

HOM Damper Design for 56MHz SRF Cavity for RHIC

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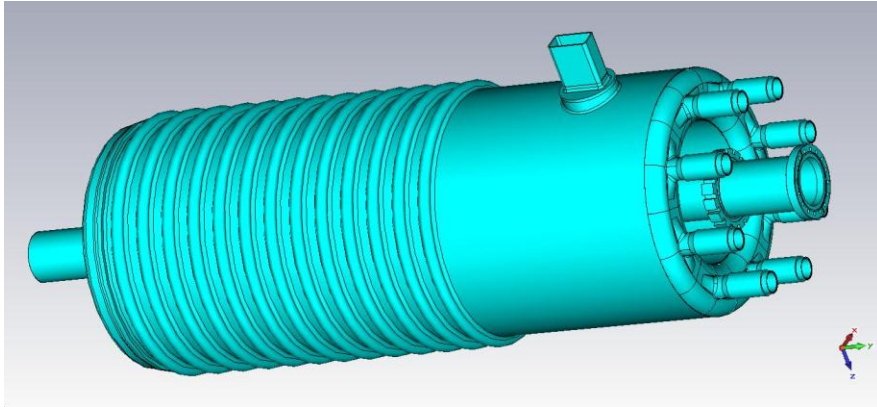
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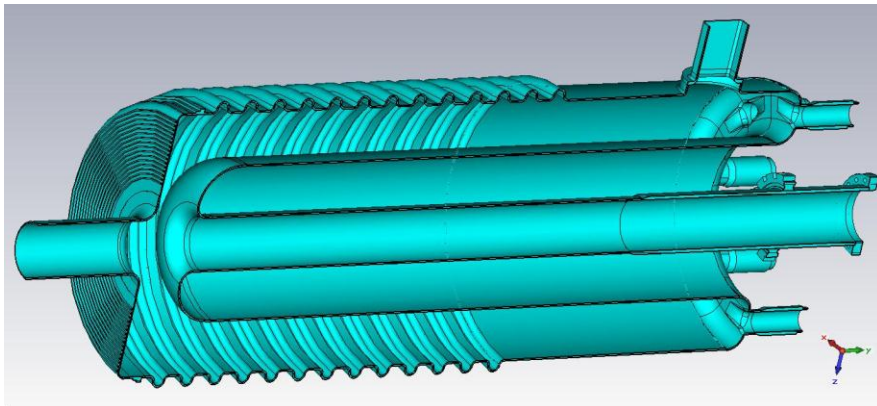
Outline

- Introduction of 56MHz SRF cavity
- HOM damper design
- High-pass filter
- Tuning of the filter
- Mechanical tolerance of the filter
- Transfer cable
- Summary

Introduction of the 56MHz SRF Cavity



The 56MHz superconducting cavity is being designed and built for the RHIC collider. It will be located at the common section of RHIC, and operated at harmonic 720 of the revolution frequency of RHIC.



The cavity is a niobium quarter-wave resonator for compact and efficient design. The beam from both rings of RHIC will traverse the symmetry axis of the resonator.

With such low frequency and a high voltage of 2.5MV at the gap, the cavity will provide for a large longitudinal bucket, which will reduce spill from intra-beam scattering.

56MHz Cavity Parameters

Stored Energy (@ 2.5MV gap voltage)	218	Joules
Operating temperature	4.2	K
Power dissipation (10nΩ residual surface resistivity)	42	W
Q_0	3E9	
Q_L	4E7	
r/Q (accelerator notation)	80.5	Ω
Maximum surface electric field	52	MV/m
Maximum surface magnetic field	112	kA/m
Tuning rate of mechanical tuner	17	kHz/mm
Coarse tuning range	25.5	kHz
Coarse tuning speed	3666	Hz/sec
Tuning sensitivity	17	Hz/um
Fine tuning range by piezo drive	60	Hz
Fine tuning resolution	0.06	Hz/Volt
Lorentz Detuning (@ 2.5MV gap voltage)	231	Hz

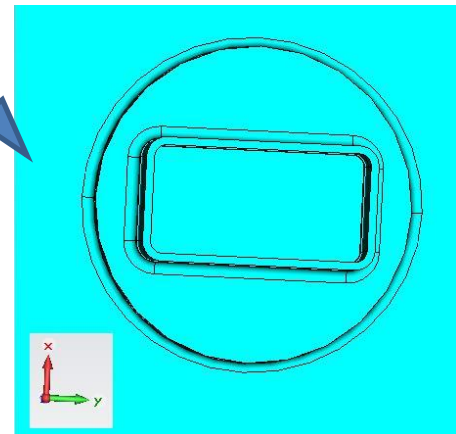
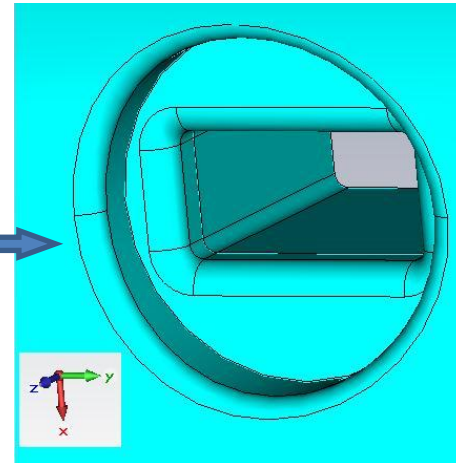
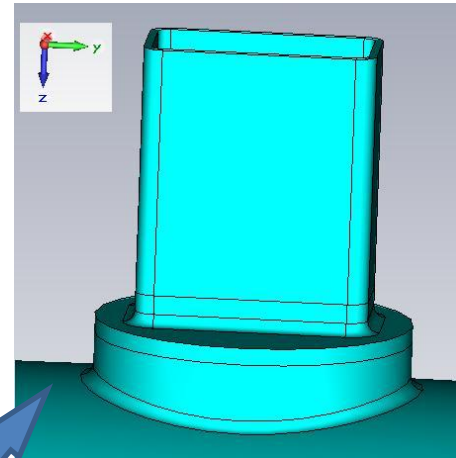
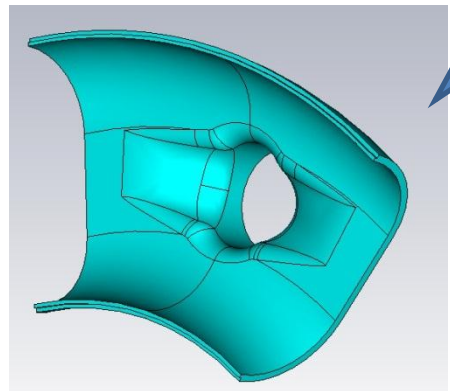
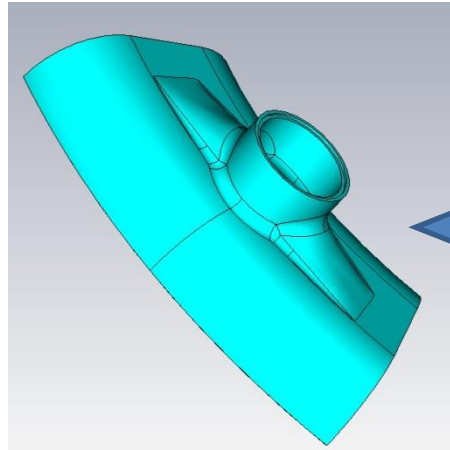
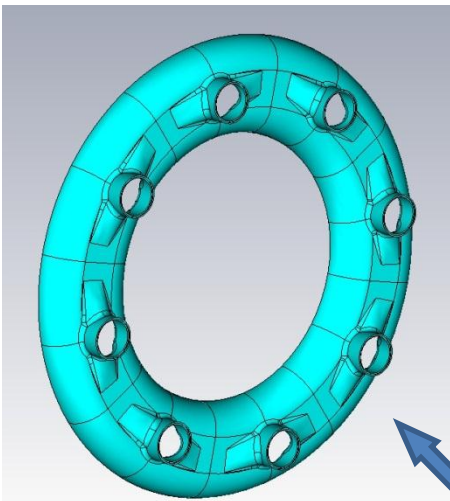
The Ports

The cavity has 8 chemical cleaning ports at the rear end, and 1 fundamental damper port on the side. All ports are specially designed at the edges to limit the field enhancement.

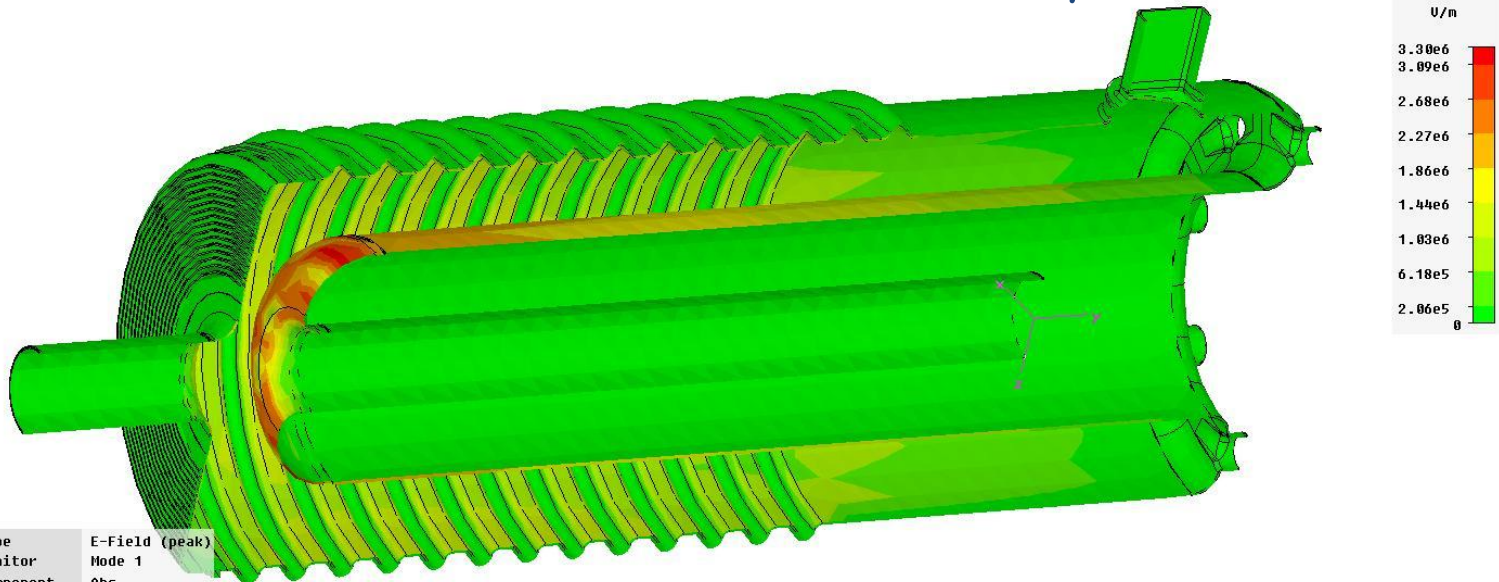
Chemical cleaning ports

Fundamental damper port

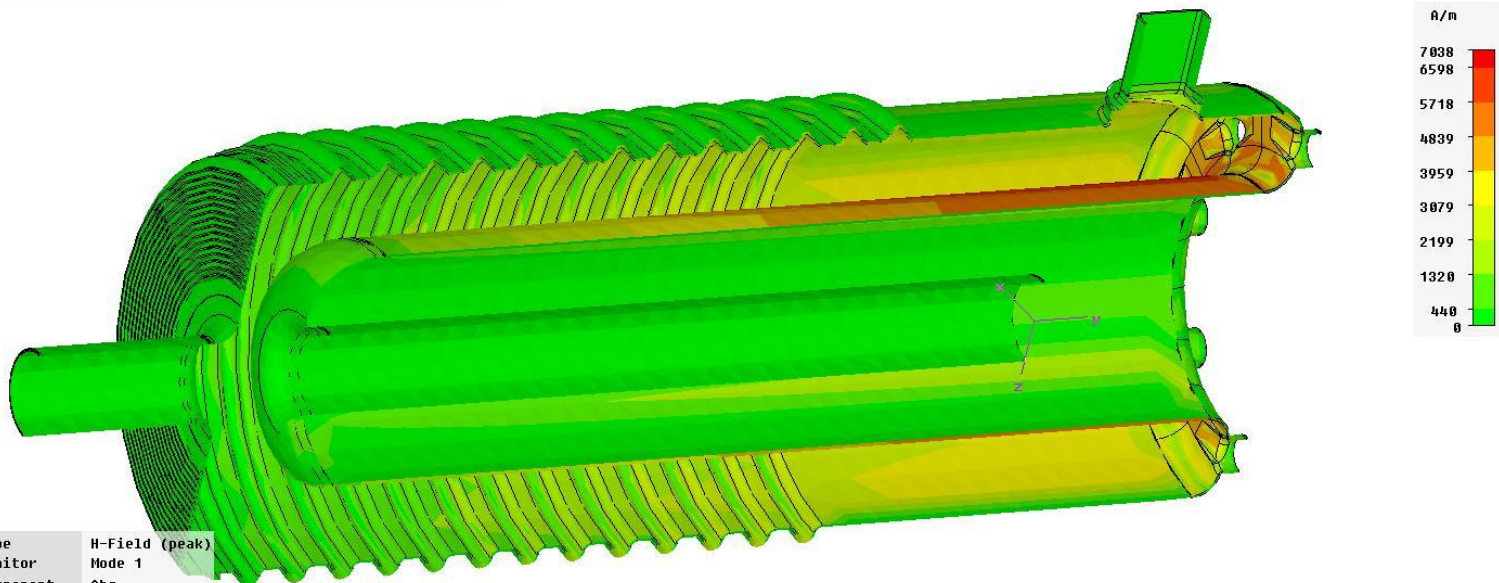
The chemical cleaning ports will be filled with 4 HOM dampers, 1 fundamental power coupler, 1 pickup probe, and 2 IR quench detectors during operation.



E field max and H field max for the bare cavity.

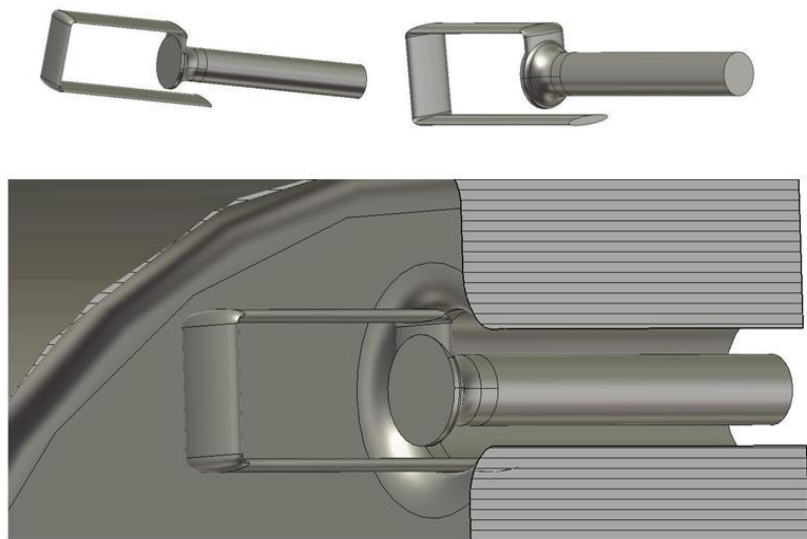


Type	E-Field (peak)
Monitor	Mode 1
Component	Abs
Maximum-3d	4.85492e+006 U/m at 1.5555 / -36.9341 / 5.40248
Frequency	55.2708
Phase	0 degrees

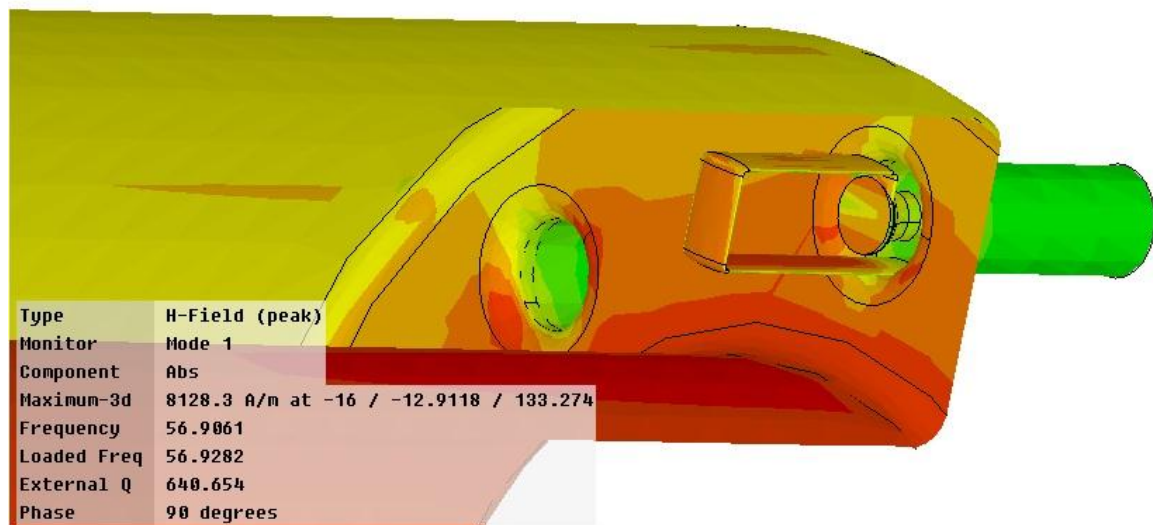


Type	H-Field (peak)
Monitor	Mode 1
Component	Abs
Maximum-3d	7735.49 A/m at 2.71191 / 9.48665 / 5.40248
Frequency	55.2708
Phase	90 degrees

HOM Damper Design



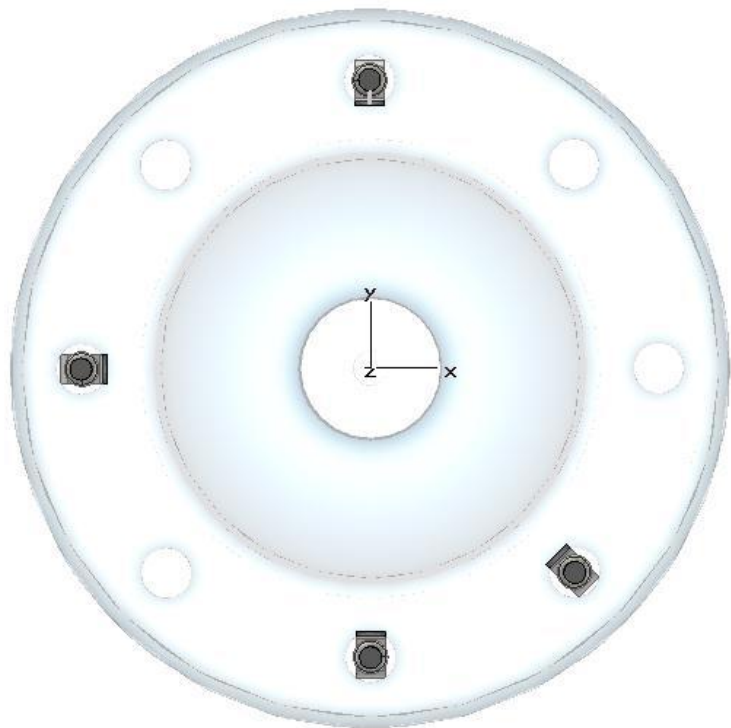
Dimension of damper inner loop	6cm x 2.88cm
Damper width	2cm
Damper thickness	0.3cm
Inner conductor radius	0.76cm
Port shape	$r = 1.74\text{cm}$



HOM dampers are:

- Inserted from the chemical cleaning ports at the rear end of the cavity
- Rectangular loop with magnetic coupling
- Rounded all edges and corners to limit the field enhancement
- Now checking for multipacting

With optimization to all HOM modes up to 1GHz, the cavity will have 4 HOM dampers. The 4 dampers are inserted in an asymmetrical configuration as shown below, which ensures all modes can be extracted to a certain degree.



Frequency [MHz]	Mode Config.	R/Q [Ω]	Q_L
56.231	M	80.53	940
167.456	M	32.34	438
260.445	D	22.18	3817
278.583	M	25.4	428
314.605	D	16.58	760
378.767	M	27.77	514
393.22	D	19.17	543
475.135	M	22.63	621
484.371	D	19.73	1115
490.072	Q	0.000874	7334
524.115	Q	0.00056	2205
573.46	M	12.91	744
577.852	Q	0.081	1390
579.53	D	19.68	1102
646.969	Q	0.0016	990
647.105	Q	0.00211	3758
670.053	D	19.30	1683
677.37	M	6.63	838
721.767	S	4.91E-05	56720
726.747	Q	0.00106	953
746.283	S	0.000477	15679
747.159	S	0.00046	9811
750.743	D	21.44	2224
751.081	D	22.43	1099
784.496	M	3.74	1510
786.022	S	0.0555	4880
813.048	Q	0.00123	1287
835.634	D	6.86	2315
838.906	S	0.00236	0.64
892.829	M	2.63	7458
902.098	Q	0.000988	5122
903.064	S	0.000843	12132
932.277	D	2.68	4584

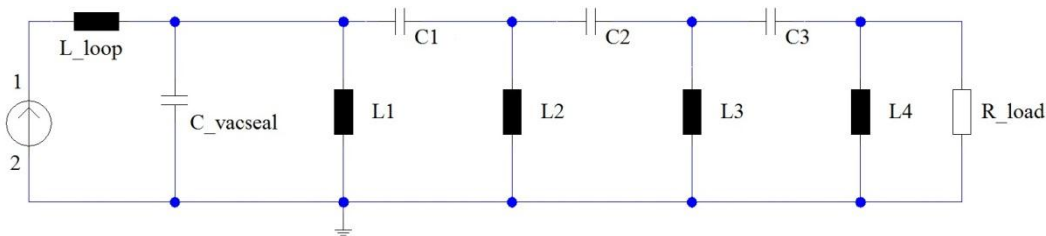
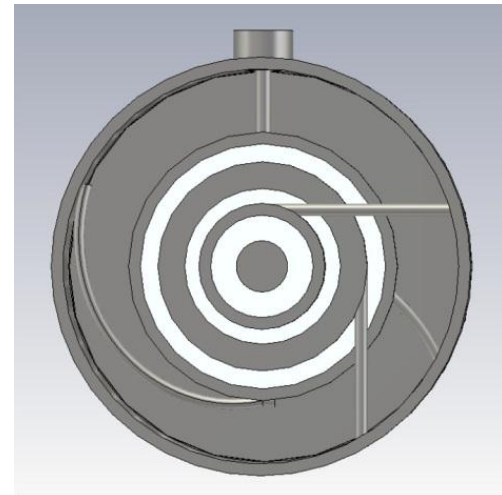
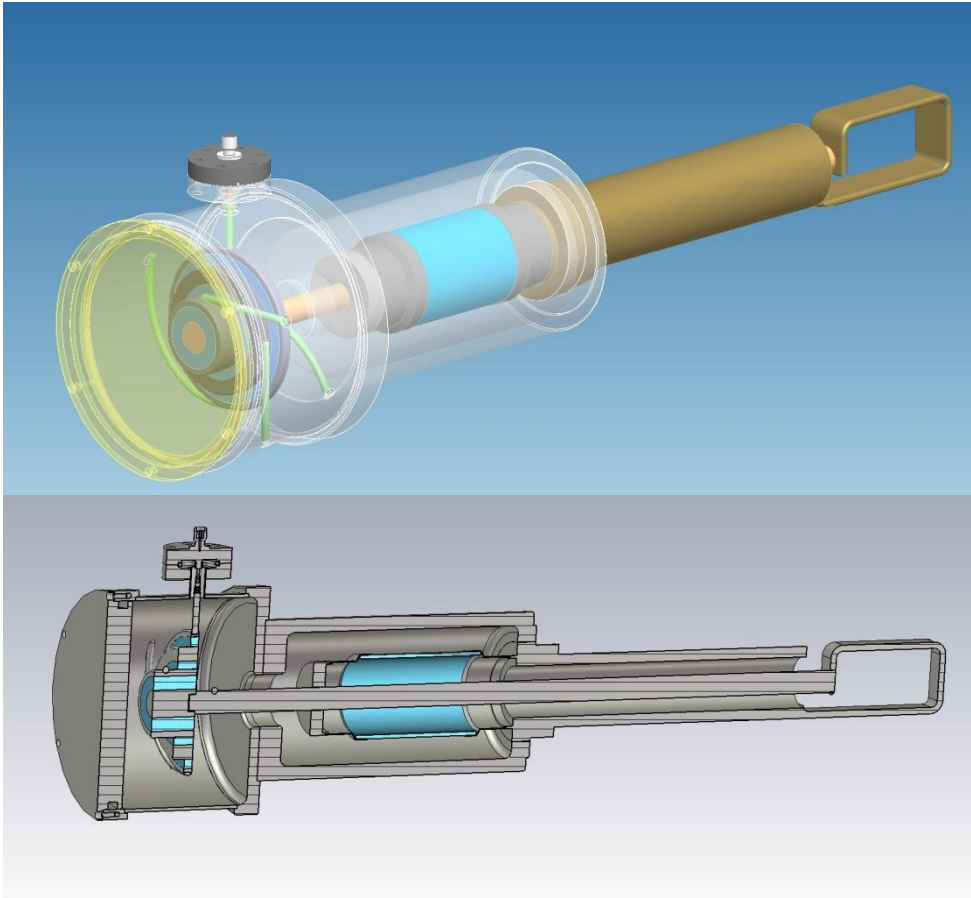
HOM Damper Filter

- ❑ The fundamental mode is strongly coupled to the HOM dampers
- ❑ Filters are needed to avoid damping of the fundamental mode
- ❑ Due to large separation from first HOM to the fundamental mode, we have the option of using a high-pass filter
- ❑ The damper loop and the metal components of the filter will all be niobium
- ❑ The capacitor components of the filter will be made with sapphire
- ❑ During operation, the filter is working at liquid helium temperature
- ❑ The HOM power will be deposited in an external load after the filter
- ❑ The temperature transaction will happen between the filter and the external load with a specially designed cable.

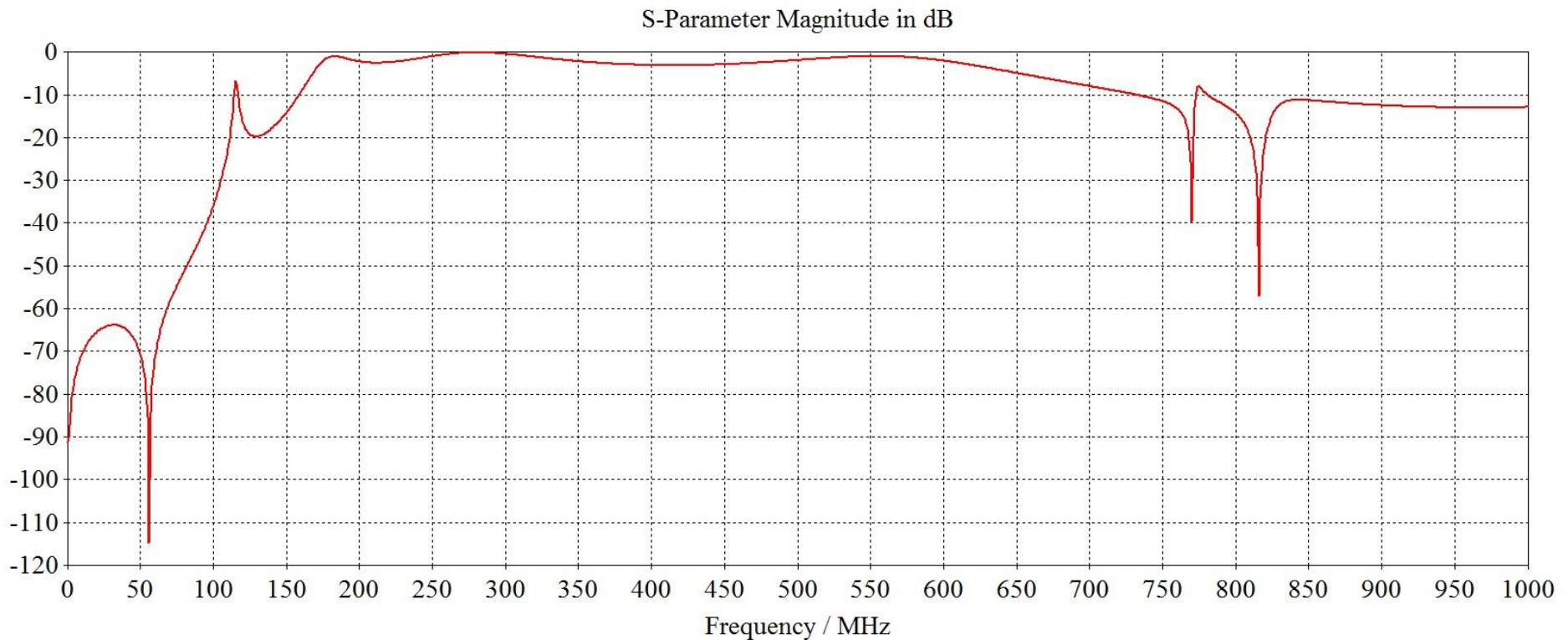
High-Pass Filter Design

The high-pass filter is designed in a coaxial pattern with niobium and sapphire as the only two material used.

The Chebyshev high-pass filter contains 3 capacitors and 4 inductors. In the same circuit loop, an additional sapphire ring is used to seal the vacuum of the cavity. As shown in the design, it also holds off the high voltage between the inner and outer conductors of the filter loop.

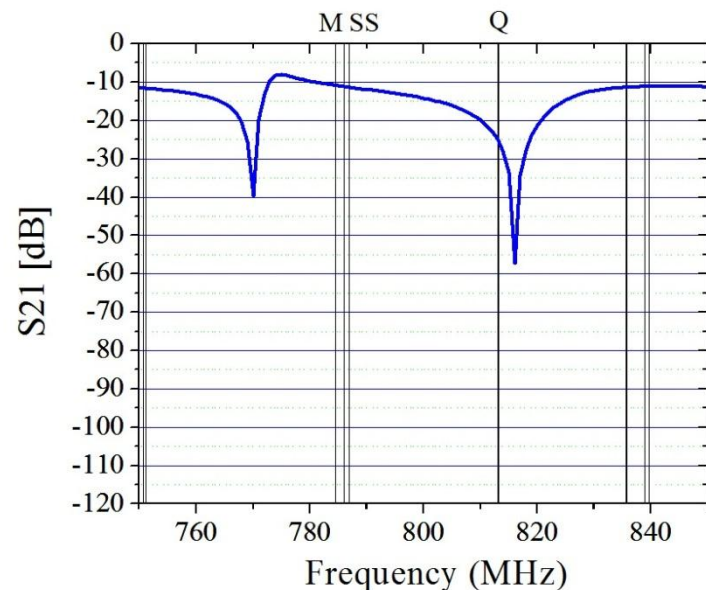
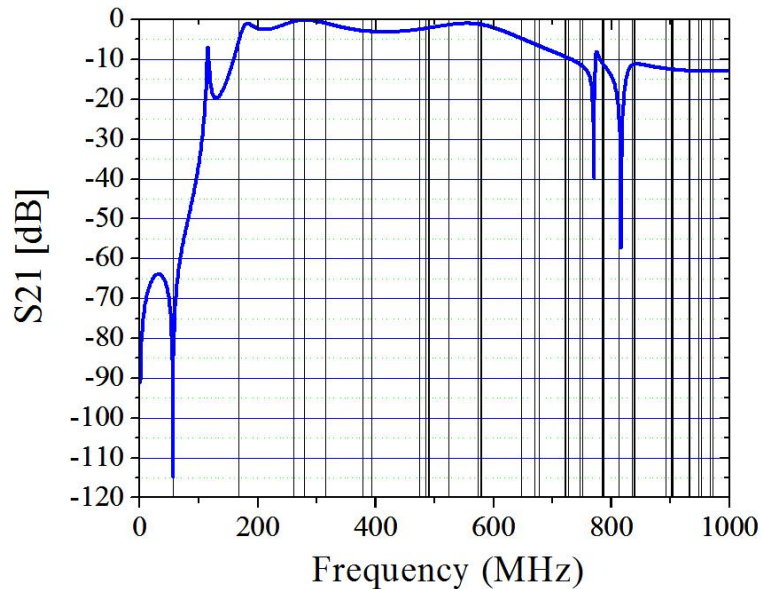


Filter Performance



The high-pass filter has very nice frequency response over the range of 0 to 1GHz, except for the two notches near 800MHz. This is caused by the capacitance between the filter sapphire rings and the end cap of the vacuum seal. However, none of the HOMs of the cavity overlays with the notches. Therefore, the notches will not effect the performance of the filter, even at the situation when all the HOMs are excited.

Overlay of the Filter Spectrum and HOMs of the Cavity



F[MHz]	Mode Type	Qext_tot	dB	R/Q	Qext_real	Qlimit
167.456	M	438	-5.35	32.34	1501	2000
378.767	M	514	-2.85	27.77	991	25000
475.135	M	621	-2.46	22.63	1093	7000
573.46	M	744	-1.17	12.91	975	5000
677.37	M	838	-6.63	6.63	3856	25000
784.496	M	1510	-10.87	3.74	18459	100000

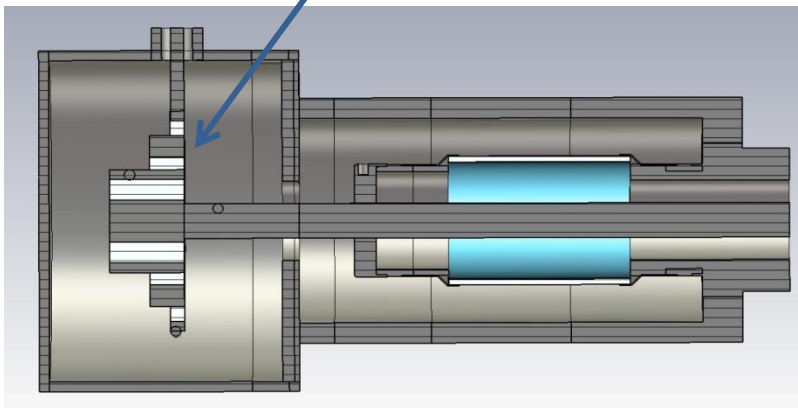
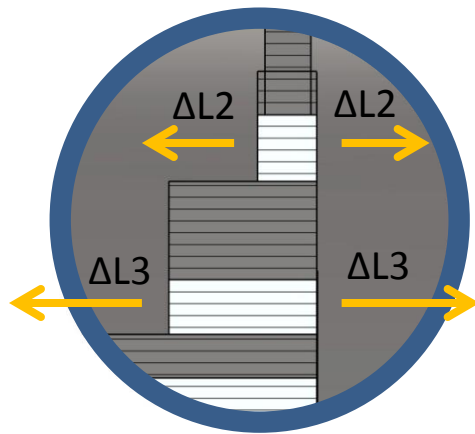
The power of the fundamental mode (FM) in the cavity is $>80\text{MW}$ with 2.5MV voltage at the gap. The filter provides -110dB attenuation at 56.3MHz , which limited the output power of the fundamental mode to less than 1mW .

The total power of the HOM modes excited by the beam in the 56MHz SRF cavity is $\sim 1.1\text{W/damper}$ during operation, both rings are included. With the filter installed, the HOM total power output is $\sim 0.33\text{W/damper}$.

The filter limited some of the HOM damping of the cavity. But more important, it significantly decreased the output power from the fundamental mode.

Tuning of the Filter

Instead of fixing all the sapphire pieces, we leave two outer most sapphire rings in the filter movable between the niobium cuffs. This will give us plenty of room to correct the error brought by fabrication.

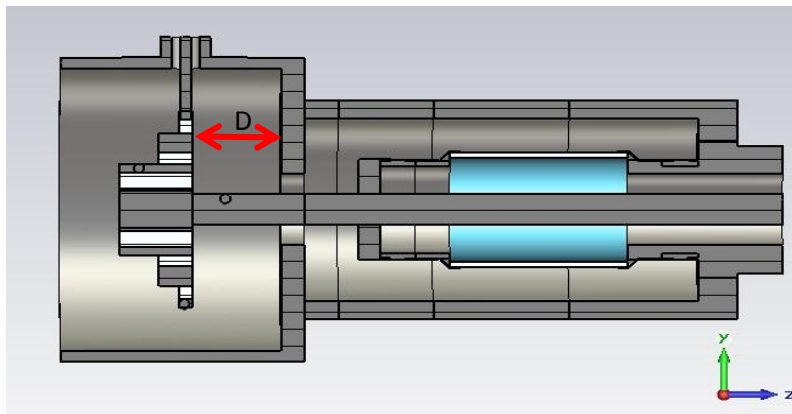
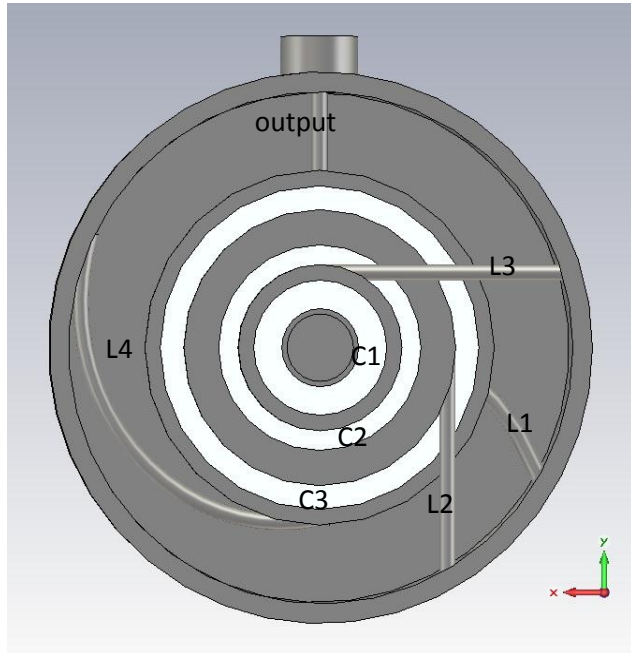


S21 @ 56MHz [dB]	S21min Frq [MHz]	$\Delta L2$ [cm]	$\Delta L3$ [cm]	S21 after adjust [dB]
-110	56	0	0	-110
-75	54	0	0.1	-92
-71	51	0.9	0.1	-95
-77	59	0	0.1	-100
-69	62	0.9	0	-93

$\Delta L2$ and $\Delta L3$ are the changes in effective capacitor length of the sapphire ring 2 and 3 respectively.

Mechanical Tolerance of the Filter

The criteria for the tolerance limit is $S_{21} < -70\text{dB}$ at the fundamental mode. The power output at -70dB for the fundamental mode is $\sim 3\text{W}$, which we used as the upper limit in the design of the connection cable between the filter and the external load.



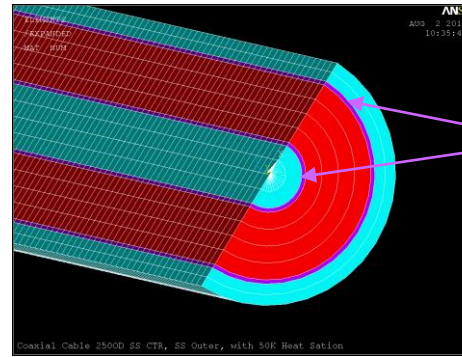
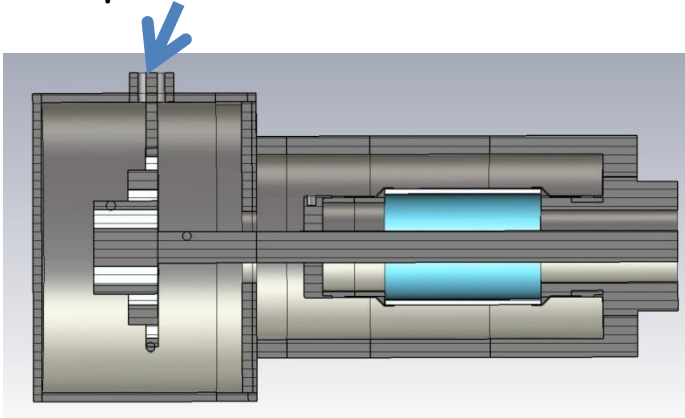
Parameter	Component	Designed Value	Tolerance
OD/ID	C1	2	$\pm 10\%$
	C2	1.2375	$\pm 10\%$
	C3	1.173	$\pm 1\%$
Length	C1	2.21cm	$\pm 10\%$
	C2	1.02cm	$> \pm 20\%$
	C3	0.41cm	$+10\%/-5\%$
Radius	L1	0.15875cm	$\pm 10\%$
	L2	0.15875cm	$> \pm 20\%$
	L3	0.15875cm	$> \pm 20\%$
	L4	0.15875cm	$\pm 8\%$
	Output	0.15875cm	$> \pm 20\%$
IR	Outer can	4.921cm	$\pm 2\%$
D	Outer can	2.67cm	$\pm 2.5\%$

Transfer Cable

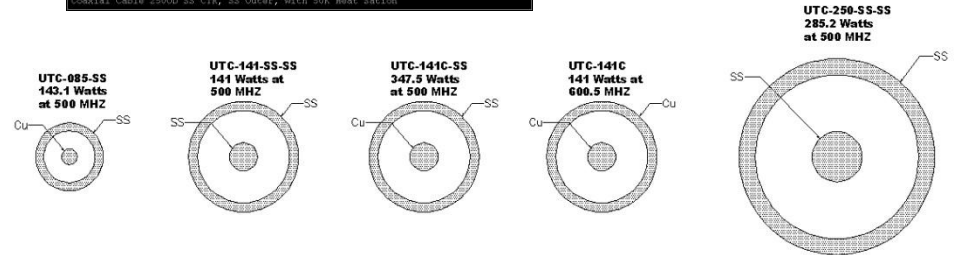
Courtesy S. Bellavia

A transfer cable is used to connect the output connector of the high-pass filter (4.5K) and the external load (RT). The thermal transfer on the cable is very important, as we want the least heat to be loaded into the cavity through this connection.

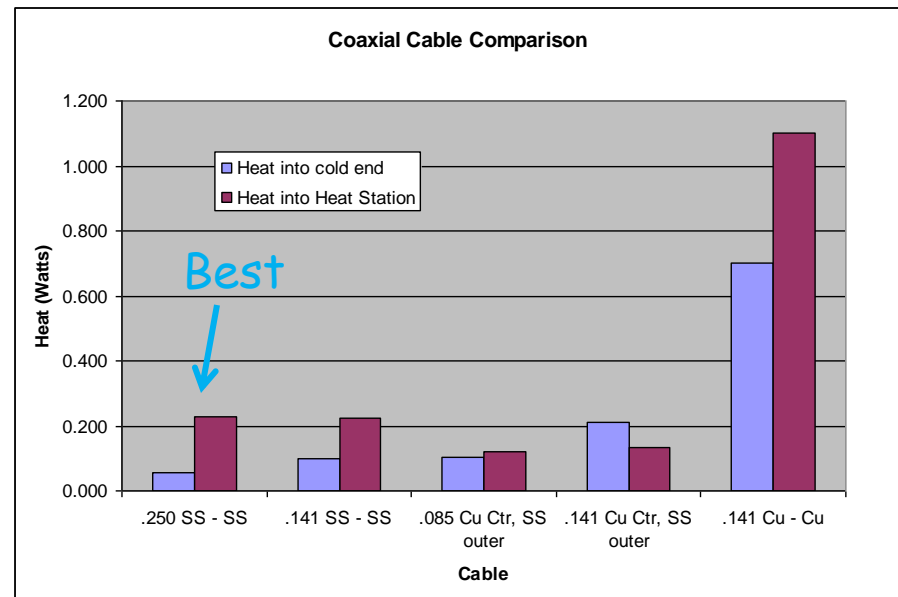
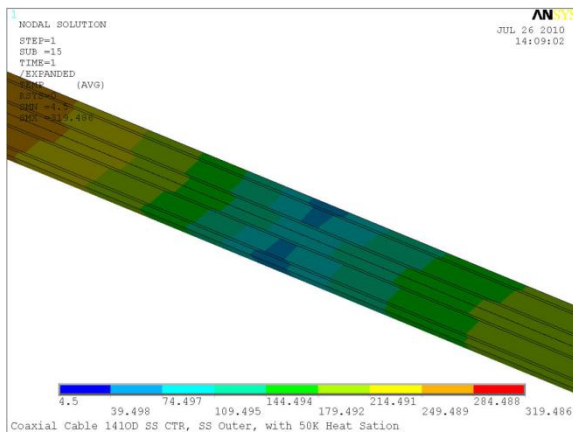
Output connector



These regions made 100X more thermally resistive than PTFE to simulate contact resistance



SS Conductors, 50K Heat Station with effect of Contact Resistance



Summary

- 4 HOM dampers will be used for the 56MHz SRF cavity for RHIC
- The dampers will be inserted at the rear end of the cavity in an asymmetrical configuration
- High-pass filters are designed to avoid damping of the fundamental mode
- Tuning of the filter is achieved by sliding the outmost sapphire ring
- Tolerance of the filter components are easy to achieve
- The transfer cable design with 50K heat station will only load $\sim 0.1\text{W}$ of heat back into the cavity, assuming 3W RF output power.

Backup – Power Calculation

Fundamental Mode Power

The current S21 for fundamental mode is close to -110dB, with less than -15dB attenuation for most of the HOMs.

The power extracted from the fundamental mode then should be:

$$P_{\text{loss}} = \frac{2\pi f_0 U_{\text{store}}}{Q_L 10^{a/10}} = 0.8mW$$

That leaves 0.2mW for each damper.

HOM Power

For 250GeV proton operation in RHIC, the current of a circulating beam with Gaussian bunches is

$$I(t) = \sum_{m=-\infty}^{\infty} \sum_{j=1}^{N_h} \frac{Ne}{\sqrt{2\pi\sigma_t^2}} \exp\left[-\frac{(t - mT_0 - jT_0/N_h)^2}{2\sigma_t^2}\right] \quad (1)$$

where N is the number of particles per bunch, T_0 is the revolution period, N_h is the number of bunches, and σ_t is the rms bunch length. To obtain the excitation for each HOM, we apply a Fourier Expansion to Equation (1)

$$I(t) = \sum_{n=-\infty}^{\infty} C_n \exp\left[-i\frac{2\pi nt}{T_0}\right] = \sum_{n=-\infty}^{\infty} C_n \exp[-in\omega_0 t] \quad (2)$$

Where

$$C_n = \frac{1}{T_0} \int_0^{T_0} I(t) \exp[-in\omega_0 t] dt \quad (3)$$

It is certain that . Thus only the term contributes. C_n then is solved from Equation (3)

$$\begin{aligned} C_n &= \frac{Ne}{T_0} \int_0^{T_0} \frac{1}{\sqrt{2\pi\sigma_t^2}} \exp\left[-\frac{(t - jT_0/N_h)^2}{2\sigma_t^2}\right] \exp[-in\omega_0 t] dt \\ &= \frac{Ne}{T_0} \sum_{j=1}^{N_h} \exp[-i\frac{2\pi nj}{N_h}] \exp[-\left(\frac{2\pi}{T_0}\right)^2 n^2 \frac{\sigma_t^2}{2}] \end{aligned}$$

It is easy to verify that only when n/N_h is an integer, C_n has a non-zero value of

$$C_n = \frac{Ne\omega_h}{2\pi} \exp\left[-\frac{m^2\omega_h^2\sigma_t^2}{2}\right] \quad (4)$$

where ω_h is the bunch frequency. Equation (2) shows that C_n is the n-th harmonic component for the beam's current. The excited power for HOM in the cavity is determined by the product of the real part of the impedance of each mode $Re[Z(\omega)]$ and C_n^2 . Therefore, for the k-th mode in the cavity

$$\begin{aligned} \text{Re}[Z_{n,k}(\omega)] &= \frac{(R/Q)_k Q_k}{1 + Q_k^2 \left(\frac{\omega_k}{n\omega_0} - \frac{n\omega_0}{\omega_k}\right)^2} \\ P_k &= 4 \sum_{n=-\infty}^{\infty} \text{Re}[Z_{n,k}(\omega)] C_n^2 \end{aligned} \quad (5)$$

where P_k is the power of the k-th mode in the cavity excited by the beam.