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E. M. Choi

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Collider Accelerator Department
Brookhaven National Laboratory

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E. M. Choi, H. Hahn



**Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973**

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Higher order mode damper study of the 56 MHz SRF cavity

E. M. Choi and H. Hahn

August 13, 2008

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 measurement, 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 eliminate 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 opening 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.

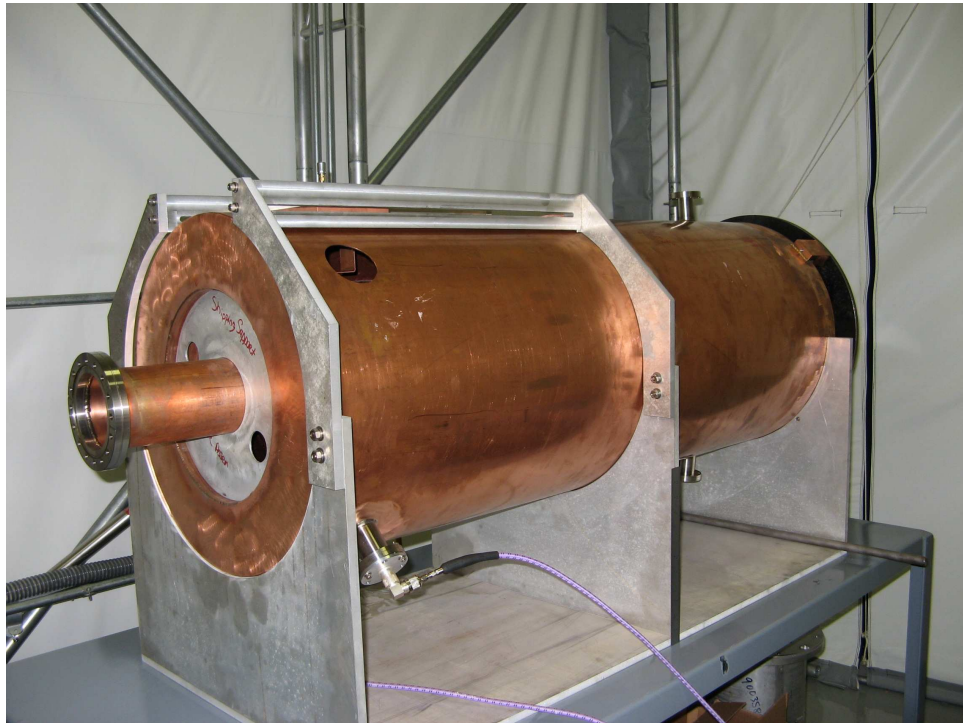


Figure 1: The picture of the 56 MHz prototype Cu cavity. The HOM damper port is seen on the left side of the cavity.

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,

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

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 | |

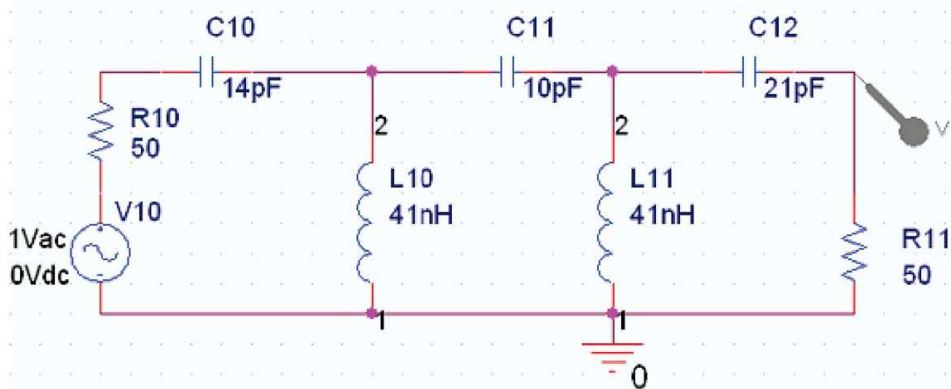


Figure 2: The circuit schematic of the high pass filter for the 56 MHz cavity HOM damper.

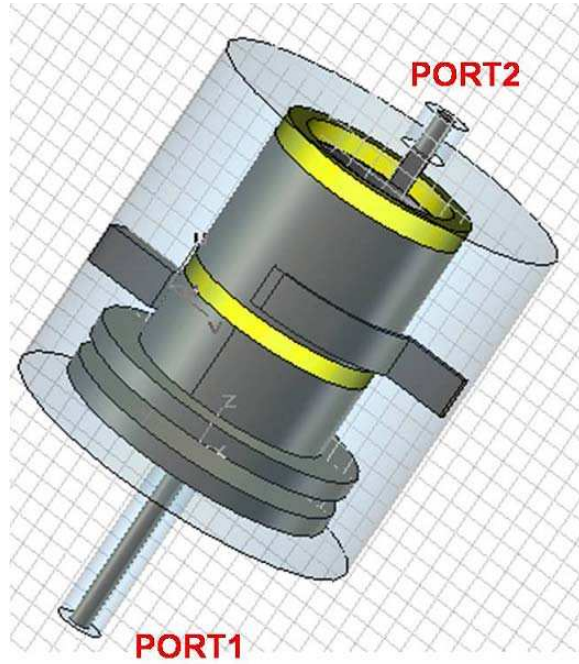


Figure 3: The HOM filter drawing of the MWS simulation

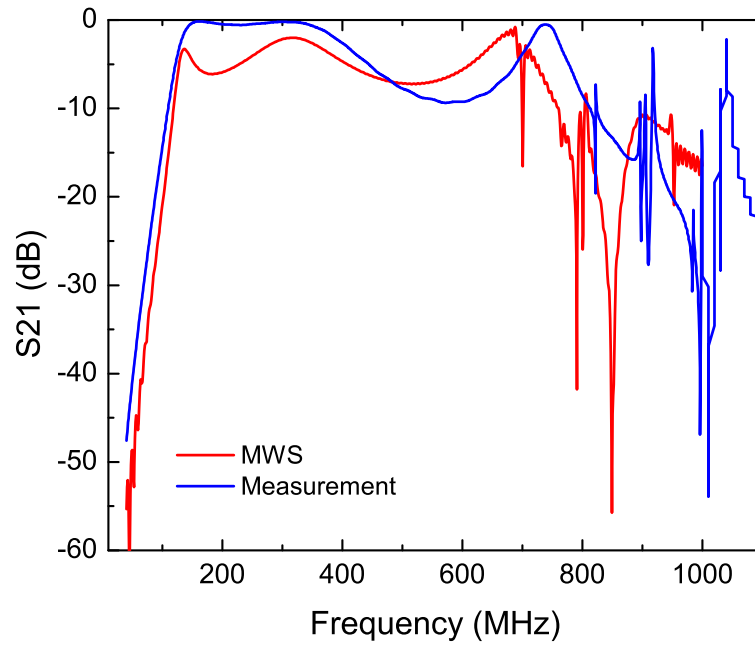


Figure 4: Comparison between the simulation and the measurement

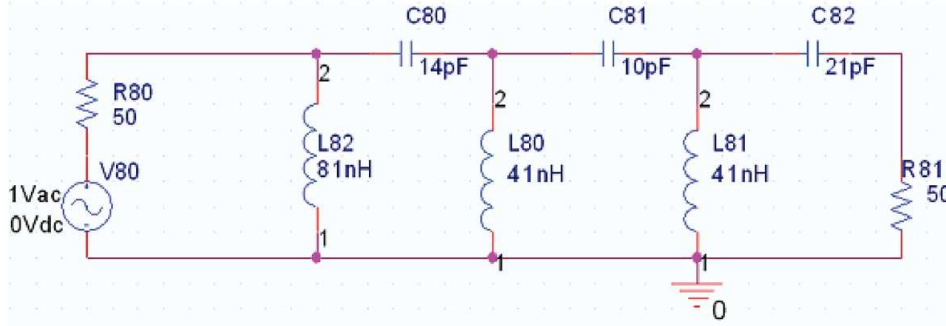


Figure 5: A modified inductor first circuit

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 separated 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 ,

$$\omega L = 0.714 \Omega \quad (2)$$

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

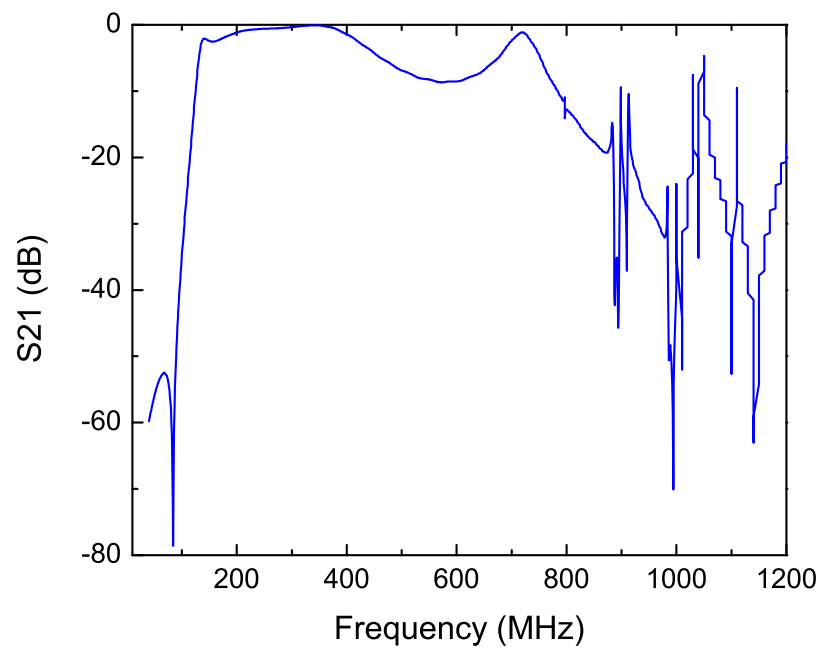


Figure 6: S_{21} measurement from a modified inductor first high pass circuit

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 eliminate 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 opening 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 | | | |

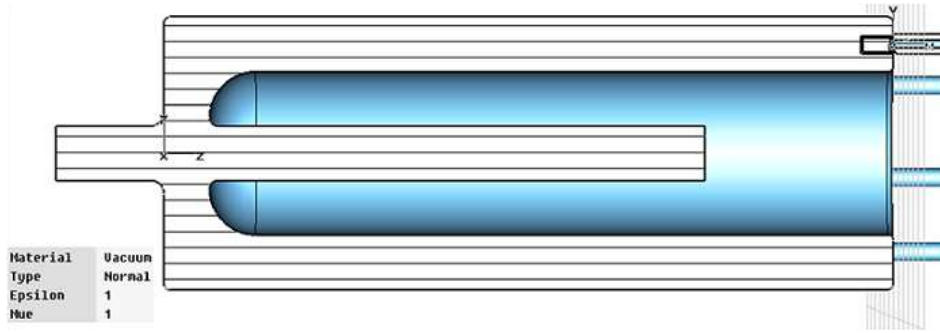


Figure 7: A MWS model of the new HOM damper using the chemical cleaning port

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 incorporate 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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