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Optimizing of the Higher Order Mode Dampers in the 56MHz SRF Cavity

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Abstract

Earlier, we reported that a 56 MHz cavity was designed for a luminosity upgrade of the RHIC, and presented the requirements for Higher Order Mode (HOM) damping, the design of the HOM dampers, along with measurements and simulations of the HOM dampers.

In this report, we describe our optimization of the dampers' performance, and the modifications we made to their original design. We also optimized the number of the HOM dampers, and tested different configurations of locations for them.

1. Optimization of the HOM damper and chemical port

The optimization of our original design of the HOM dampers for the 56MHz cavity [1] was based on the following criteria:

a. All monopole and dipole HOMs below 1GHz should be damped effectively. All other HOMs with a high R/Q should be similarly treated.
b. The change in the fundamental mode frequency due to inserting the damper should be well quantified.
c. The HOM dampers should be inserted through the chemical cleaning ports located at the rear of the cavity.
d. The field enhancement around the HOM dampers and ports should be such that the peak surface-magnetic fields do not exceed the maximum in the rest of the cavity.
e. In considering the smallest gap between the port and the damper, the HOM damper must never be at a high voltage such that might lead to an electrical breakdown.
f. The ease of fabrication by manufacturers should be assured.

1.1. Original Model

The original design of the HOM damper, shown in Figure 1, was the outcome of a former study [2]. The findings obtained from Microwave Studio simulations with this original design had the following parameters [Table 1]:

Table 1: Parameters of original design of HOM damper

Dimension of damper inner loop	6cm x 2.88cm
Damper width	2cm
Damper thickness	0.3cm
Inner conductor radius	0.76cm
Damper shape	All sharp edges
Port shape	Round, r = 1.74cm
Mesh size around damper	~0.3cm
Minimum mesh size	0.24cm
Maximum mesh size	1.5cm
Mesh cell number	833382
Equilibrate mesh ratio	1.4
Accuracy	1E-6

Figure 1 shows the original design of the HOM damper and the inserted configuration. The damper is designed such that it can be inserted into the cavity from the chemical-cleaning port, located at the cavity's rear end [2]. The size of the damper's loop was optimized to assure maximum coupling of the magnetic field, while also leaving it accessible through the 1.5" diameter opening of the chemical port.

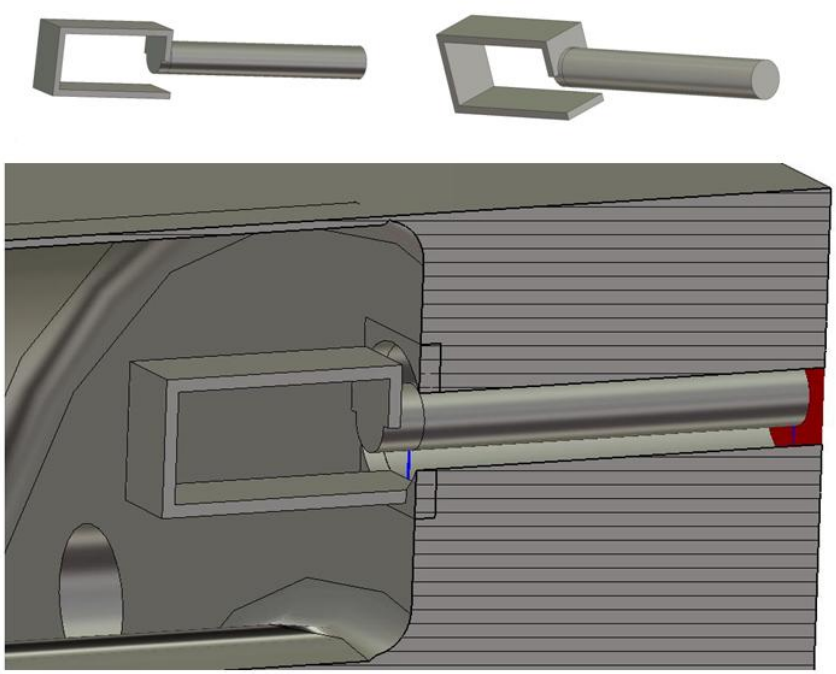

Figure 1: The original design of HOM damper.

Table 2 lists the results of the Microwave Studio (MWS) [3] simulation of the 56MHz cavity's fundamental mode with single HOM damper.

Table 2: MWS simulation results of the fundamental mode of the 56MHz cavity with one damper in its original design.

Fundamental mode frequency	56.2383MHz
External Q factor	4255
R/Q	79.9
V_{acc}	0.168MV
Q_0	10198
Shunt impedance	8.15E5Ohm
V_{damper}	1630V

As Figure 1 shows, all the edges and corners of the damper and the chemical ports are sharp. This easily engenders a considerable enhancement of in the local electric field, thereby increasing the possibility of causing electrical break down and quenching in the cavity. The field around the port can be obtained from the MWS simulation.

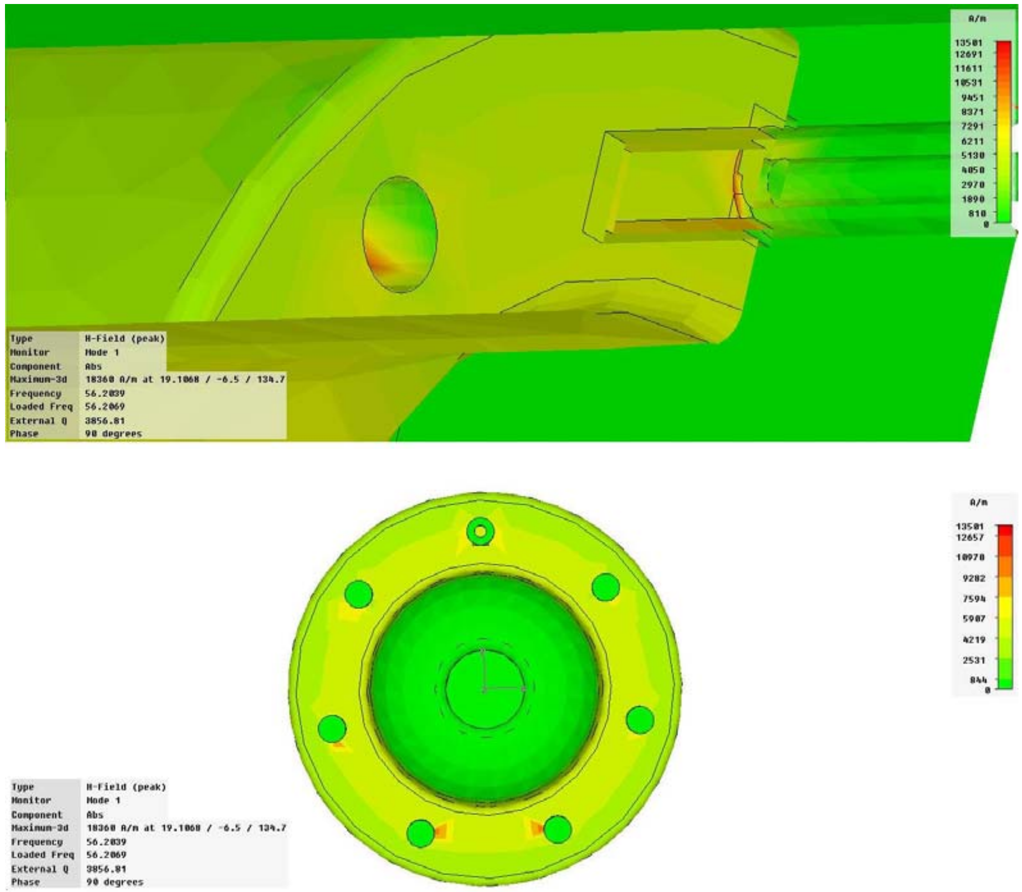

Figure 2: Peak magnetic field at HOM damper port. Top: Cross section view. Bottom: Rear end view.

The 56MHz cavity will be operated at the store stage for the RHIC; thus, the HOM damper then will experience the cavity's full voltage, which is designed to reach 2.5MV. The highest corresponding magnetic field is generated at the sharp edge of the chemical port, as depicted in Figure 2; it is of the magnitude of $2.6 \times 10^5 A/m$ (the normalization factor of this cavity is 14.66 for the MWS simulation). This strong field will generate heat locally, and cause a rapid rise in the cavity's temperature. Blending of the ports' edge is essential for lowering the peak surface-magnetic-field.

1.2.Modified design of the damper and chemical ports

To avoid a high peak field that might cause electrical break down, we need to smooth all the sharp edges on the dampers while maintaining the same inner loop area.

Figure 3 shows the modified HOM damper we designed. . The cross-section of the loop is elliptical and the corners are rounded, while the inner area of the loop remains unchanged, i.e. 6cm by 2.88cm. The width and the thickness of the loop also are unchanged as are the values of the long and short axes of the new elliptical cross-section.

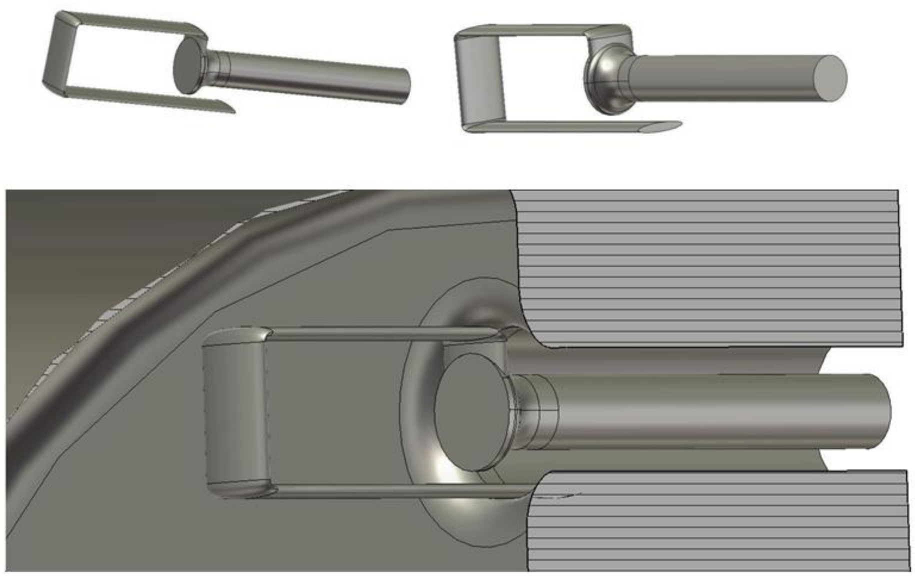

Figure 3: Modified HOM damper.

The radius of the connection of inner conductor and the loop of the HOM damper changes gradually, so that the radial ratio of the coaxial structure always remains constant, thereby ensuring that all HOM modes can be coupled out to the external load.

Figure 4 illustrates the magnetic field at the end of the cavity with HOM damper inserted; the maximum field on the damper is $8.4 \times 10^4 A/m$. This value is only 1/3 of the that in our original design, and even lower than the field generated on the cavity's shell, which is $9.5 \times 10^4 A/m$. The peak field at the port opening is $1.2 \times 10^5 A/m$.

The modified HOM damper maintains the original inner loop area and thickness, thus preserving the parameters of the performance table. We checked this by an MWS simulation that we discuss in the next section.

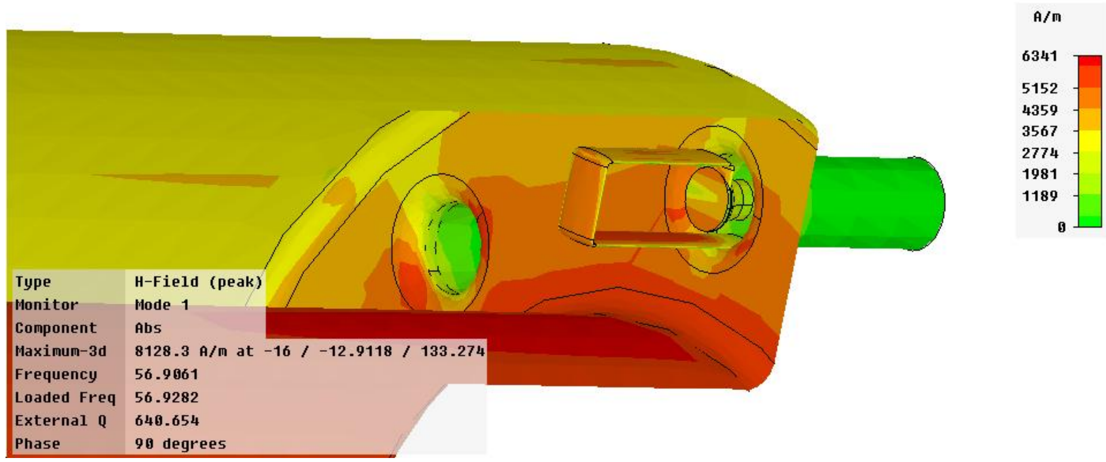

Figure 4: Maximum magnetic field around the HOM damper for the fundamental mode of operation.

We modified the chemical port is further to lower the electric field at its opening. Our final design is depicted in Figure 5. The field was calculated with the software ANSYS [4] it revealed that the peak field at the chemical cleaning port decreased to the same level as that at the end of the inner cavity.

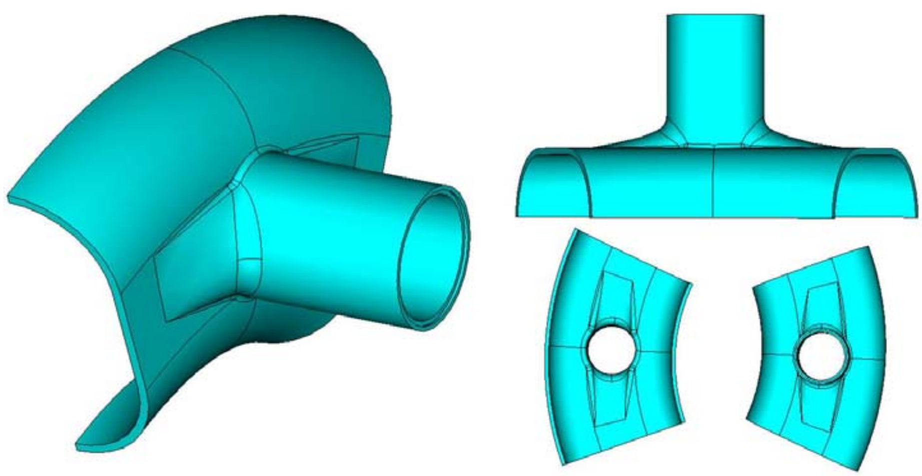

Figure 5: Final design of chemical port. [5] (M. Grau, private discussion)

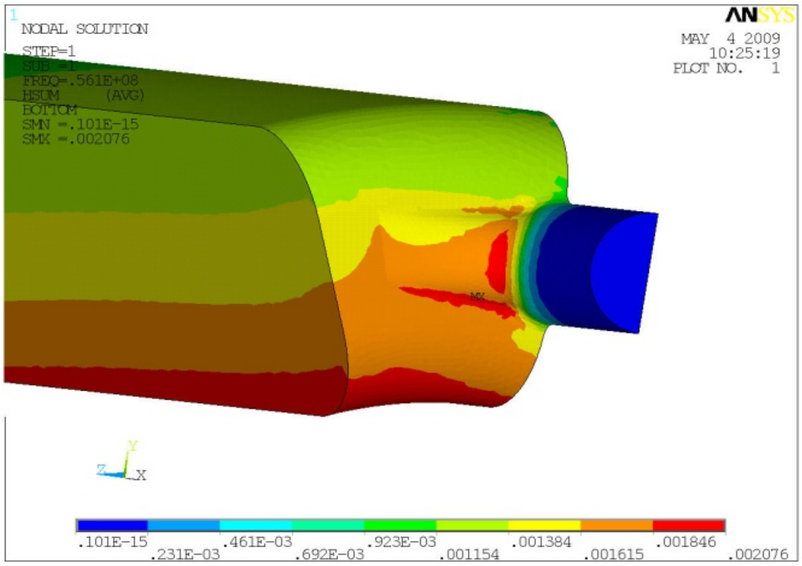

Figure 6: Magnetic field at the chemical port and rear end of cavity in final design. [6] (C. Pai, private discussion)

This latest design of the chemical port and the HOM damper greatly will reduces the risk of magnetic break down, and quenching of the cavity.

2. The performance of the modified HOM damper

With the modified HOM damper, we carried out simulations with Microwave Studio (MWS) to demonstrate its damping effect in the 56MHz cavity.

2.1. Damping with 1 HOM damper

The HOM damper inner area was optimized with only 1 damper present [2]. Table 3 shows the damping effect of this one damper located in the chemical port.

Table 3: MWS simulation of frequencies and Q_Ls in the 56MHz cavity with 1 modified damper.

Frequency [MHz]	Q_L	Frequency [MHz]	Q_L
56.182	3828	785.44	5532
167.53	1814	786.73	7619
254.38	248	839.02	5519
260.38	6412	840.13	4879
276.51	1806	884.84	18918
314.46	2168	895.97	24324
377.84	2236	903.98	64555
393.05	1528	903.22	104470
474.56	2789	949.52	153460
573.20	3494	968.72	23131
525.27	6771	971.41	49716
578.64	11802	976.50	6527
579.73	1207	986.44	5407
647.59	3135	1002.71	4349
670.75	2284	1003.21	6389
677.59	2989	1106.15	3282
722.69	75269	1122.23	1410
727.36	2968	1131.10	8651
747.10	22054	1158	2063
752.41	2711		

Table 3 shows that with one damper some frequencies of the HOMs in the 900MHz range are not depressed effectively. Ideally, in the presence of an HOM damper, all the modes would be extracted from the cavity, and the fundamental mode then would be reflected back by the high pass filter behind the damper. However, the size of the HOM damper is limited in this design of the cavity by the accessible radius and location of the chemical port. With only 1 HOM damper, it would be difficult to effectively suppress modes with numbers of poles higher than 2, e.g. quadrupole, sextupole.

In addition, the tolerances of HOMs also are highly dependent on the R/Qs, or the shunt impedance obtained from the product of Q_L and R/Q for each mode.

Therefore, we need to increase the number of the HOM dampers and change the configuration of their locations to enhance the damping effect. The R/Q and shunt impedance of each mode should be calculated to quantify the tolerance of each mode and improve the efficiency of damping.

2.2. Damping with 4 HOM dampers at symmetrical locations

There are 8 existing chemical ports at the rear end of the cavity two of which are occupied by the fundamental coupler and the pickup. The 6 remaining chemical ports can be used for HOM dampers and their locations chosen. We explored the effects using 4 HOM dampers at symmetrical ports, as shown in Figure 7.

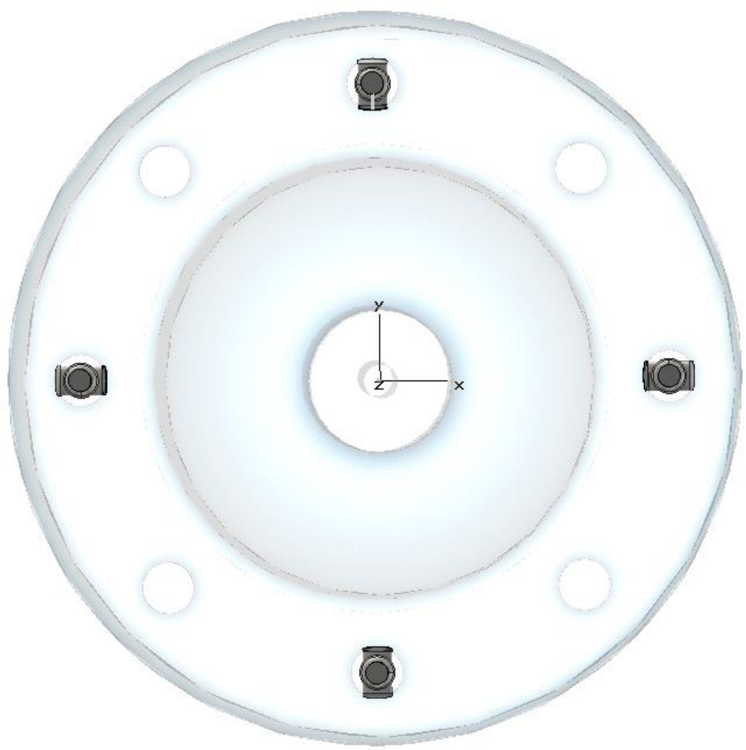

Figure 7: Rear view of the cavity with 4 HOM dampers inserted in symmetrical ports.

The damping effect in such a configuration is given in Table 4 from MWS simulations of frequency and Q_L.

Table 4: MWS simulations of frequencies and Q_Ls in the 56MHz cavity with 4 modified dampers inserted in symmetrical chemical ports.

Frequency [MHz]	Q_L	Frequency [MHz]	Q_L
56.197	933	722.51	3.44E+04
167.68	451	726.68	9.18E+08
259.82	3208	727.25	727
259.78	3218	746.83	1.36E+04
275.9	454	747.02	1.40E+04
314.32	1105	751.25	1350
314.29	1107	751.11	1350
377.96	547	784.92	1140
392.947	782	786.57	5340
392.942	784	786.77	5580
474.57	636	813.12	1.16E+09
484.111	748	813.87	988
484.108	748	836.36	2610
490.24	4.28E+08	836.28	2660
491.35	6080	839.49	0.634
523.98	9.73E+09	839.67	3750
525.28	1760	892.92	1.35E+04
572.87	707	902.17	3.58E+09
577.36	1.11E+08	902.42	4.47E+04
578.91	992	903.58	1.50E+05
579.24	829	903.71	9.60E+07
579.23	831	932.47	9240
646.1	1.50E+09	932.55	1.33E+04
647.88	765	949.21	6.12E+04
670.12	1060	952.89	8.96E+10
670.1	1060	968.44	1.03E+04
677.49	807	972.11	3.57E+10
722.28	3.32E+04	975.85	279

The configuration and R/Q of each mode also was simulated with MWS.

Table 5: MWS simulation of frequencies, mode configurations, and R/Qs in the 56MHz cavity with 4 modified dampers inserted in symmetrical chemical ports. (Mode configuration: M, monopole; D, dipole; S, sextupole; and, Q, quadrupole)

Frequency [MHz]	Mode Config.	R/Q [Ω]	R_{SH} [Ω/cm]	Frequency [MHz]	Mode Config.	R/Q [Ω]	R_{SH} [Ω/cm]
56.197	M	77.8	538	722.51	S	1.31E-05	0.068
167.68	M	31.3	105	726.68	Q	2.30E-04	32134
259.82	D	8.1	1415	727.25	Q	2.50E-04	0.028
259.78	D	9.8	1715	746.83	S	1.50E-13	3.19E-10
275.9	M	24.66	83	747.02	S	1.50E-03	3.28
314.32	D	14.3	1041	751.25	D	22.5	4770
314.29	D	14.3	1043	751.11	D	22.7	4814
377.96	M	26.9	109	784.92	M	3.8	32
392.947	D	13.4	864	786.57	S	1.11E-05	0.0098
392.942	D	13.6	876	786.77	S	3.90E-05	0.036
474.57	M	22.15	105	813.12	Q	4.00E-04	79019
484.111	D	13.3	1011	813.87	Q	4.00E-04	0.067
484.108	D	13.3	1011	836.36	D	9.0	4112
490.24	Q	1.96E-05	861	836.28	D	9.1	4237
491.35	Q	3.77E-05	0.024	839.49	S	7.90E-04	8.81E-5
523.98	Q	5.35E-05	57126	839.67	S	7.00E-04	0.46
525.28	Q	8.83E-05	0.017	892.92	M	2.62	262
572.87	M	12.89	68	902.17	Q	8.80E-04	595268
577.36	Q	1.33E-04	1785	902.42	Q	3.50E-04	2.96
578.91	Q	1.59E-04	0.019	903.58	S	2.43E-06	0.069
579.24	D	15.4	1551	903.71	S	3.00E-05	545
579.23	D	15.4	1548	932.47	D	2.7	4873
646.1	Q	1.39E-04	28214	932.55	D	2.8	7150
647.88	Q	1.89E-04	0.020	949.21	O	1.40E-05	0.17
670.12	D	22.4	3338	952.89	O	3.34E-10	5.97
670.1	D	22.5	3346	968.44	O	2.60E-05	0.054
677.49	M	6.64	40	972.11	O	2.20E-09	16.0
722.28	S	1.14E-05	0.057	975.85	S	1.00E-05	0.00057

The R/Qs of the cavity and shunt impedances per unit length for the monopoles are defined as:

$$\frac{R}{Q} = \frac{V(axis)^2}{\omega_0 U} = \frac{\left|\int E_z(axis)\, e^{ikz} dz\right|^2}{\omega_0 U}$$

$$R_{SH} = \frac{\left|\int E_z(axis)\, e^{ikz} dz\right|^2}{P_C\, l} = \frac{R}{Q} \times \frac{Q_L}{l}$$

Both R/Qs and shunt impedances of the cavity for the dipoles are defined as:

$$\frac{R}{Q} = \frac{1}{k^2 1cm^2}\frac{V(1cm)^2}{\omega_0 U} = \frac{1}{k^2 1cm^2}\frac{\left|\int E_z(1cm)|_{max}\, e^{ikz} dz\right|^2}{\omega_0 U}$$

$$R_{SH} = k\frac{1}{k^2 1cm^2}\frac{\left|\int E_z(1cm)\, e^{ikz} dz\right|^2}{P_C} = k\frac{R}{Q} \times Q_L$$

Both R/Qs and shunt impedances of the cavity for modes other than monopole and dipole are defined as:

$$\frac{R}{Q} = \frac{V(1cm)^2}{\omega_0 U} = \frac{\left|\int E_z(1cm)|_{max}\, e^{ikz} dz\right|^2}{\omega_0 U}$$

$$R_{SH} = k\frac{\left|\int E_z(1cm)|_{max}\, e^{ikz} dz\right|^2}{P_C} = k\frac{R}{Q} \times Q_L$$

In all equations above, z is the direction along the center axis, and $E_z(axis)$ is the electric field in z direction on the axis; $E_z(1cm)$ is the axial electric-field with $1cm$ offset to the center. P_c is the power loss of the specified mode due to the HOM damper. Thus, $V(1cm)$ is the accelerating voltage of each mode with an offset of 1cm. l is the length of the cavity. Also, ω_0 and U are, respectively, the frequency and stored energy of the specified mode. In the MWS simulation, the cavity material is lossless, thus $Q_{ext} = Q_L$.

In this configuration of the locations of the HOM dampers, most of the higher order modes are damped effectively. However, quadrupoles with a configuration of 45 rotated from the location of the HOM dampers barely are damped due to the orthogonality between them. All these quadrupoles have a shunt impedance of $> 1 \times 10^4$Ω/cm. Quadrupoles do not affect the performance of the cavity as much as do the monopoles and dipoles, but their effect still is non-negligible with such a high R/Q and accumulation as the beam stores in RHIC.

2.3. Damping with 4 HOM dampers at asymmetrical locations

To effect a compromise between all the HOMs and optimize the damping effeciency, the 4 HOM dampers must be placed asymmetrically.

We chose the 4 locations shown in Figure 8.

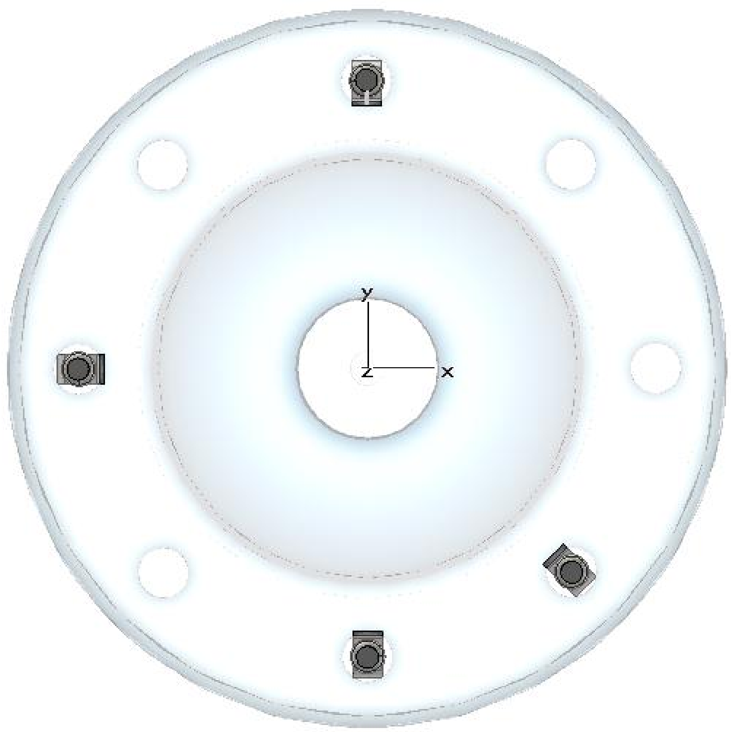

Figure 8: Rear view of the cavity with 4 HOM dampers inserted in asymmetrical ports.

Table 6: MWS simulation of frequencies and Q_Ls in the 56MHz cavity with 4 modified dampers inserted in asymmetrical chemical ports.

Frequency [MHz]	Q_L	Frequency [MHz]	Q_L
56.231	940	722.661	28425
167.456	438	726.747	953
260.445	3817	726.786	4381
261.133	2519	746.283	15679
278.583	428	747.159	9811
314.605	760	750.743	2224
315.028	1597	751.081	1099
378.767	514	784.496	1510
393.22	543	786.022	4880
393.72	1146	786.862	4392
475.135	621	813.048	1287
484.371	1115	813.159	11579
484.921	531	835.634	2315
490.072	7334	835.845	4306
490.762	19858	838.906	0.64
524.115	2205	839.705	3847
524.644	6675	892.829	7458
573.46	744	902.098	5122
577.852	1390	902.16	47060
578.168	5378	903.064	12132
579.53	1102	903.867	13428
580.059	577	932.277	4584
646.969	990	932.513	2620
647.105	3758	948.68	41626
670.053	1683	952.71	4.12E+08
670.471	813	967.912	8302
677.37	838	971.89	1.34E+07
721.767	56720		

Table 7: MWS simulation of frequencies, mode configurations, and R/Qs in the 56MHz cavity with 4 modified dampers inserted in asymmetrical chemical ports. (M, monopole; D, dipole; S, sextupole; and. Q, quadrupole)

Frequency [MHz]	Mode Config.	R/Q [Ω]	R_{SH} [Ω/cm]	Frequency [MHz]	Mode Config.	R/Q [Ω]	R_{SH} [Ω/cm]
56.231	M	80.53	562	722.661	S	2.49E-05	0.11
167.456	M	32.34	105	726.747	Q	0.00106	0.15
260.445	D	22.18	4618	726.786	Q	0.0014	0.93
261.133	D	17.38	2395	746.283	S	0.000477	1.17
278.583	M	25.4	81	747.159	S	0.00046	0.71
314.605	D	16.58	830	750.743	D	21.44	7497
315.028	D	9.65	1017	751.081	D	22.43	3877
378.767	M	27.77	106	784.496	M	3.74	42
393.22	D	19.17	857	786.022	S	0.0555	44.6
393.72	D	8.38	792	786.862	S	0.00594	4.30
475.135	M	22.63	104	813.048	Q	0.00123	0.27
484.371	D	19.73	2231	813.159	Q	0.00102	2.01
484.921	D	8.43	455	835.634	D	6.86	2778
490.072	Q	0.000874	0.66	835.845	D	7.34	5534
490.762	Q	0.00125	2.55	838.906	S	0.00236	2.6E-4
524.115	Q	0.00056	0.14	839.705	S	0.00528	3.57
524.644	Q	0.000656	0.48	892.829	M	2.63	146
573.46	M	12.91	71	902.098	Q	0.000988	0.96
577.852	Q	0.081	13.6	902.16	Q	0.0069	61.4
578.168	Q	0.0405	26.4	903.064	S	0.000843	1.93
579.53	D	19.68	2633	903.867	S	0.000321	0.82
580.059	D	9.28	651	932.277	D	2.68	2395
646.969	Q	0.0016	0.21	932.513	D	2.78	1422
647.105	Q	0.00211	1.07	948.68	O	9.83E-06	0.08
670.053	D	19.30	4557	952.71	O	8.44E-08	6.94
670.471	D	26.12	2982	967.912	O	2.32E-05	0.04
677.37	M	6.63	41	971.89	O	3.50E-08	0.10
721.767	S	4.91E-05	0.42				

The R/Qs and shunt impedances in Table 7 has the same definition as that given in section 2.2.

Table 6 is the frequency table in such geometry. The loaded Qs for all monopole and dipole modes are $\leqslant 8 \times 10^3$. Those loaded Qs for all quadrupoles are $\leqslant 5 \times 10^4$. All R/Q for HOM's are $\leqslant 33\Omega$, and all shunt impedance values are $\leqslant 7.5 \times 10^3\,\Omega$/cm. The higher order modes are very well damped in this configuration. The HOM damping effect in such geometry meets with the requirements for the cavity.

3. Acknowledgement

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Reference

[1] I. Ben-Zvi, C-A/AP/337, 2009.

[2] E. Choi, H. Hahn, C-A/AP/319, 2008.

[3] CST Microwave Studio Suite 2008.

[4] ANSYS v11.0.

[5] Private discussion with M. Grau.

[6] Private discussion with C. Pai.