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Higher Order Mode Damper Study of the 56 MHz SRF Cavity

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Abstract

This report summarizes the study on the higher order mode (HOM) damper for the 56 MHz SRF cavity. The Q factors and frequencies of the HOMs with the HOM damper are measured and compared to the simulation. The high pass filter prototype for rejecting the fundamental mode is designed and tested. The filter measurement is also compared to the simulation. Based on the mearuement, a new location of the HOM damper is chosen.

1 Introduction

A 56 MHz superconducting RF cavity (SRF) is being designed and prototype-tested as an AIP (Accelerator Improvement Project) for the luminosity upgrade of the Relativistic Heavy Ion Collider (RHIC). The 56 MHz cavity is intended to be turned on at store, which requires a stable fundamental mode operation without exciting the higher order modes (HOM). The HOMs result in some instabilities, and especially when the monopole HOMs are excited, the coupled bunch (CB) mode instability leads to a severe beam instability. Therefore, suppressing the excitation of the HOMs is of great importance for running the cavity stably. The HOM dampers are necessary components for operating the cavity which damp out HOMs that are present in the cavity. The HOM dampers are designed to be inductively coupled structure which couples out the magnetic fields of the cavity. For the quarter wave SRF 56 MHz cavity, the end of the cavity will have the strongest magnetic field location which determines the location of the HOM dampers. Two orthogonally posed HOM dampers are going to be installed at that location to allow to couple the dipole modes with two orthogonal polarities. The fundamental mode of the cavity, however, has to be rejected, which requires some kind of filtering of the damper.

2 The identification of HOMs

Fig. 1 shows the Cu prototype 56 MHz cavity. On the left side of the cavity (from Fig. 1), an opening for the HOM damper is seen with 45° tilted angle with respect to the vertical coordinate of the cavity. To elminate all HOMs including opposite polarities, the second HOM damper will be also used and 90° apart from the first HOM damper on the same vertical plane (In Fig. 1, the second HOM damper opeing is located 90° apart from the first HOM damper which is hidden in the picture.). First of all, the HOMs of the 56 MHz cavity are identified experimentally by a network analyzer.

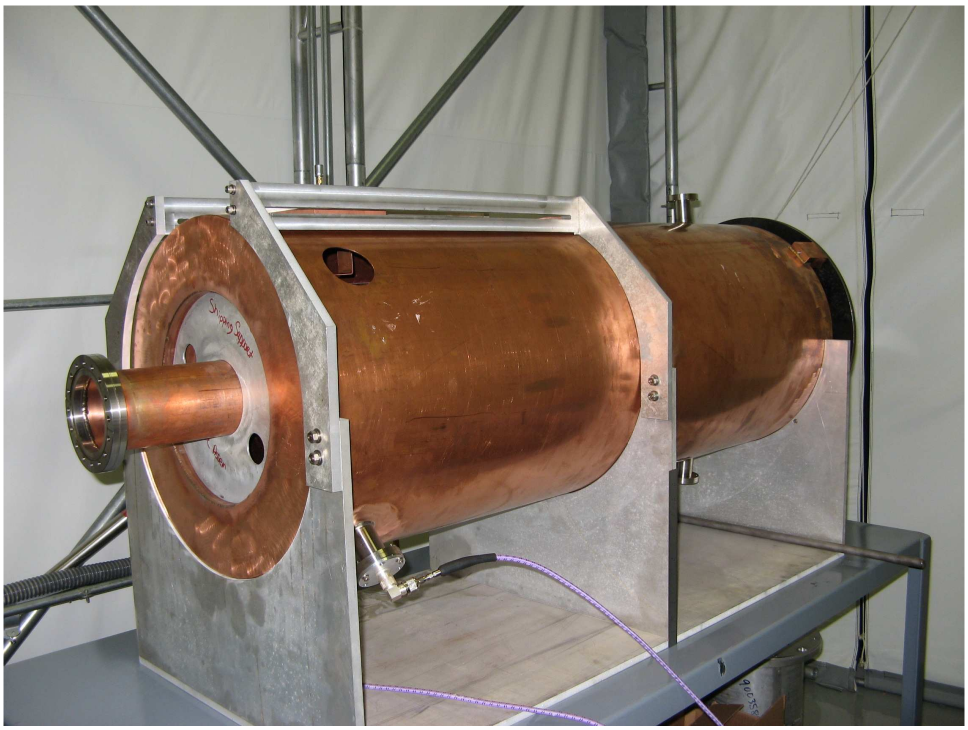

Figure 1: The picture of the 56 MHz prototype Cu cavity. The HOM damper port is seen on the left side of the cavity.

Table 1: Measured frequencies and Q factors of the 56 MHz prototype

Frequency (MHz)	Q_0	Frequency (MHz)	Q_0	Frequency (MHz)	Q_0
56.192	8640	687.843	20100	986.883	6670
168.059	13600	724.621	9640	1004.018	4690
260.166	18010	727.565	14770	1014.963	12000
277.977	17180	749.281	8530	1044.513	5120
314.409	14220	761.441	11630	1054.350	7170
383.995	18890	788.587	7750	1056.707	1990
392.447	16490	795.420	20550	1057.690	9040
483.203	16800	814.570	11160	1059.523	7170
485.553	17150	841.448	6590	1096.814	5530
491.205	18680	850.434	15740	1104.785	10640
525.221	13380	904.360	13640	1139.381	6250
578.686	12900	906.844	9840	1140.640	8070
579.172	18770	948.541	13380	1152.074	4320
584.828	16950	954.698	9190	1156.541	5470
647.554	12990	973.383	6370	1164.193	5280
673.315	13270	978.663	4410	1179.994	6490

Table 1 summarizes the measured HOMs and quality factors of the 56 MHz prototype cavity. Almost all distinguishable HOMs were measured up to 1.2 GHz. However, identifying mode configurations (monopoles, dipoles and etc.) is not trivial. The MWS simulation was used to identify the mode configurations by comparing the closest frequencies to the measurement frequencies. Table 2 is the result of MWS simulation for the HOMs.

3 The HOM high pass filter

Since the HOM damper couples out the HOMs inductively, an unwanted coupling of the fundamental mode via the HOM damper also happens. Therefore, a kind of filter device is necessary for rejecting the fundamental mode in the HOM damper. For the 56 MHz HOM damper, a high pass filter is adopted for several reasons. First of all, the first HOM of the quarter-wave 56 MHz cavity is quite apart from the fundamental mode, which makes the filter design be easier in a sense that it does not have to notch out the exact fundamental mode frequency. Second, the high pass filter concept has been already successfully used for the RHIC 28 MHz accelerating cavities. The 56 MHz HOM high pass filter is a 5 element high pass filter, which consists of 3 capacitors and 2 inductors terminated with a 50 Ω load.

Fig. 2 is the schematic of the filter circuit. The circuit component L and C values are obtained from the critical frequency of 120 MHz which is fundamentally calculated from the following equation,

$$\omega_{crit} \cong \frac{1}{\sqrt{LC}}. \qquad (1)$$

The first capacitor value is around 21 pF according to Eq. 1. Fig. 3 shows the MWS model

Table 2: Frequencies and R/Q of the 56 MHz prototype from MWS simulation

Frequency (MHz)	Mode config.	R/Q	Frequency (MHz)	Mode config.	R/Q
56.175	monopole	78.9	788.613	sextupole	
167.86	monopole	30	793.964	monopole	6.2
260.327	dipole	10.1	814.148	quadrupole	
277.452	monopole	23.2	841.768	sextupole	
314.531	dipole	17.2	849.463	dipole	8.8
383.271	monopole	22.6	902.875	sextupole	
392.169	dipole	16	903.263	sextupole	
482.586	dipole	14.3	906.085	monopole	4.9
483.988	monopole	21.4	947.114	dipole	3.5
491.057	quadrupole		953.994	octupole	
525.013	quadrupole		973.310	octupole	
577.846	dipole	14.8	979.222	sextupole	
578.212	quadrupole		985.184	quadrupole	
582.244	monopole	15.8	1004.859	octupole	
647.978	quadrupole		1011.532	monopole	6.5
673.006	dipole	17.1	1100.111	monopole	23.4
687.000	monopole	9.8	1101.774	octupole	
724.170	sextupole		1137.525	quadrupole	
727.650	quadrupole		1142.655	sextupole	
748.816	sextupole		1149.096	monopole	11.6
760.778	dipole	16.8	1162.453	quadrupole	

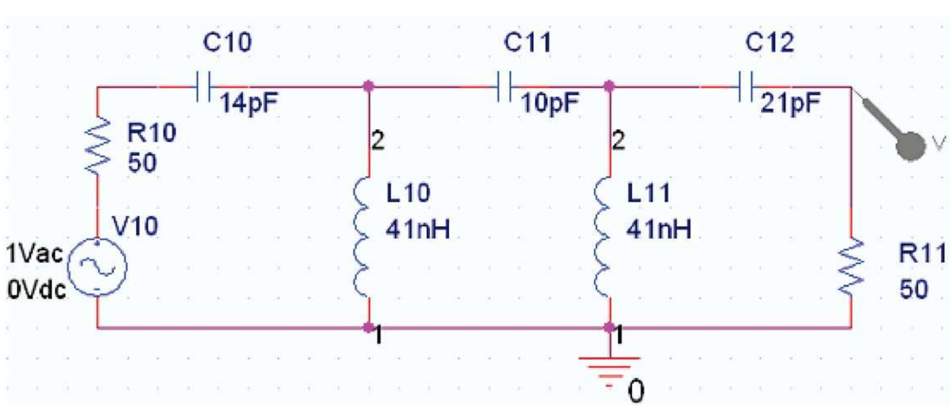

Figure 2: The circuit schematic of the high pass filter for the 56 MHz cavity HOM damper.

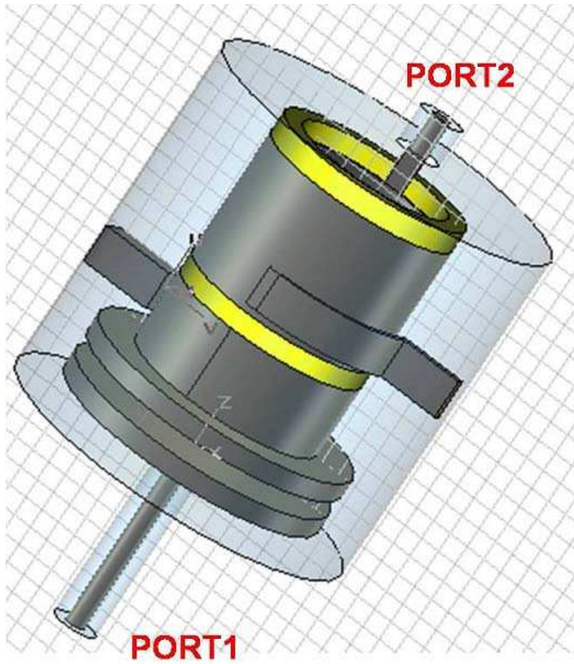

Figure 3: The HOM filter drawing of the MWS simulation

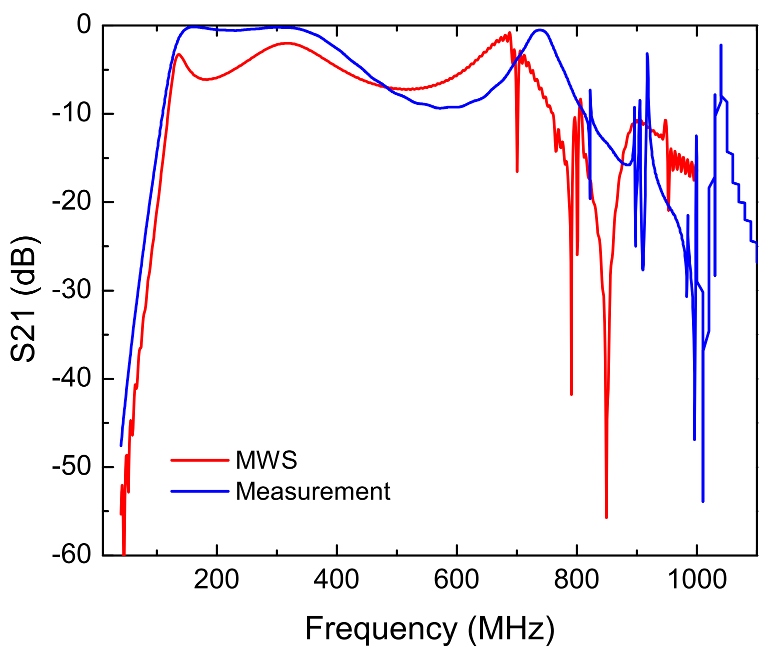

Figure 4: Comparison between the simulation and the measurement

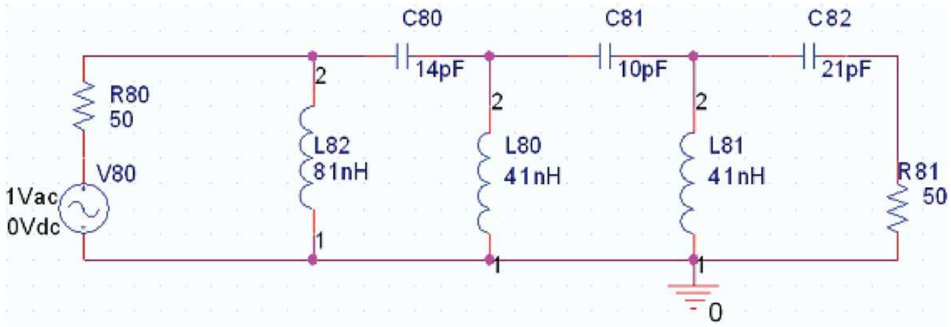

Figure 5: A modified inductor first circuit

of the HOM filter circuit, which is a real physical geometry of the filter. The first capacitor consists of two disks with radius of 7 cm seperated approximately by 1 cm. A separation distance of 1 cm between the two capacitor plates gives a capacitance of 14 pF, which can be adjustable by changing the gap distance of the plates. The nominal capacitance of 21 pF can be achieved when the separation distance if 0.7 cm. As shown in Fig. 2, the Pspice simulation used a value of 14 pF of the first capacitor. Following capacitors are a coaxial geometry whose gap is filled with Rexolite. The inductors were realized by having a long thin slab geometry. Fig. 4 is a plot of the S_{21} measurement. The measured S_{21} is compared to the simulation result. As shown in Fig. 4, the measurement agrees well with the simulation. A slightly modified circuit which has an inductor as a first component as shown in Fig. 5 has a big advantage. If the inductor comes first, the inductor slab would serve as a cooling path for the HOM damper. A quick modification was done by adding an additional slab structure in front of the first disk capacitor. Fig. 6 is the result of the measured S_{21}. Up to 700 MHz, the filter works properly and gives around -54 dB at the fundamental frequency of 56 MHz. However, as the frequency becomes higher, there exists oscillations and degraded performance in amplitudes. By the nature, designing a broad high pass filter that covers from 50 MHz to 1 GHz is quite difficult.

The first inductor of the modified high pass filter was measured with a network analyzer. The first inductor part is physically removed from the rest of the filter circuit components by the fact that the first inductor is connected to the disk capacitor which can be easily separable. And an extended line towards the HOM damper is connected to an N-type connector which allows to measure S_{11} parameter. By measuring the S_{11} over the frequency range between 9 kHz and 60 MHz, the impedance of the inductor was measured. At 1.6 MHz, the imaginary part of the S_{11} is 0.714 Ω,

$$\omega L = 0.714\ \Omega \tag{2}$$

at 1.6 MHz. Therefore, the first inductance of L is around 71 nH. Another frequency point at 16 MHz gives an impedance of 7 Ω from imaginary part of the S_{11}, which results in the consistent L value of 71 nH. The design inductor value of the first inductor is 81 nH as indicated in Fig. 5, which is very close to what was measured. Measuring the rest of

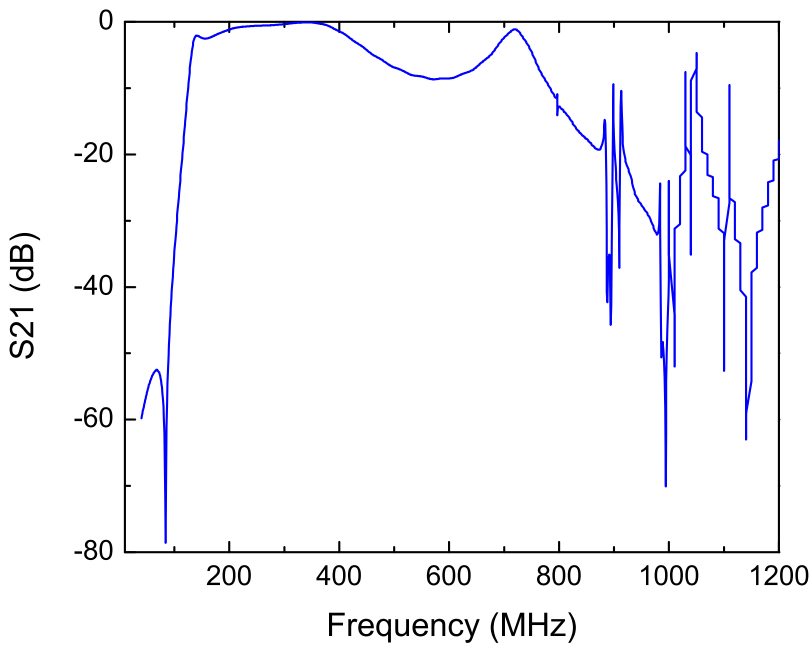

Figure 6: S_{21} measurement from a modified inductor first high pass circuit

circuit components was not as easy as measuring the first inductor since the rest of the circuit part is not separable.

4 The HOM damper measurement

Fig. 1 shows the Cu prototype of the 56 MHz cavity. On the left side of the cavity, an opening for the HOM damper which is 10 cm away from the cavity end is seen with 45° tilted angle with respect to the vertical coordinate of the cavity. To elminate all HOMs including opposite polarities, the second HOM damper will be also used and 90° apart from the first HOM damper on the same vertical plane (In Fig. 1, the second HOM damper opeing is located 90° apart from the first HOM damper which is hidden in the picture.). The prototype HOM damper for the 56 MHz copper prototype cavity is constructed as a 6 by 4 cm loop and it is connected to an inductor first high pass filter as discussed in Sec. 3 terminated with a 50 Ω load. The HOMs of the cavity are identified and the Q values are measured with one HOM damper inserted. The following measurements on the HOM damper were done.

- Measure Q values when the HOM damper is inserted
- Find the best axial position of the HOM damper

The frequencies and Q values are measured with the HOM damper including the HOM filter. Table 3 shows the result of the HOM measurements. As seen in Table 3, almost all HOMs are well damped except for the modes between 260 MHz and 314 MHz, unexpectedly. The reason that one sees a window of frequencies that are not damped at all is that the location of the HOM damper which is 10 cm away from the end of the cavity is not optimized. Due to the fact that the higher the frequency is, the more axial variations occurs, some modes are not coupled strongly inductively at the current location (10 cm away from the cavity end). The best position for the HOM damper would be the real end location from the cavity because the surface boundary condition at the end allows the strongest magnetic field at the real end of the cavity for all HOMs. Therefore a new HOM damper location was chosen to be the real end of the cavity (the center of the HOM damper loop is 2.5 cm away from the end of the cavity).

Table 4 summarizes HOM frequencies and Q values at the new location. The mode configuration of the HOMs was identified from the simulated HOM frequencies. Some question marks are seen in the mode configuration in Table 4 because of some uncertainties of identifying modes. However, in general, the HOMs are well damped at the new location from the measured loaded Qs, Q_L, with the HOM damper and the filter.

5 A new HOM damper

The 56 MHz cavity will have a few ports at the end of the cavity plane for allowing the chemical cleaning ports to be accessible. This open port may be also used for the

Table 3: Measured frequencies and Q_L of the 56 MHz prototype with the HOM loop and filter at a location of 10 cm away from the end of the cavity

Frequency (MHz)	Q_L	Frequency (MHz)	Q_L
56.215	8300	842.183	1710
168.039	3650	850.305	2220
260.154	16000	904.311	4120
277.603	12740	905.014	2130
314.190	10410	946.843	570
382.238	1190	954.445	6220
391.398	1980	971.330	1050
484.049	4380	976.610	790
525.356	12750	986.919	3300
578.924	11010	1001.787	440
580.039	1290	1014.397	1910
586.366	310	1038.054	1120
647.813	13540	1048.22	800
673.504	190	1054.4	490
685.925	250	1058.4	1300
724.646	5370	1091.708	450
727.861	16730	1104.951	8060
749.182	1640	1140.736	7680
761.133	710	1161.18	560
791.133	710	1179.68	2860
791.046	340	1190.36	520
819.965	240	1222.8	1570

Table 4: Measured frequencies and Q_L of the 56 MHz prototype with the HOM loop and filter at a real end location

Frequency (MHz)	mode config.	Q_L	Frequency (MHz)	mode config.	Q_L
56.219	monopole	8160	595.440	dipole (?)	220
168.045	monopole	1600	649.609	quadrupole	840
260.161	dipole	4640	675.14215	dipole	380
277.922	monopole	1520	689.500	monopole	200
314.271	dipole	990	724.718	sextupole	5300
383.759	monopole	1000	749.808	sextupole	2550
391.982	dipole	1020	762.220	sextupole	620
484.561	dipole (?)	8570	789.032	monopole	1520
491.023	monopole (?)	10680	1101.461	?	6900
522.162	quadrupole	470	1108.572	monopole	3380
578.994	quadrupole (?)	14640			
582.933	monopole (?)	1130			

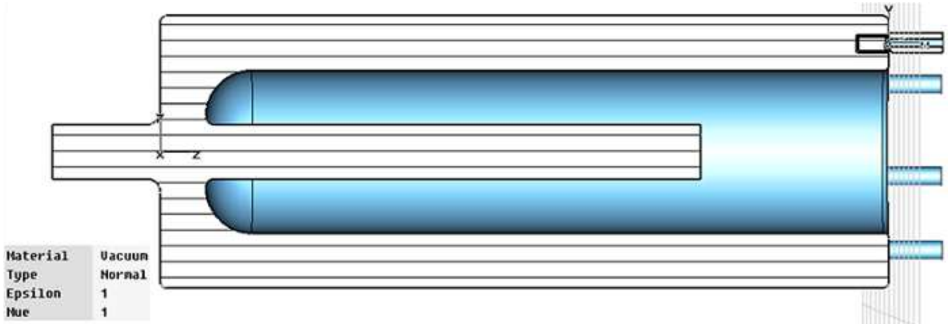

Figure 7: A MWS model of the new HOM damper using the chemical cleaning port

Table 5: MWS Simulated frequencies and Q_L of the 56 MHz production cavity with the HOM loop inserted through the chemical cleaning port

Frequency (MHz)	Q_L	Frequency (MHz)	Q_L
56.16	4070	679.8	2480
167.563	1880	788.8	3770
275.731	1800	898.2	49840
377.863	2060	1008	5710
474.9	2380	1112	4840
574.3	2950	1139	11160

ports of the HOM damper. According to Sec. 4, the location of the HOM damper has to be the real cavity end, which may be realizable through the existing chemical cleaning ports. This new accessibility of the HOM dampers is much more favorable in terms of engineering design work which should incorporates the cryogenic design. Therefore, the new location which allows the HOM damper to be inserted horizontally (previously, it is vertical insertion) through the chemical ports is studied via MWS simulation. The opening diameter of the chemical port is $1.5''$, which limits the allowable HOM damper size. From a MWS model drawing in Fig. 7, the new HOM damper is accessed at the end of the cavity horizontally via the chemical cleaning port. The new HOM damper size is constructed with a 6 by 2.88 cm square with a width of 2 cm. Using EigenSolver of the MWS simulation, the Q_L values of some key monopole HOMs were obtained. Table 5 is a summary of the simulation result of the new HOM damper. It is seen that almost all HOMs are well damped with the new HOM loop inserted through the chemical cleaning port. Based on the simulation result, the newly designed HOM damper will be tested in the prototype cavity.

6 Acknowledgement

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