

## Design report for eRHIC splitter cavities

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# Design report for eRHIC Splitter Cavities.

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## Introduction

The designed operation parameters of hadron ring of eRHIC is shown in Figure 1.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
Bunch intensity [ $10^{10}$ ]	19.7	6.3	6.0	15.1	6.0	15.1	4.7	15.1	1.1	12.9
No. of bunches	330		1320		1320		1320		1320	
Beam current [A]	0.81	0.26	1.0	2.5	1.0	2.5	0.77	2.5	0.18	2.14
RMS norm. emit., h/v [ $\mu\text{m}$ ]	3.6/1.6	775/115	2.7/0.38	391/20.1	3.6/0.19	391/23.6	2.6/0.28	196/20	2.0/0.11	196/20
RMS emittance, h/v [nm]	12.4/5.5	22.0/3.3	9.2/1.3	20.0/1.0	33.8/1.8	20.0/1.2	24.7/2.6	20.0/2.0	45.9/2.6	20/2
$\beta^*$ , h/v [cm]	90/4.0	51/6.8	90/4.0	42/5.0	90/4.0	152/5.9	90/4.0	111/5.1	95/4.0	218/5
IP RMS beam size, h/v [ $\mu\text{m}$ ]	106/14.9		91/7.2		174/8.5		149/10.2		209/10.1	
$K_x$	7.1		12.7		20.8		14.7		20.8	
RMS $\Delta\theta$ , h/v [ $\mu\text{rad}$ ]	117/371	208/220	101/179	219/143	194/211	115/143	166/255	134/200	220/253	96/202
BB parameter, h/v [ $10^{-3}$ ]	4/1	100/95	13/7	64/99	10/9	66/53	13/9	100/67	15/13	24/11
Long. bunch area [eV·sec]	0.4		0.4		0.4		0.4		0.2	
RMS bunch length [cm]	5	1.7	5	1.9	7	1.9	7	2.3	7.5	2.3
RMS $\Delta p/p$ [ $10^{-4}$ ]	4.6	10	4.6	5.5	9.1	5.5	9.1	5.8	10.3	5.8
Max. space charge	0.004	negl.	0.004	negl.	0.028	negl.	0.019	negl.	0.048	negl.
Piwinski angle [rad]	5.2	1.8	6	7	4.4	6.1	5.2	1.4	4	1.2
Long. IBS time [h]	2		2.2		2.4		3.2		3.1	
Transv. IBS time [h]	2.6		2.1		2.0		2.0		2.0	
Hourglass factor $H$	0.89		0.87		0.82		0.81		0.80	
Luminosity [ $10^{33}\text{cm}^{-2}\text{sec}^{-1}$ ]	1.45		10.05		4.18		3.07		0.43	

Figure 1: eRHIC beam parameters for different center-of-mass energies ps, with strong hadron cooling. High divergence configuration.

In order to achieve the designed luminosity in eRHIC, the initial 330(+30 gap) beam pattern needs to be split twice into 660+60 and 1320+120 pattern. To realize this bunch splitting we plan to use the 56 MHz and 112 MHz cavities to perform this RF gymnastic together with the 28 MHz system that provides initial RF buckets.

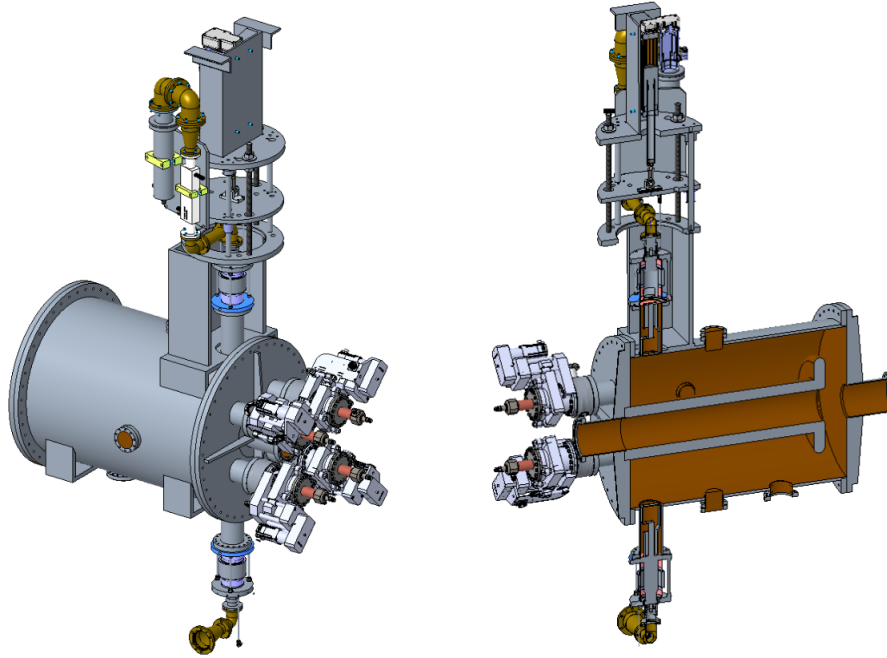


Figure 2: The conceptual design view of 56 MHz splitter cavity. For shortest bunch length we need to add HOM couplers to further reduce the impedance of higher order mode. 112 MHz cavity will be a direct scale down of the 56 MHz cavity.

### Requirements

The RF performance requirements and the real estate boundaries are shown in the table 1.

The section view of the RF volume of the cavity including FPC, universal damper, fundamental tuners and HOM tuners are shown in Figure 3

Table 1: RF Requirement and and Geometric limitation for 56 MHz and 112 MHz Cavity.

	56 MHz	112 MHz
Frequency (MHz)	56.3	112.6
Voltage (kV)	200	250
Tuning Range (kHz)	9.2	14.7
OD (mm)	< 750	< 750
Length (mm)	< 2000	< 2000
Peak HOM power (kW)	< 20	< 20

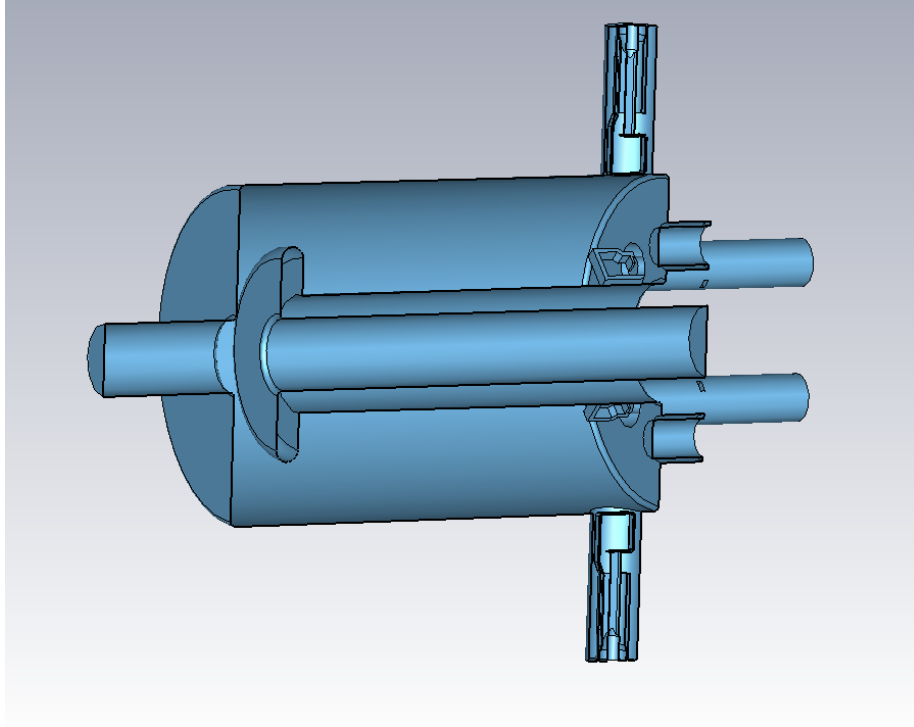


Figure 3: The section view of 56 MHz / 112 MHz cavity including FPC, HOM and fundamental Damper, fundamental tuners.

## Cavity Design

The relatively low frequencies of the cavities call for a quarter wave resonator (QWR) shape in order to keep the diameter of the cavities under requirement. Although the QWR cavity has lower R/Q ( $\simeq 100 \Omega$ ) compares to cavities morphed from pillbox shape ( $> 200 \Omega$ ), we can bear with the extra power requirement because of the relatively low voltage of the cavity. In order to keep the cavity length below budget, we adopted the capacitor disk design from the 100 MHz cavity at MAX IV storage ring [1]. At the tip of the nose cone, there is a capacitor disk that provide extra capacitance to compensate the inductance shortage due to the decreased length of the cavity. The position of the fundamental power coupler was chosen to cause the least perturbation to the frequency of the cavity, since we might need to move it during the operation. The HOM power estimation under worst-case scenario, namely all HOM peaks beat with the closest peak in beam spectrum within  $\pm 14$  MHz range, shows significant HOM power from the first HOM due to the high current component at that frequency. Therefore, we will need to detune the first HOM in both cavities. The design parameters of 56 MHz and 112 MHz cavities are shown in the table 2.

Table 2: Design parameters of 56 MHz and 112 MHz cavity

	56 MHz Cavity	112 MHz Cavity
Diameter (mm)	700	350
Length (mm)	1400	700
Gap (mm)	102.72	51.36
Beampipe radius (mm)	74.4	37.2
Thickness of nose cone (mm)	48.81	24.41
Radius of capacitor disk (mm)	221.55	110.78
Thickness of capacitor disk (mm)	50	25
Radius of corner blending (mm)	10	5
Frequency (MHz)	56.301	112.602
R/Q (Acc. Def)	130.7	130.7
Eacc (MV/m)	2.0 @ 200 kV	4.9 @ 250 kV
E <sub>max</sub> (MV/m)	3.44 @ 200 kV	11 @ 250 kV
$Q_0$	$1.8 \times 10^4$	$1.3 \times 10^4$
$R_{sh}(\Omega)$	$2.34 \times 10^6$	$1.7 \times 10^6$
RF power loss (kW)	17.1 @ 200 kV	37.0 @ 250 kV

## FPC Design

The FPC design was adopted from the fundamental damper for current BNL 56 MHz SRF cavity [2]. The copper loop is cooled by water running through the center conductor and we are confident that the FPC is able to handle the

40 kW with out issues based on previous experience. As for the window and feedthrough we can directly use the existing design for the 56 MHz SRF cavity with very little modification.

### HOM consideration

First we calculated the HOM spectrum of the bare cavity, based on the worst case scenario (try to align the beam spectrum with the impedance spectrum within  $\pm 2\%$  of the frequency of each impedance peaks) estimation we calculated the HOM power for different running cases.

The bare cavity impedance spectrum, beam spectrum and HOM power spectrum for each different running scenario are shown in Figure 4. The transverse impedance was calculated with the following equations:

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

$$R_T = \left(\frac{R}{Q}\right)_T Q_L \left(\frac{dx \pi f}{c}\right)^2$$

And the dx, dy are both selected to be 5 mm.

The transverse impedance of the bare cavity and the HOM power from dipole modes are shown in Figure 5 and 6. We assumed the offset of beam center to be 5 mm.

For the bare cavity only 2% detuning can generate unbearable amount of HOM power. We need to design a HOM damping system. The current HOM coupler design is shown in figure 7. It is basically a loop type coupler with one end shorted to the coupler port wall and the other end connected to a high pass filter.

We installed four of this couplers at the back wall of the cavity in order to simulate the coupling strength and see if this setup will give us low enough impedance or not. The simulation results are shown in Figure 6, 7 and 6

There are still two HOM, 343 MHz and 1.21 GHz has relatively high impedance. Then we tried with the loop coupler located near the front of the cavity as shown in Figure 8. However the one loop coupler at front is not enough. The new longitudinal impedance of the 343 MHz is still around  $1.2e4 \Omega/\text{cavity}$  and the one of 1.2 GHz is above  $3000 \Omega/\text{cavity}$ .

We also tried with the E probe type of coupling as shown in Figure 9. The coupling is even lower than the loop coupler. The impedance of the 343 MHz mode is above  $40000 \Omega/\text{cavity}$ .

For the HOM filter, different designs have been considered. RHIC 28 MHz HOM filter was first considered to be scaled to 56 MHz. However this filter has a certain power limitation that might not be suitable for this application. Double Quarter Wave (DQW) crab cavity HOM filter was also considered. This HOM filter is a chebyshev type filter that can give a sharp increase in S21 between 56 MHz and 80 MHz, with the cost of oscillation in S21 on the pass band at frequencies between 200 MHz and 2 GHz, which gives a relatively big rejection



(between -10 dB and -30 dB) in that frequency range. Butterworth type 3-pole filter, shown in Figure 13, is chosen due to its simple structure and reasonable attenuation ( $< -10$  dB except at around 1.7 GHz) on the pass band, with its S21 parameter shown in Figure 14.

To evaluate the possibility of using 2 HOM couplers instead of 4, wake field simulations were done using 1 nC 68 mm sigma Gaussian bunch with velocity at the speed of light. The bunch was set with 5 mm offset on both x and y (transverse) directions, with z direction the beam pipe (longitudinal) direction. 4 configurations were simulated, shown in Figure 15: bare cavity, cavity with 4 HOM filters, cavity with 2 HOM filters that are 180 degree with the beam pipe port, and cavity with 2 HOM filters that are 90 degree with the beam pipe port. The wake impedance in x, y and z directions for each configuration are shown in Figure 16. Simulation results indicate that 2 HOM filters with 90 degree is a better choice than that with 180 degree. There is one longitudinal mode at 300 MHz, and two transverse modes, at 1065 MHz and 1080 MHz, appeared in this wake field simulation, that does not match the eigen mode results showed previously. Further investigation is needed.

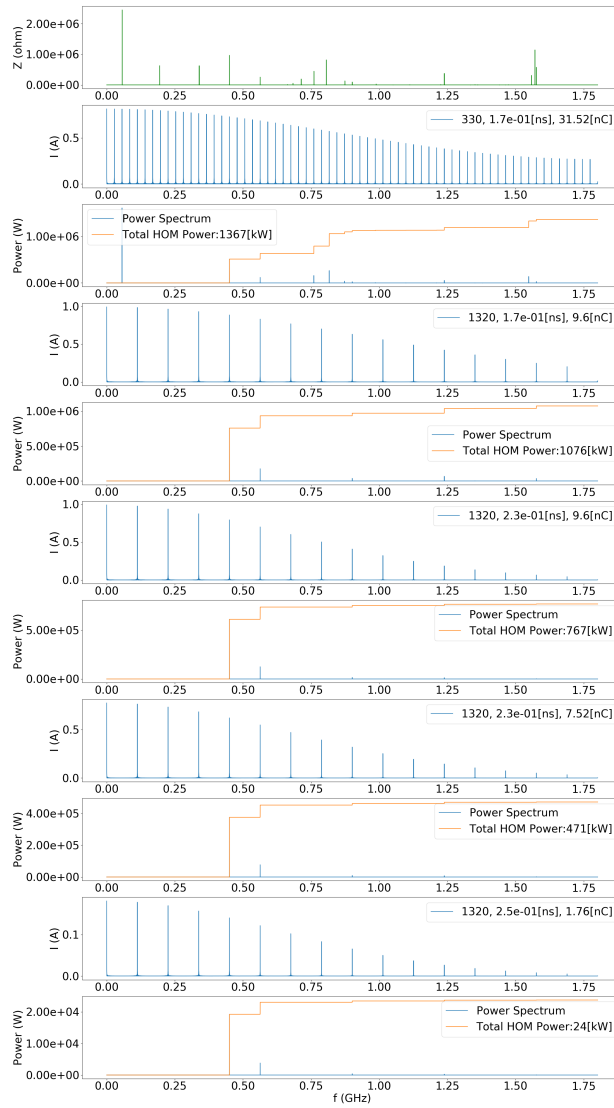


Figure 4: Top: 56 MHz bare cavity impedance spectrum. Blue comb shape plots are the beam spectrum of different running scenario. After each beam spectrum are the HOM power spectrum and integrated HOM power (orange line)

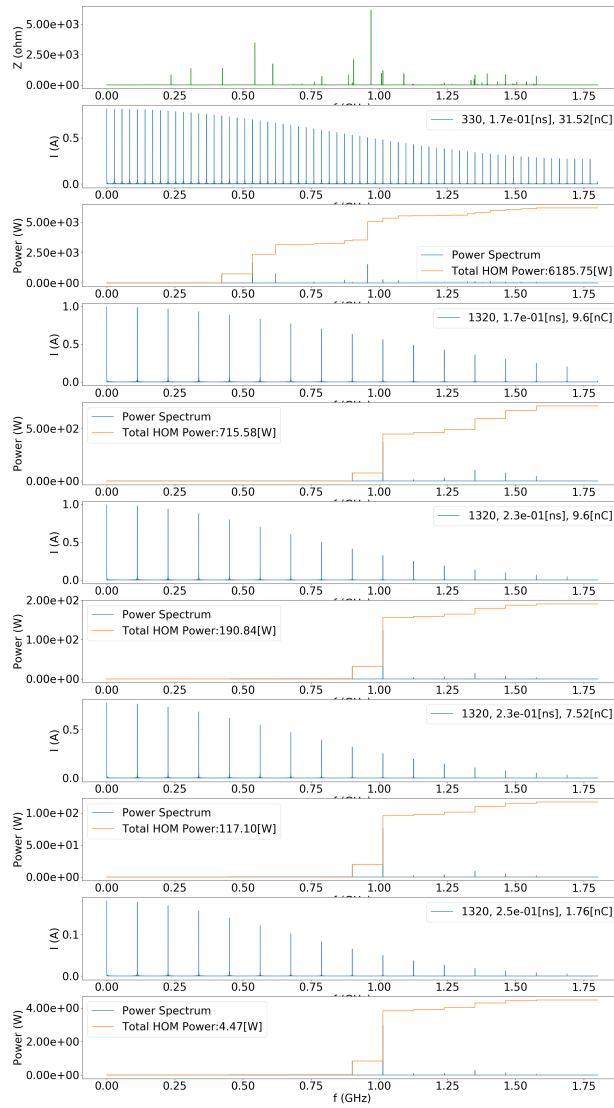


Figure 5: Transverse impedance (Green lines). Beam spectrum of different running scenario and the wake power of dipole modes.

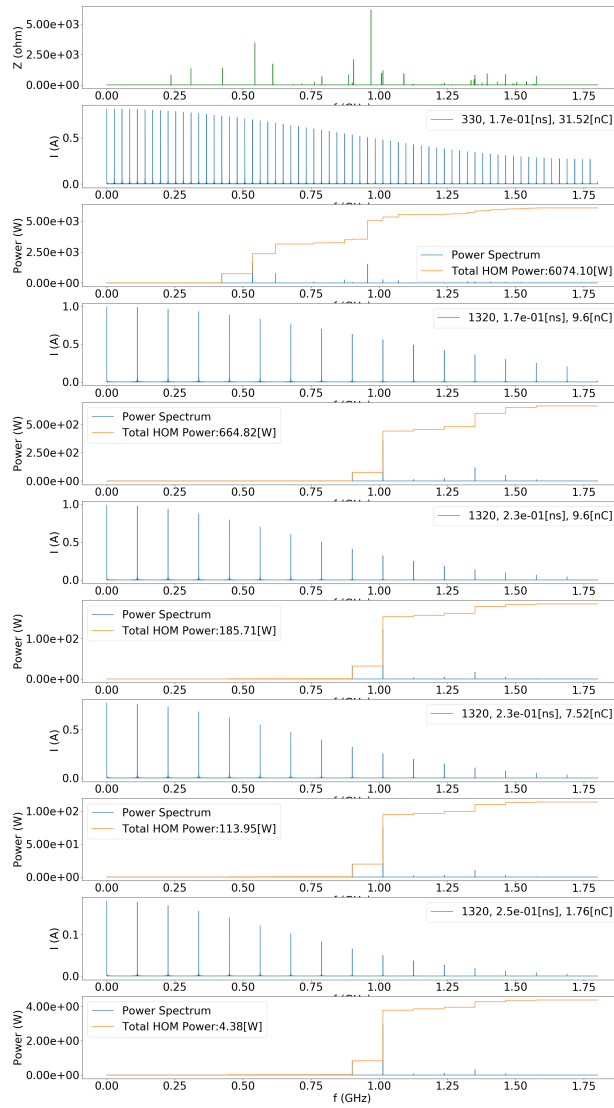


Figure 6: Transverse impedance (Green lines). Beam spectrum of different running scenario and the wake power of dipole modes.

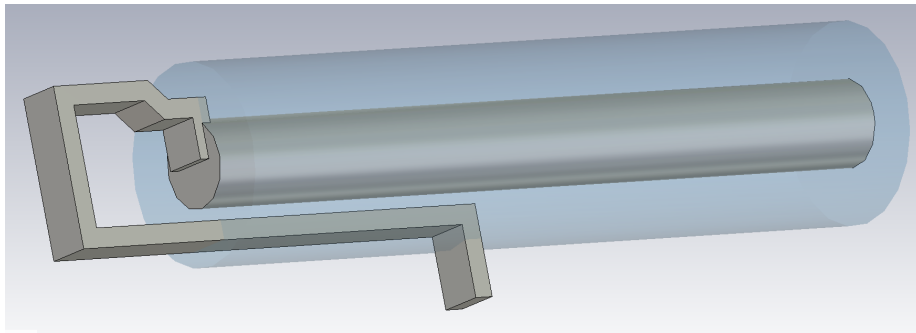


Figure 7: Prototype HOM coupler.

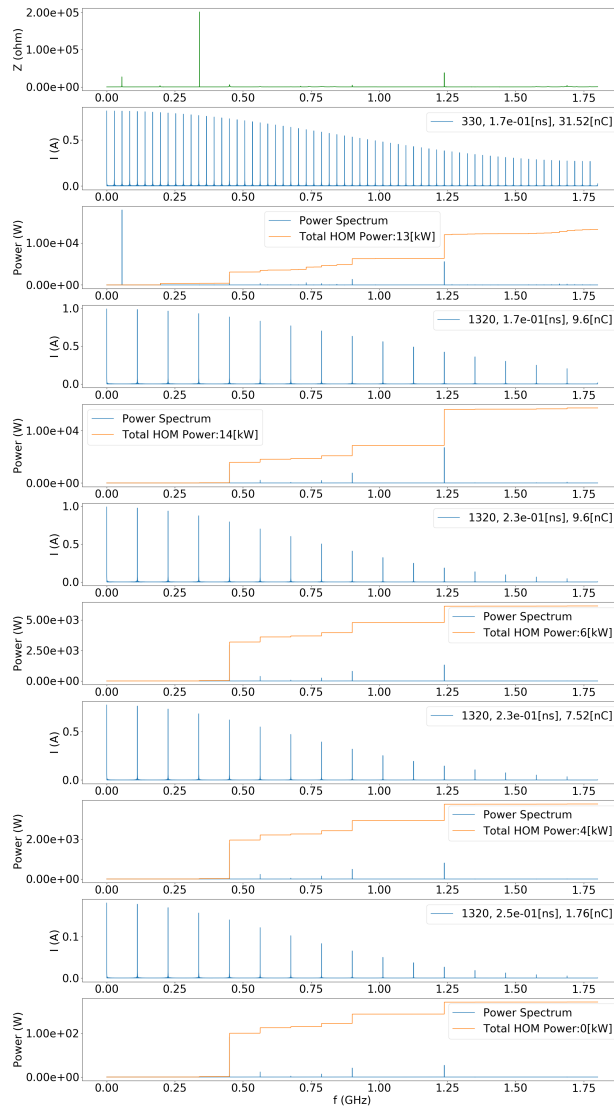


Figure 8: Longitudinal impedance and power spectrum of cavity with four HOM coupler installed.

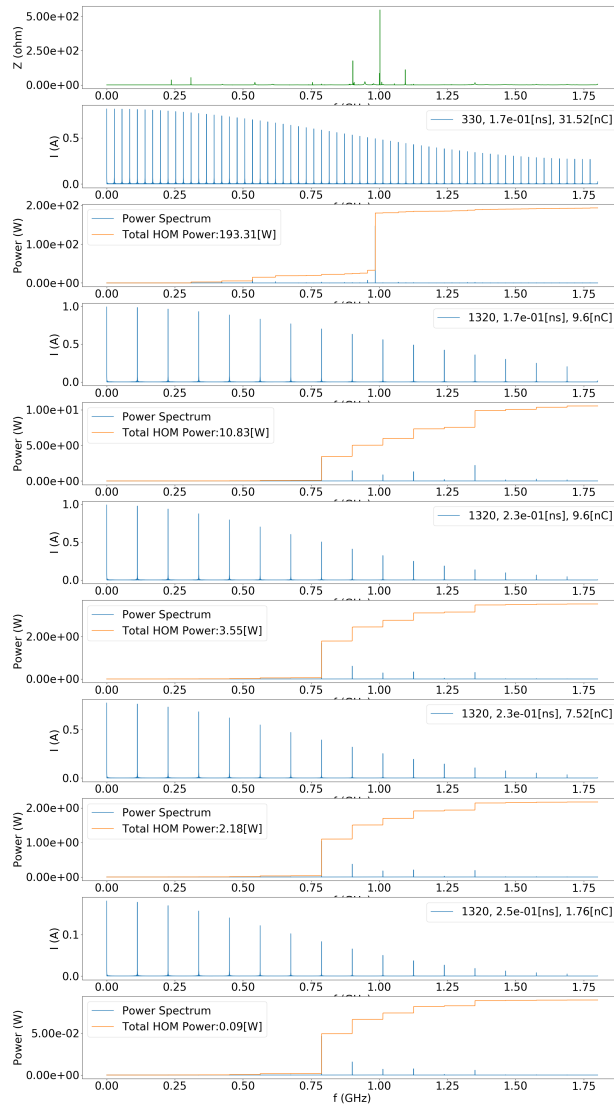


Figure 9: Transverse impedance in horizontal direction and power spectrum of cavity with four HOM coupler installed..

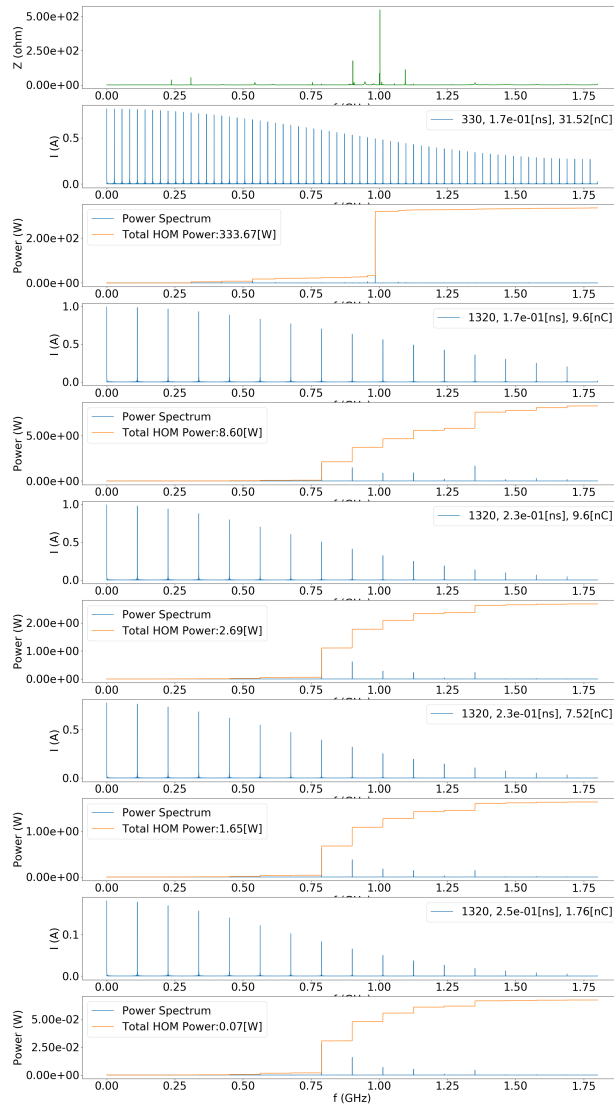


Figure 10: Transverse impedance in vertical direction and power spectrum of cavity with four HOM coupler installed..



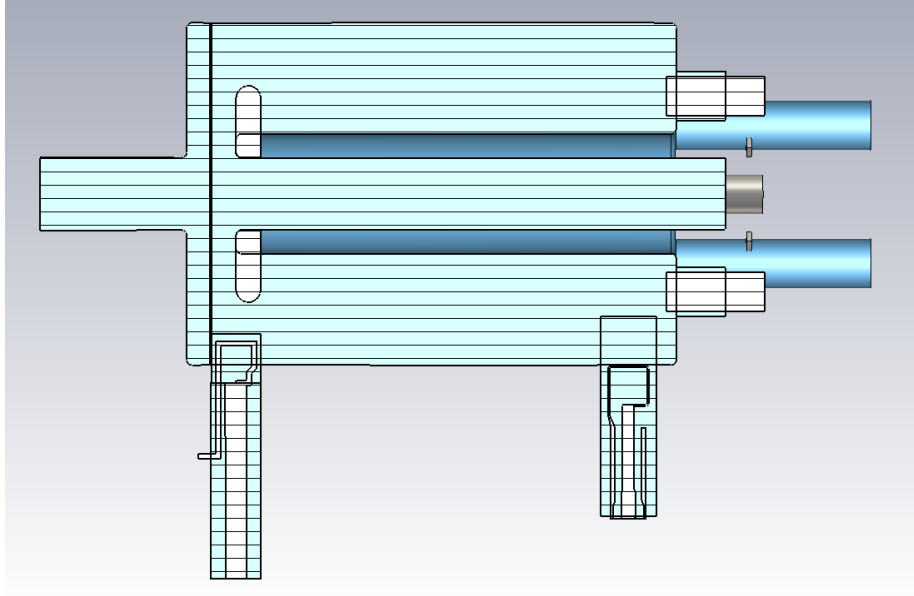


Figure 11: Added loop coupler at the front of the cavity intended to couple the 343 MHz and 1.2 GHz mode.

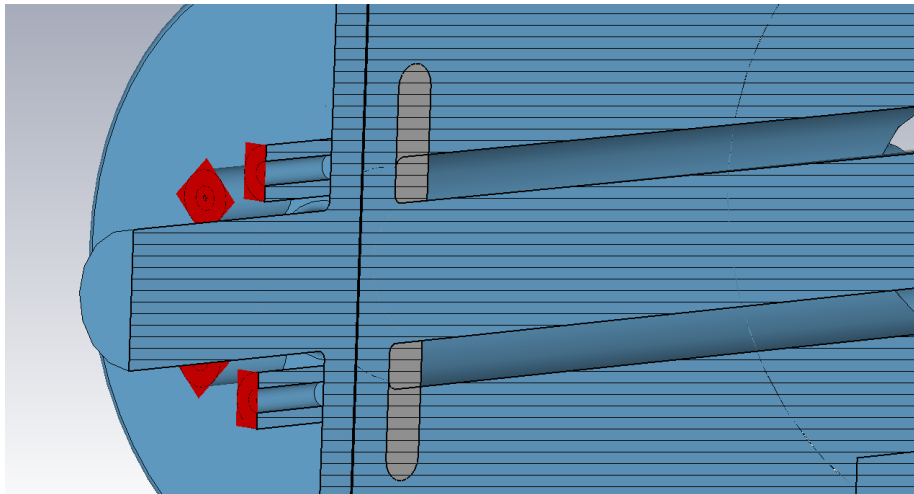


Figure 12: E probe type of couplers to couple the 343 MHz and 1.2 GHz mode. We tried with eight probes.

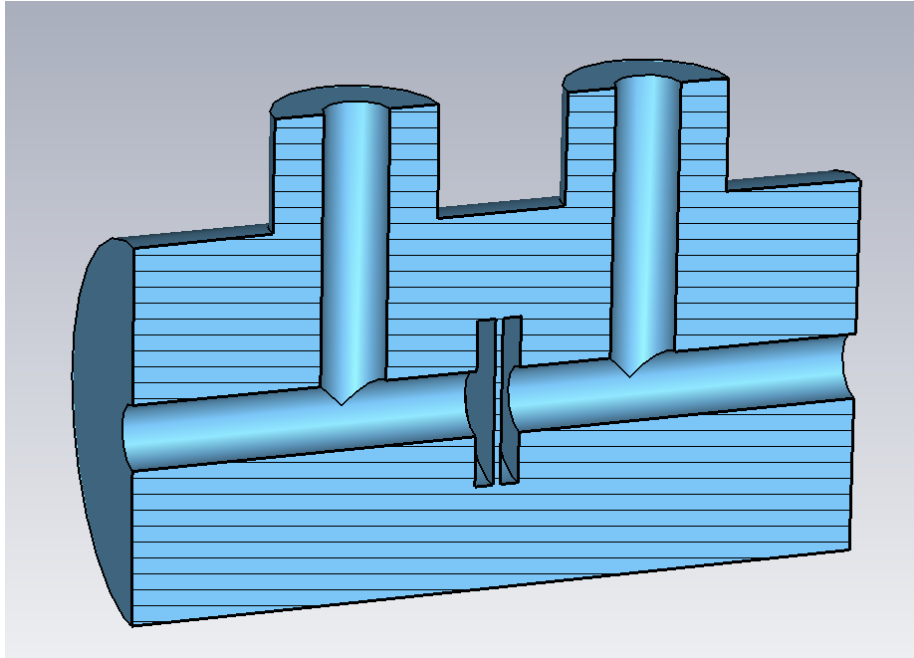


Figure 13: Butterworth type 3-pole HOM filter vacuum model, with input and output ports on the left and right..

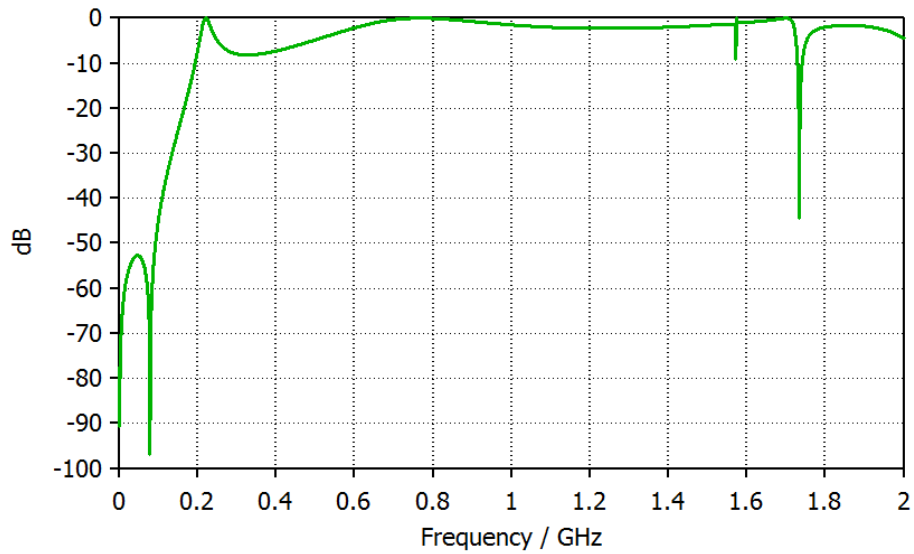


Figure 14: S21 of the Butterworth type 3-pole HOM filter..

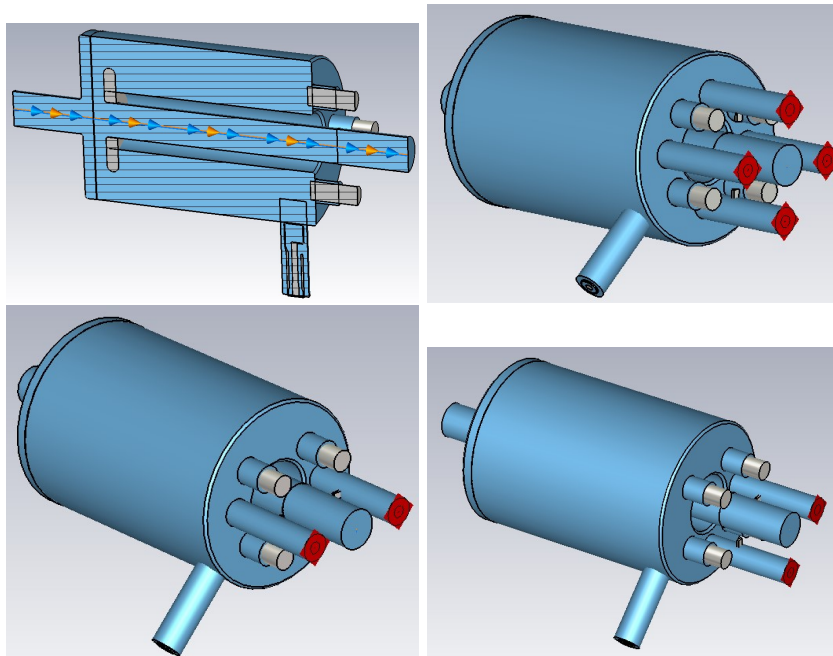
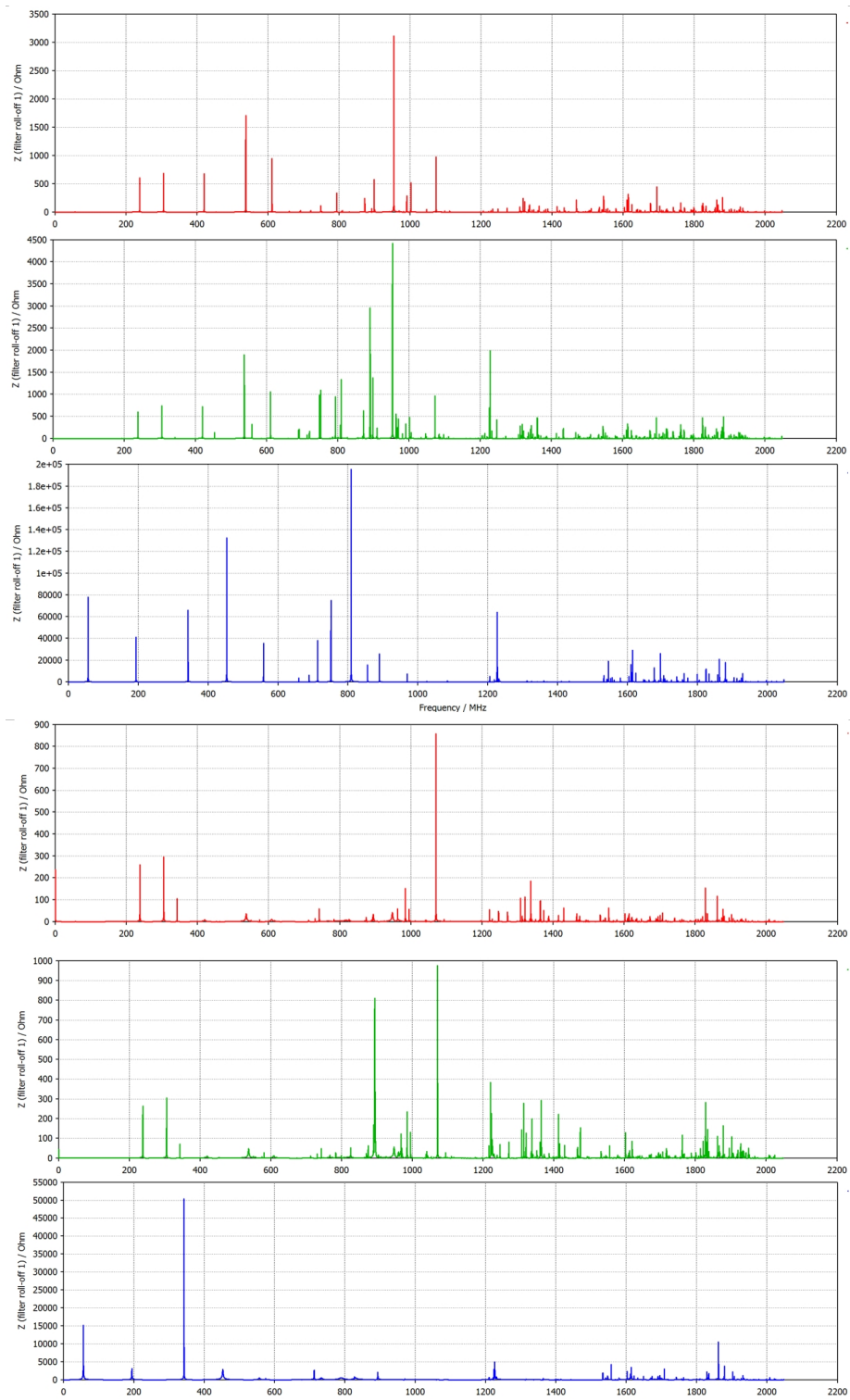


Figure 15: Configurations for wake field simulations: (a) top-left, bare cavity; (b) top-right, cavity with 4 HOM filters; (c) bottom-left, cavity with 2 HOM filters that are 180 degree with the beam pipe port; (d) bottom-right, cavity with 2 HOM filters that are 90 degree with the beam pipe port..



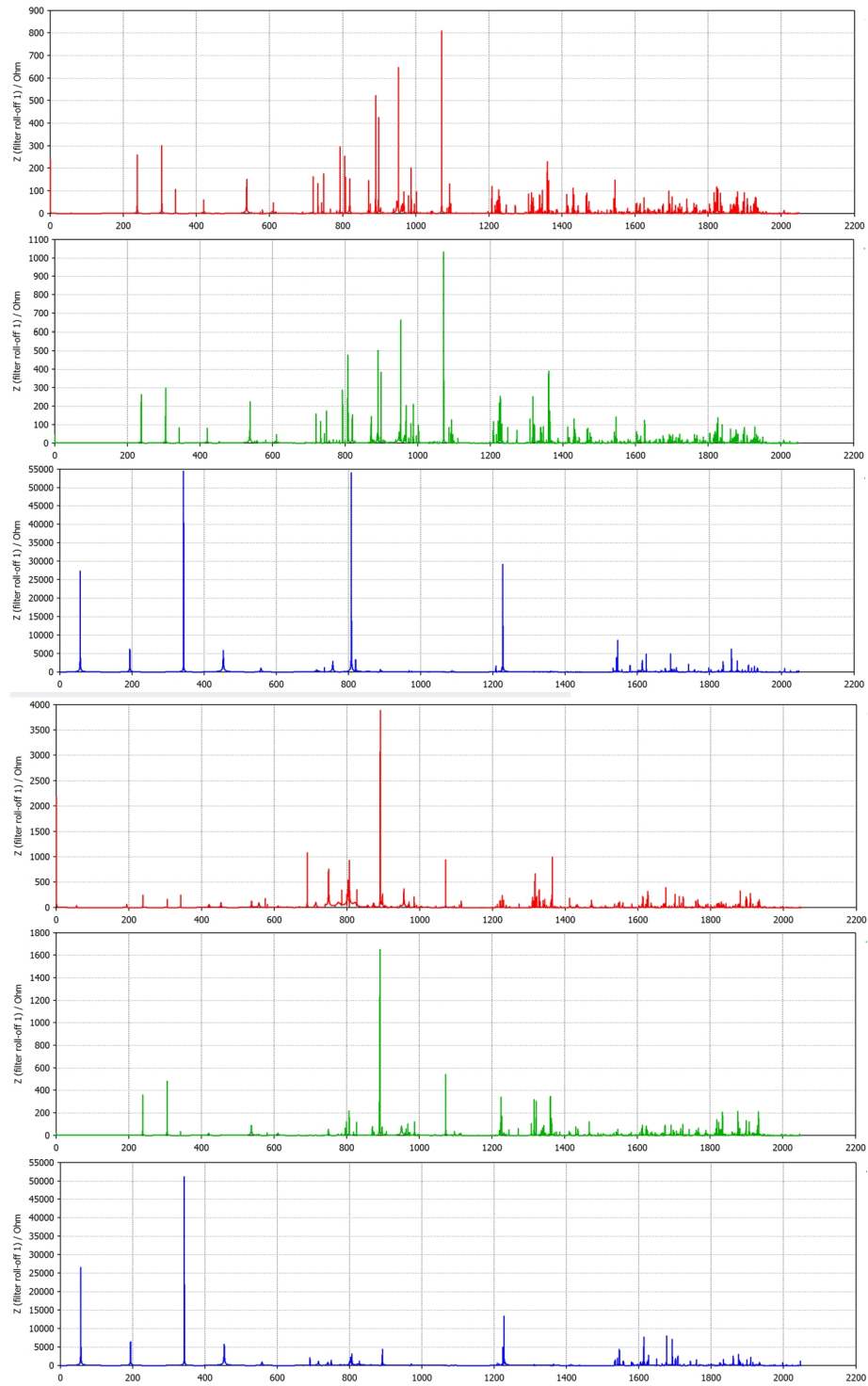


Figure 16: Wake impedance of x, y and z (from top to bottom for each case) directions, from top to bottom: (a) for bare cavity; (b) for cavity with 4 HOM filters; (c) for cavity with 2 HOM filters that are 180 degree with the beam pipe port; (d) for cavity with 2 HOM filters that are 90 degree with the beam pipe port..

## Tuner Design

We need the to tune the cavity fundamental mode frequency away from the repetition frequency of the bunch to compensate the active beam loading. Define the detuning as  $\delta = \frac{\omega - \omega_c}{\omega_c}$  and  $\tan\psi = -2Q_L\delta$ . Then we have:

$$\tan\psi = \frac{I_{RF}R_{sh}}{V_c(1 + \beta)} = \frac{2 \times 1.2 \times 10^6}{2 \times 10^5 \times 2} = 6 \quad (1)$$

Where  $I_0 = 2 A$  is the beam current at that frequency,  $R_{sh} = 1.2 \times 10^6 \Omega$  is the loaded shunt impedance of the fundamental mode of 56 MHz cavity,  $\beta$  is the coupling factor which is 1 since there is no real beam loading. Therefore the detuning of 56 MHz cavity in terms of frequency is:

$$\Delta f \approx 18.4 kHz$$

With the fundamental tuners shown in 3 the tuning range from 56 MHz is more than 77 KHz, which is more than enough to cover the detuning requirement from beam loading.

The 112 MHz cavity fundamental mode also needs to be detuned to compensate the beam loading. In this case, the calculation is exactly the same as the 56 MHz case. For the 112 MHz the shunt impedance is  $R_{sh_{112}} = \frac{R_{sh_{56}}}{\sqrt{2}}$ ,  $V_c = 250 kV$ .

Hence the detuning tangent of 112 MHz cavity is:

$$\tan\psi_{112} \approx 3.34$$

In terms of frequency the detuning is,

$$\Delta f_{112} \approx 29.2 kHz$$

In the original design we had a dedicated tuner for the first HOM, which is 193 MHz in 56 MHz cavity and 386 MHz in 112 MHz cavity. We need that tuner to tune the first most dangerous mode away from the current spectrum resonance line. For that to work as planned, we have to keep in mind that the fundamental tuner will change the frequency of the first HOM mode as well. For the 56 MHz cavity the ratio between the detuning of 56 MHz and 193 MHz is 4.26, therefore the frequency shift on 193 MHz caused by fundamental tuner is about 78.4 kHz. Similarly, the ration of frequency shifts in 112 MHz cavity is 4.46 and the detuning on 386 MHz mode is 130.2 kHz.

Therefore, we have to design an HOM tuner that is able to cover the detune on HOM caused by fundamental tuner and move the HOM frequency out of the danger zone of beam spectrum. For the 56 MHz cavity, the HOM tuner has to tune the 193 MHz mode by  $78.4 kHz + 31 kHz = 109.4 kHz$ . Meanwhile, we would like to have minimum effect on the fundamental mode so that it will not compete will the fundamental tuner. By carefully choose the location of the HOM tuner, we were able to achieve this requirement. The tuner is able to tune

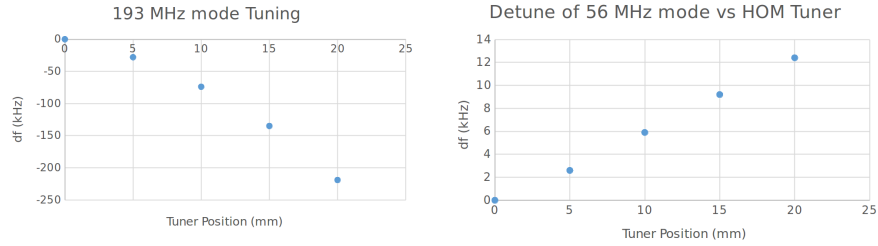


Figure 17: Left: Tuning range of 193 MHz mode. Right: Detune of 56 MHz mode caused by the HOM tuner.

the 193 MHz mode by  $\pm 110$  kHz while only change the fundamental mode by  $\pm 6$  kHz (see Figure 8)

For the 112 MHz cavity, the design is essentially the same. The frequency shift on the 386 MHz caused by the motion of fundamental tuner is 66 kHz. In total, we need to design a tuner that can tune the 386 MHz mode by 218 kHz so that in the worst case scenario we can move the impedance peak out of the  $\pm 88$  kHz zone of the 394 MHz beam spectrum peak.

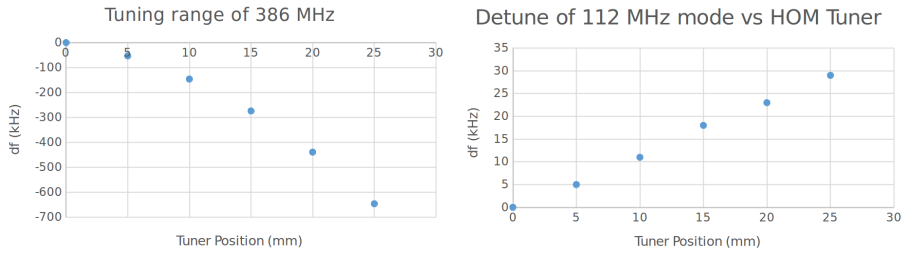


Figure 18: Left: Tuning range of 386 MHz mode. Right: Detune of 112 MHz mode caused by the HOM tuner.

As we can see, the first HOMs in both cavities have approximately 20 time higher sensitivity to the HOM tuners. Therefore we can safely use the HOM tuner to tune the dangerous mode away from the beam spectrum and use the fundamental tuner to fine tune the fundamental mode frequency to required value.

### Summary

We have worked on the design of the splitter cavities and came up with the disk capacitor type of QWR cavity. We did the HOM analysis and found that the bare cavity has too high impedance across the board and definitely need

dedicated HOM couplers/filters to handle the higher order modes. Then we designed the loop type of HOM couplers and simulated the efficiency of couplers in terms of the reduction of impedance of the dangerous modes. There are still two dangerous HOM modes we can not couple effectively enough with current coupler position. Further work is needed to address the issue of these two modes with either extra couplers at different position or change the design of the cavity shape so to eliminate these two modes, at one of them, completely.



# Bibliography

- [1] THE 100 MHZ RF SYSTEM FOR THE MAX IV STORAGE RINGS, . Andersson, E. Elaffi, M. Eriksson, D. Kumbaro, P. Lilja, L. Malmgren, R. Nilsson, H. Svensson, P. F. Tavares, Proceedings of IPAC2011, San Sebastian, Spain.
- [2] Fundamental Damper Power Calculation of the 56MHz SRF Cavity for RHIC \* Q. Wu, S. Bellavia, I. Ben-Zvi, M. Grau, G. Miglionico, C. Pai, Proceedings of PAC2011, New York, USA.