion is 55mm. Both the ferrite and ceramic are lossless.

Mesh	Ferrite	F(MHz)	Q0	R/Q (Ω)	dF (KHz)
442k	**μr=1.2**	**53.396**	**9457**	**56.676**	**584**
	μr=2.5	**52.812**	**9613**	**51.228**	
1693k	**μr=1.2**	**53.396**	**9453**	**56.689**	**584**
	μr=2.5	**52.812**	**9604**	**51.234**	

Tuner intrusion is 55mm. Both the ferrite and ceramic are lossy.

Mesh	Ferrite	F(MHz)	Q0	R/Q (Ω)	QLoad
442k	**μr=1.2**	**53.396**	**9457**	**56.676**	**130194**
	μr=2.5	**52.812**	**9612**	**51.227**	**28670**
1693k	**μr=1.2**	**53.396**	**9453**	**56.689**	**130128**
	μr=2.5	**52.812**	**9604**	**51.234**	**28643**

The results converge with 442K mesh elements and the effects of ferrite and ceramic losses on frequency can be ignored.

3.2 Operating Mode RF Parameters

MI-Cavity-I: Tuner intrusion is 55mm.

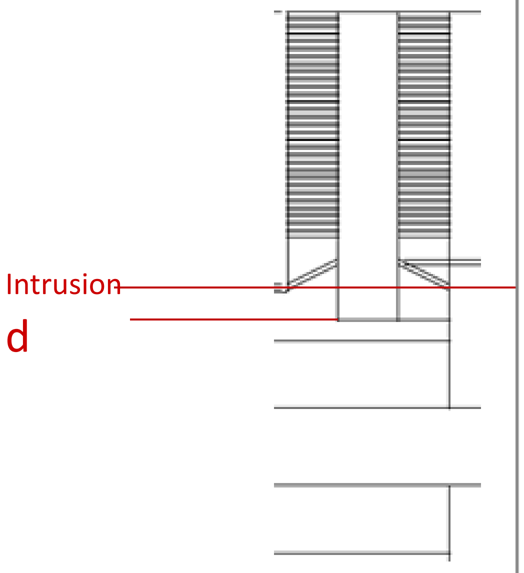
	F(MHz)	Q0	R/Q (Ω)	dF (KHz)
μr=1.2	**53.396**	**9457**	**56.68**	**584KHz**
μr=2.5	**52.812**	**9613**	**51.23**	

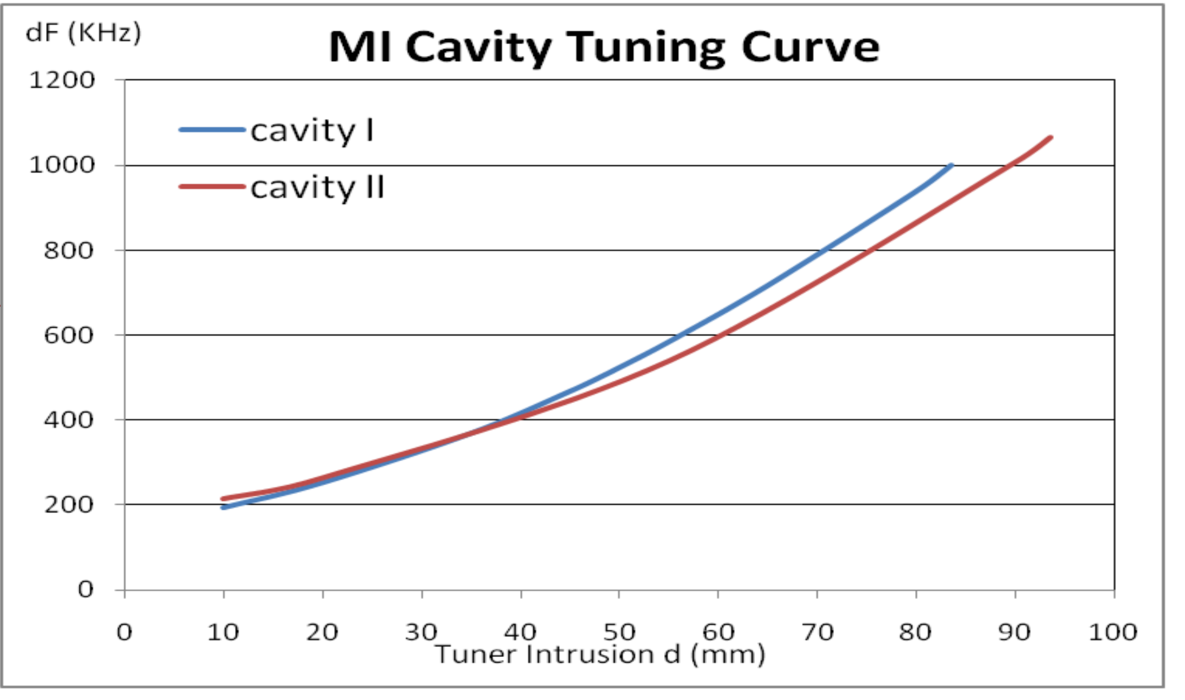
MI-Cavity-II: Tuner intrusion is 55mm.

	F(MHz)	Q0	R/Q (Ω)	dF (KHz)
μr=1.2	**54.096**	**9529**	**61.30**	**539KHz**
μr=2.5	**53.557**	**9679**	**56.95**	

The MI-cavity-II has a slightly higher R/Q. But it can be reduced by adjusting the coaxial line impedance.

3.3 Tuning Range vs. Tuner Coupling





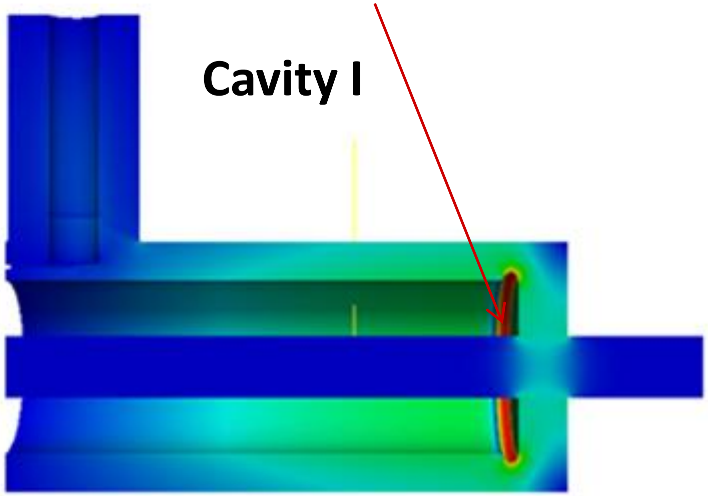
0 mm: Tuner center conductor is at the cavity outer surface for both the cavity I and II.
85/95 mm: Tuner loop is touching the cavity inner conductor for the cavity I/II.

The cavity II has a slightly larger tuning range than the cavity I due to its larger distance between the cavity inner and outer conductors.

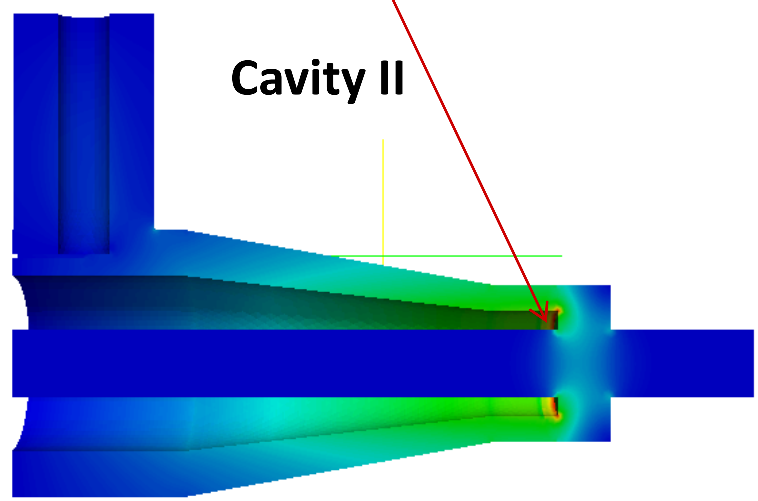
3.4 Maximum Surface E/B-Fields

Maximum Surface E-Fields @ Vgap=240kV

maxEs=**7.4**mV/m
@ μr=1.2 and μr=2.5
with 20mm gap rounding



maxEs=12.8mV/m @
μr=1.2 and μr=2.5
w/o gap rounding



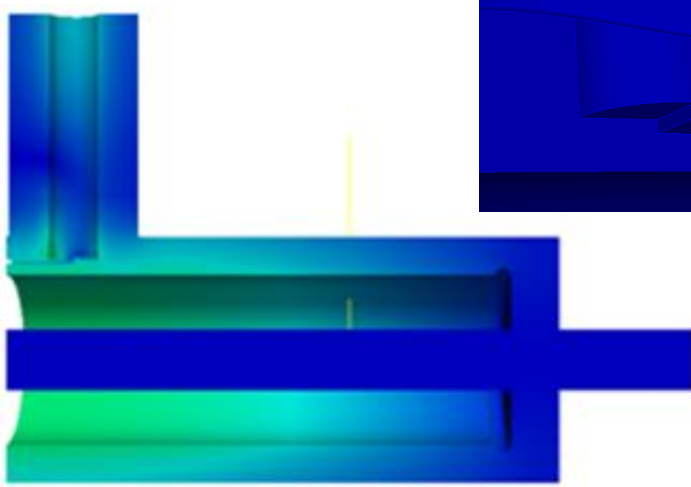
maxEs=**12.2**mV/m
@ μr=1.2 and μr=2.5
with 20mm gap rounding

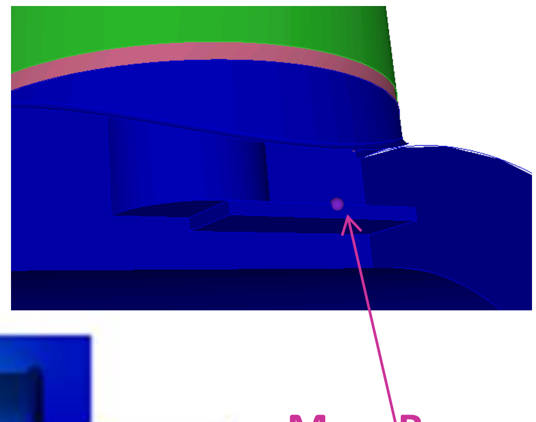
The maximum peak Es is stronger in the cavity II than in the cavity I. The magnetic permeability of the ferrite won't affect the maximum surface E-fields.

3.4 Maximum Surface E/B-Fields (Cont'd)

Maximum Surface B-Fields @ Vgap=240kV

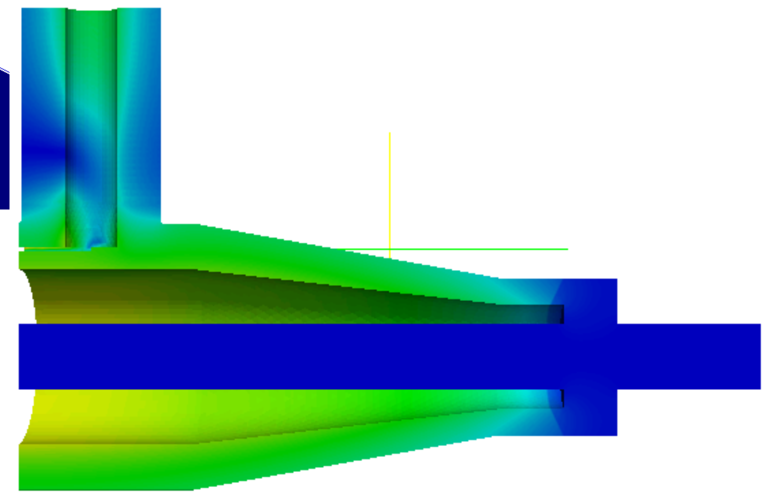
Cavity I





Max. Bs location

Cavity II



maxBs=18.4 T @ μr=1.2
maxBs=37.2 T @ μr=2.5

maxBs=16.3 T @ μr=1.2
maxBs=30.9 T @ μr=2.5

The maximum peak Bs is less in the cavity II than in the cavity I. Rounding the loop edges can reduce the maximum Bs.

3.5 Power Distributions

MI-Cavity-I: Tuner intrusion is 55mm. Vgap=240KV								
	F(MHz)	R/Q (Ω)	Q0 (copper)	*QL1 (ferrite)*	*QL2 (ceramic)*	*P (kW) (wall)*	*P (kW) (ferrite)*	*P (kW) (ceramic)*
μr=1.2	**53.396**	**56.68**	**9457**	**134802**	**3809242**	**108**	**8**	**0.3**
μr=2.5	**52.812**	**51.23**	**9613**	**29162**	**1700058**	***117***	***39***	***0.7***

MI-Cavity-II: Tuner intrusion is 55mm. Vgap=240KV								
	F(MHz)	R/Q (Ω)	Q0 (copper)	*QL1 (ferrite)*	*QL2 (ceramic)*	*P (kW) (wall)*	*P (kW) (ferrite)*	*P (kW) (ceramic)*
μr=1.2	**54.096**	**61.30**	**9529**	**140978**	**143691**	**99**	**7**	**7**
μr=2.5	**53.557**	**56.95**	**9679**	**35918**	**156190**	***104***	***28***	***6***

There are less power dissipated on the wall and deposited in the ferrite cores, and more power in the ceramic ring in the cavity II than in the cavity I due to the ceramic ring being closer to the accelerating gap.

3.6 Monopole HOMs Below 300MHz

MI-Cavity I	F (MHz)	R/Q (Ω/cavity)	Q0	Rs (kΩ/cavity)
Ur=1.2	164.42	15.44	15310	236
	269.17	17.75	20026	355
Ur=2.5	161.83	22.06	16580	366
	269.72	15.45	19973	309

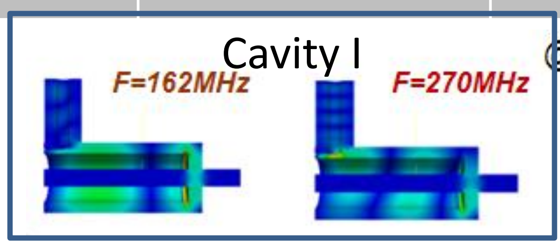
MI-Cavity II	F (MHz)	R/Q (Ω/cavity)	Q0	Rs (kΩ/cavity)
Ur=1.2	169.25	12.70	14113	179
	279.07	12.13	18114	220
Ur=2.5	166.51	19.34	14476	280
	279.17	11.84	18157	215

$$\frac{R}{Q} = \frac{|Vz|^2}{\omega U}$$

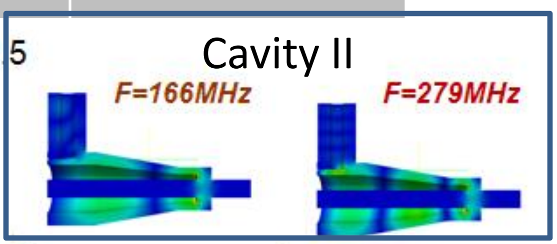
$$Q = \frac{\omega U}{P}$$

$$Rs = (\frac{R}{Q}) * Q$$

E-field patterns
@ μr=2.5



@μr=2.5



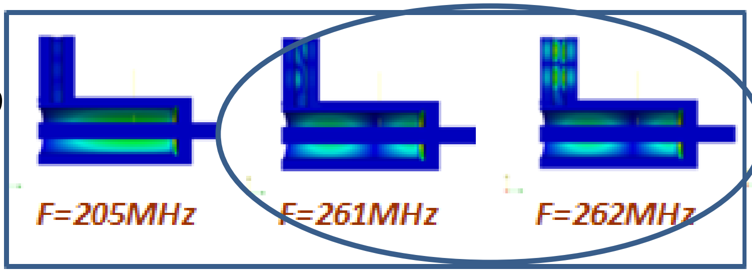
The cavity monopole HOM modes have lower Rs in the cavity II than in the cavity I.

3.7 Dipole HOMs Below 300MHz

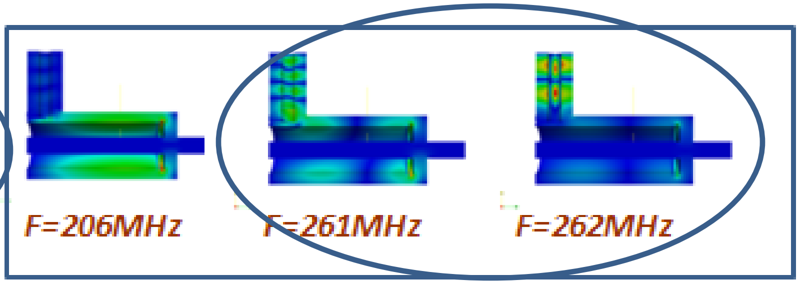
MI-Cavity I		F(MHz)	R/Q_T (Ω/cavity)	Q0	Rsh_T (kΩ/mm/cavity)
Ur=1.2	H-dipole	205.31	16.65	20161	1.44
		261.09	**19.75**	**22103**	**2.39**
	V-dipole	206.04	17.13	20000	1.48
		263.50	**17.61**	**21500**	**2.09**
Ur=2.5	H-dipole	205.39	16.79	20210	1.46
		261.08	**15.60**	**23769**	**2.03**
		261.63	**4.03**	**29714**	**0.66**
	V-dipole	206.39	17.05	20005	1.47
		260.52	**5.71**	**28421**	**0.89**
		261.52	**0.53**	**32045**	**0.09**

E-field patterns @ μr=2.5

Horizontal Dipole



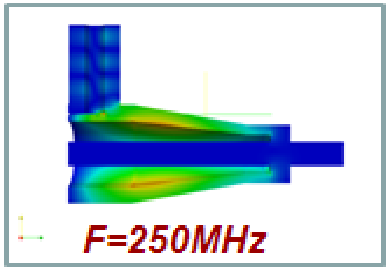
Vertical Dipole



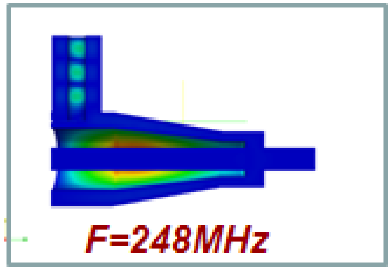
3.7 Dipole HOMs Below 300MHz (Cont'd)

MI-Cavity II		F (MHz)	R/Q_t (Ω/cavity)	Q0	Rs (kΩ/mm/cavity)
Ur=1.2	H-dipole	247.57	1.57	20555	0.17
	V-dipole	249.36	1.57	20082	0.17
Ur=2.5	H-dipole	248.24	1.47	21566	0.17
	V-dipole	249.76	1.61	20264	0.17

E-field patterns
@ μr=2.5



Vertical dipole



Horizontal dipole

$$\left(\frac{R}{Q}\right)_T = \frac{|V_T|^2}{\omega U} = \frac{|V_z|^2 /(r_0 * \omega / c)^2}{\omega U}$$

$$R\_t = \left(\frac{R}{Q}\right)\_t * Q * (\omega / c)$$

The cavity dipole modes have lower transverse shunt impedances in the cavity II than in the cavity I, thus their wakefield contributions to the beam are smaller.

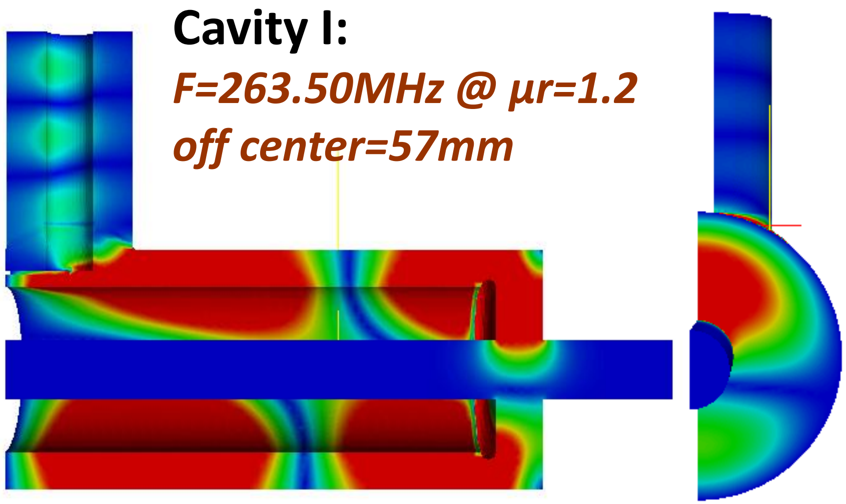
3.7 Dipole HOMs Below 300MHz (Cont'd)

Off-center Vertical Dipole Mode

- Due to the ferrite vessel, the vertical dipole modes are all off-center;
- Even the beam is on z-axis, the vertical dipole modes can be excited and generate transverse kick to the beam. The monopole component effects to the beam need to be considered in beam dynamic analysis.

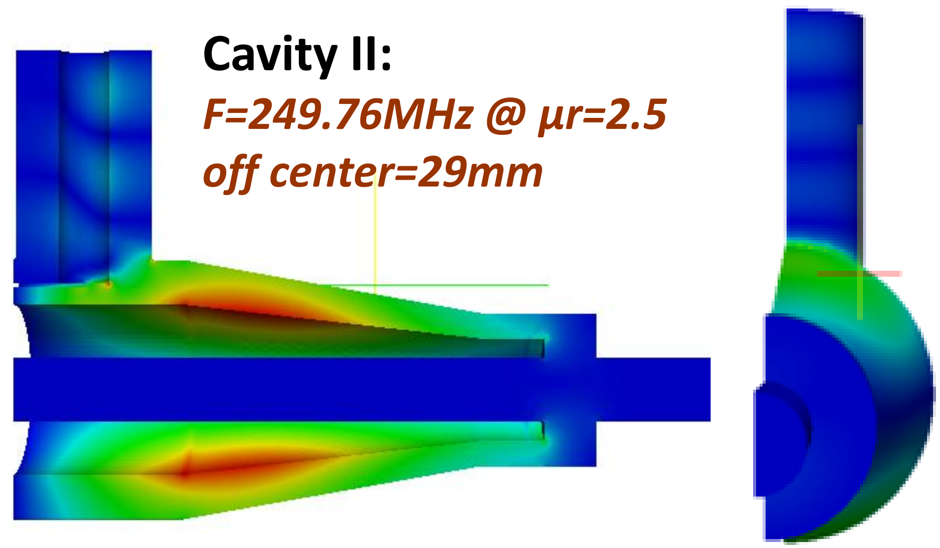
Cavity I:

F=263.50MHz @ μr=1.2
off center=57mm



Cavity II:

F=249.76MHz @ μr=2.5
off center=29mm



The vertical dipole modes have larger off-center shifts in the cavity I than in the cavity II.

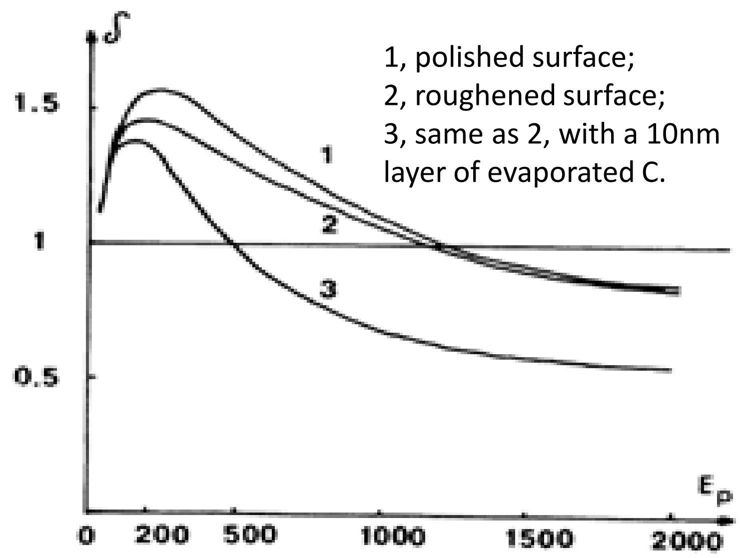
4. MI Cavity MP Simulation Using Track3P

MP Phenomenon:

- Electrons are released from RF surface
- Secondary emitted electrons are in resonance with the RF fields
- Impact energies of the secondary electrons fall within the **SEY** curve > 1
- The number of resonant electrons multiplies exponentially, leading to a phenomenon of electron avalanche

MP effect:

- Distortion or loss of RF signal
- Significant power loss
- Low achievable field gradient
- Thermal breakdown in SC structures



1, polished surface;
2, roughened surface;
3, same as 2, with a 10nm layer of evaporated C.

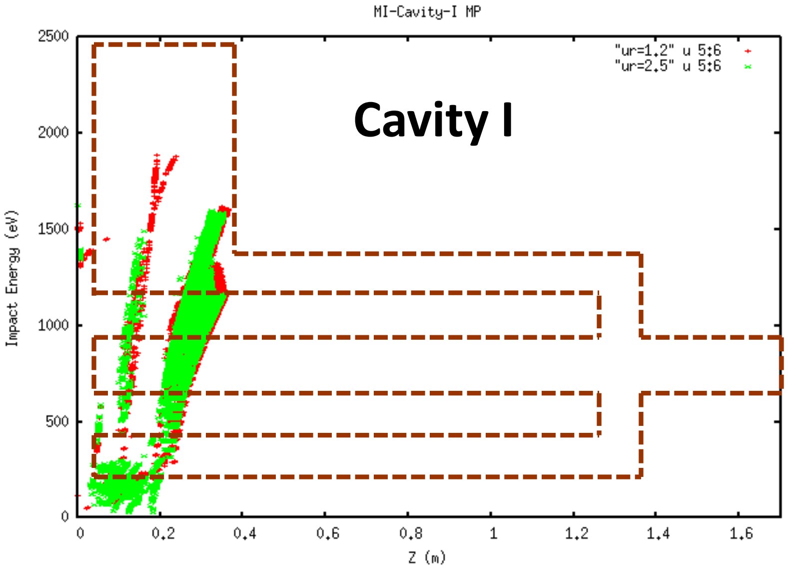
A. Septier & M. Belgaroui, IEEE Trans. Vol. EI-20, No.4, 1985

4.1 MP Locations

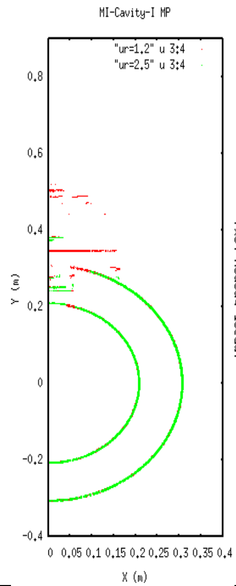
Track3P Simulation:

- Emitting particles on external walls;
- Scan the gap voltage from 5kV to 255kV with 5kV interval;
- Record survived resonant particles after 50 RF cycles with impact energy below 2500eV

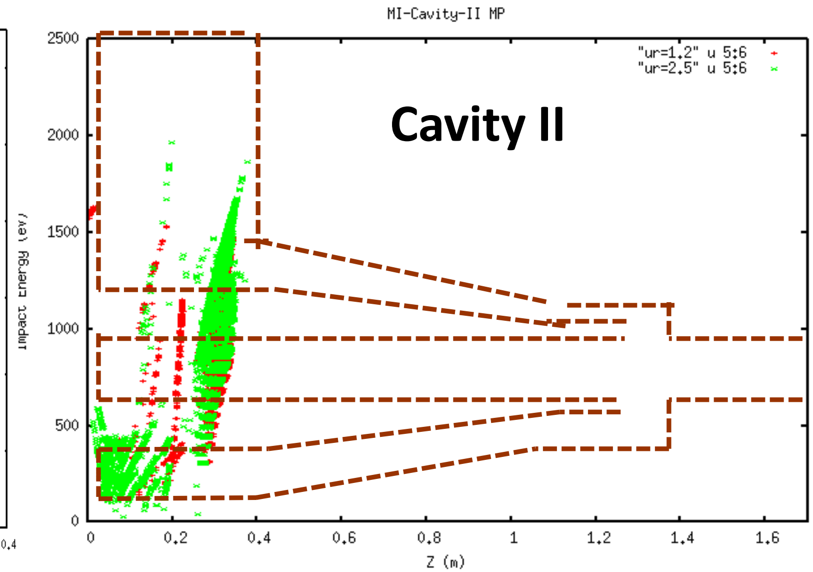
MP @ Z-location



MP @ XY-plane

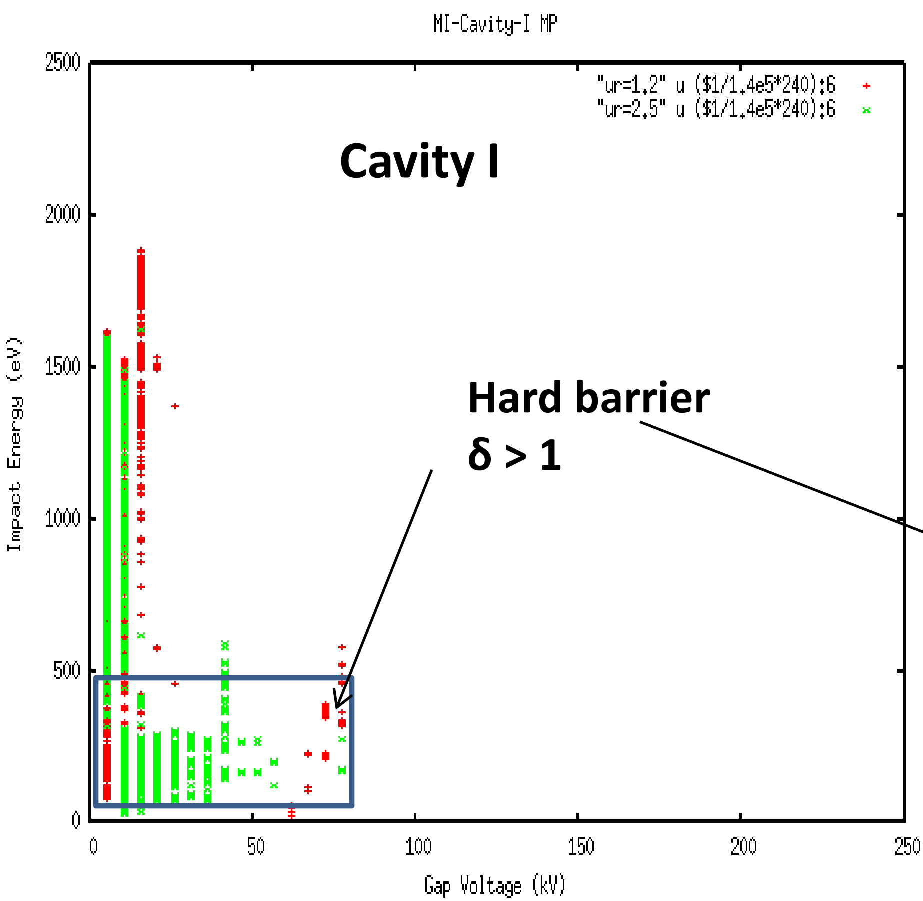


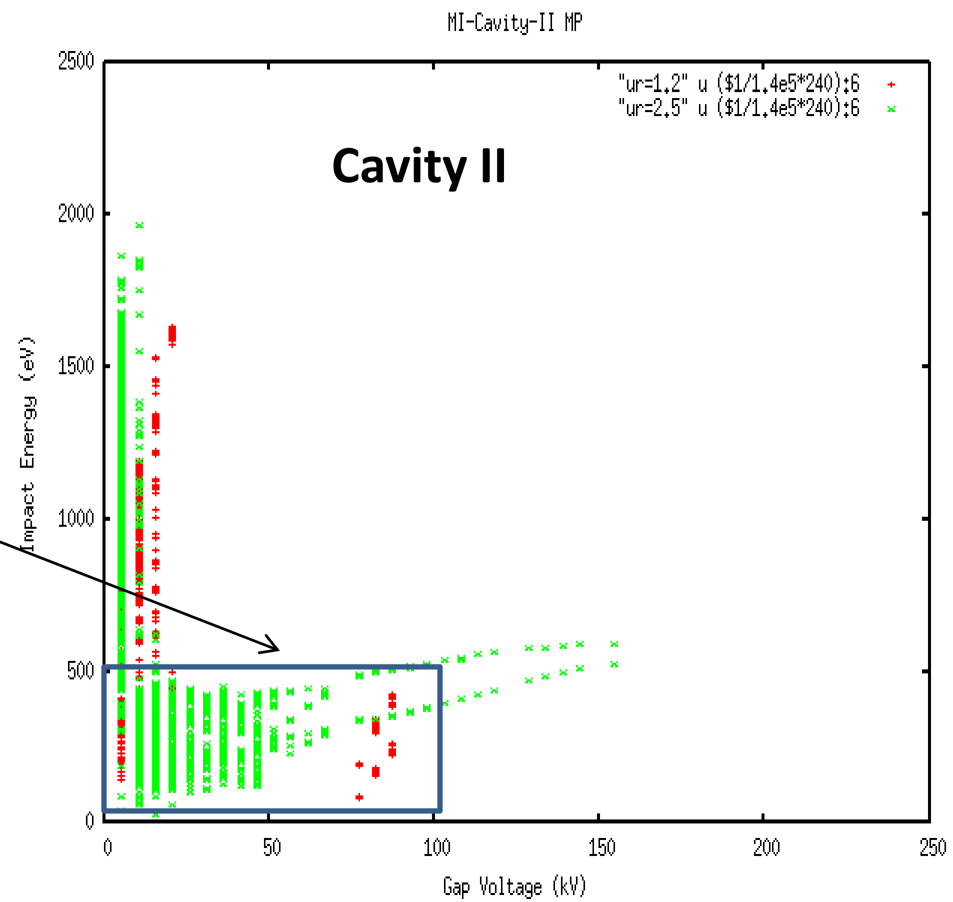
MP @ Z-location



There are MP activities in the end of the coaxial cavity I and II. And most of MP activities are between the coaxial cavity inter and outer conductors.

4.2 MP Barriers



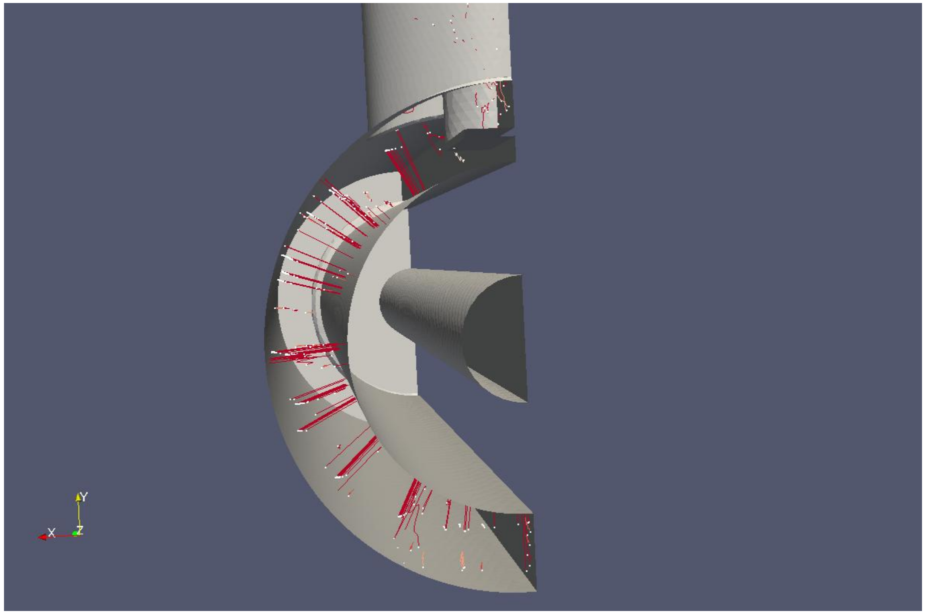


Strong MP barriers happened at lower gap voltage for both the cavity I and II, and soft MP barriers are wider in the cavity II than in the cavity I.

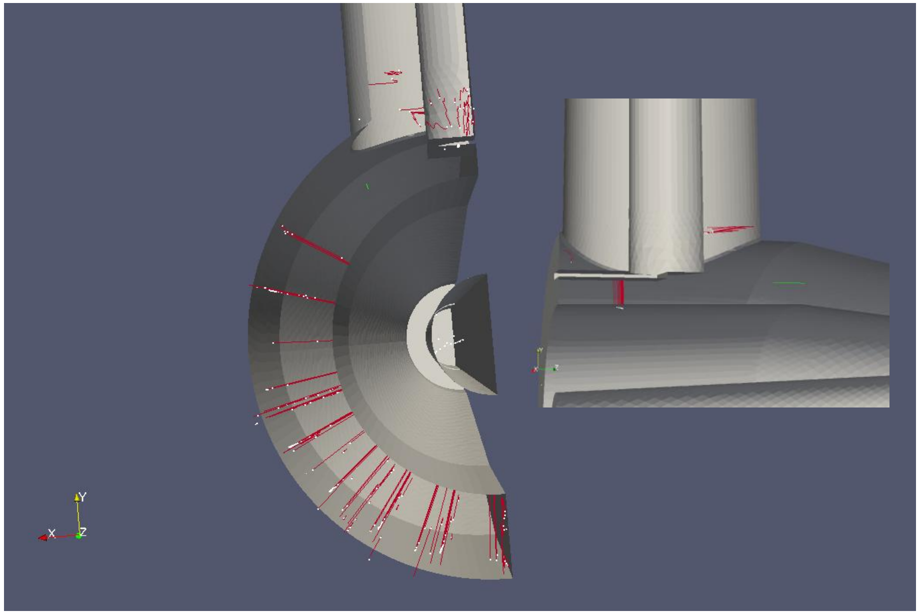
4.3 MP Trajectories at 5kV Gap Voltage

2-point 1st order MP

Cavity I



Cavity II



There are 2-points 1st order MP in the end of the coaxial cavity I and II.

5. Summary

@μr=2.5, Vgap=240kV, tuner intrusion=55mm		MI-Cavity-I	MI-Cavity-II
Operating Mode	R/Q (Ω)	51.23	56.95
	Δf (KHz)	584	539
	Max. Es (mV/m)	7.4	12.2
	Max. Bs (T)	37.2	30.9
Monopole HOM Modes <300MHz	No. of Modes	2	2
	Max. R/Q (Ω)	22	19
Horizontal Dipole Modes < 300MHz	No. of Modes	3	1
	Max. R/Q_T (Ω)	17	1.5
Vertical Dipole Modes < 300MHz	No. of Modes	3	1
	Max. R/Q_T (Ω)	17	1.6
	Max. center shift (mm)	43	29
Power Distributions	P(kW) (wall/ferrite/ceramic)	117/39/0.7	104/28/6
MP	Gap Voltage for MP barrier (kV)	<75kV	<150kV

5.1 MI-Cavity-I & II Observations

- ***The operating mode parameters (F, Q0, R/Q) are calculated with converged meshes using Omega3P for both the cavity I and II.***

- ***The tuning range can be achieved from 200kHz to 1000kHz with different tuner coupling.***

- ***The locations of the peak surface E and B fields are determined. Both the peak surface E and B fields are acceptable for 240kV accelerating voltage for the cavity I and II.***

- ***The power distributions obtained can be used for designing the cooling system.***

- ***HOMs below 300MHz are identified. Both the cavity I and II have similar monopole HOMs' R/Qs. However, there are less dipole modes in the MI cavity II than in the cavity I, and the MI cavity II has smaller R/Q_T than the cavity I.***

- ***There are strong MP activities in the cavity I and II at low accelerating voltage.***

- ***Overall, the MI cavity II has better RF performance than the cavity I.***

5.2 MI Cavity Simulation Future Plan

SLAC will closely collaborate with FNAL to finalize the MI cavity design to meet Project-X requirements.

- Simulate the MI cavity I and II including power amplifier.
- Investigate dampers for monopole HOMs.
- Find solutions to remove MP hard barriers.
- Choose one design from the MI cavity I & II and optimize for the final design.