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Abstract

We present results of Higher Order Modes (HOMs) measurements in the RHIC accelerating (28 MHz system) and storage (197 MHz system) cavities. The power of the excited HOMs deposited into the HOM damper is measured and compared with an analytical calculation of the HOMs power. The quality factors (Q) are also measured and compared to previous measurements.

1 Introduction

The Relativistic Heavy Ion Collider (RHIC) consists of two counter rotating beams which collide at two different experiments (PHENIX at IP8 and STAR at IP6). The particles that are accelerated range from protons to gold ions and each accelerator ring has the capability to accelerate a different specie. Table 1 summarizes the main machine parameters. The RF system on both rings has to be able to capture, accelerate and store up to 120 bunches with an average total bunch intensity of 1.0×10^9 particles/bunch for gold ions and 2×10^{11} for protons. In the case of heavy ions the RF system must capture the particles at injection, accelerate them through transition and transfer the bunches from the 28 MHz system to the 197 MHz system. The 28 MHz accelerating cavities operate with 300 kV before transition and 150 kV throughout the rest of the energy ramp for ions and the 197 MHz system operates with 4 MV total gap voltage. In the case of protons, since the particles are injected above transition, only acceleration and storage is needed and the 28 MHz RF cavity is used with a voltage of 300 kV while the 197 MHz system uses a much smaller voltage of 50 kV only to increase the synchrotron frequecy spread and improve Landau damping. The harmonic numbers of the 28 MHz system and the

Table 1: Machine parameters.

Parameter	Value	
	gold ions	protons
Energy	100 GeV/n	
Circumference	3833.852 m	
Revolution Frequency	78.2 kHz	
Beam Frequency (120 bunches)	9.831 MHz	
rms bunch length (σ_t)	5 ns	
Gamma Transition (γ_{tr})	22.8	25
28 MHz System Voltage	300 - 150 kV	300 kV
197 MHz System Voltage	4 MV	50 kV

197 MHz system are 360 and 2520 for the accelerating and the storage part, respectively. Both cavities have a HOM dampers and the 197 MHz also have a damper for the fundamental mode since it is not active during the energy ramp for ions and protons. This report summarizes the recent measurements on the HOM power and Q factors of each HOM for the 28 MHz cavities and frequencies in the 197 MHz cavities and the results are compared with previously measured and simulated values [1, 2]. The measured power value is compared to an analytical calculation.

2 Experimental Setup

The measurement was performed during the 2008 proton run with two different energies and intensities:

- at injection ($\gamma = 25.4$), a single bunch with $N_b = 1.3 - 1.5 \times 10^{11}$ particles and
- at store ($\gamma = 106.8$), 109 bunches with $N_b = 1.2 - 1.6 \times 10^{11}$ particles each.

In order to measure frequencies and power of the HOMs inside the cavities we looked at the frequency spectrum in both, the 28 MHz cavity and 197 MHz cavity systems, using a Spectrum Analyzer (Agilent MXA N 9020A). The power was also measured independently by a power meter which is a termination of the HOM damper line.

For the 28 MHz system we measured the power and the quality factors of all modes. The power measured for the fundamental mode was attenuated by 60 dB since the HOM filter has a rejection band around its frequency. The HOM power obtained at either the power-meter or the spectrum analyzer was at least down by 21 dB due to losses in the cable (1 dB) and an attenuator (20 dB) used to protect the equipments. For the 197 MHz we measured only the frequencies present in the HOM damper spectrum.

3 Measurement of HOM frequencies in the 197 MHz System

The measured spectrum for one of the common 197 MHz cavities for the Yellow and Blue rings for the cases of a single bunch and also multibunch is shown in Fig. 1. We were able to identify most of the modes predicted by the URMELT simulation [1] of the 197 MHz cavity and a collection of the measured HOM loaded quality factor is shown in Table 2. The frequency results of the 197 MHz cavity are in a good agreement with the simulation results.

4 Measurement of the total HOM power, frequencies and Q factors in the 28 MHz cavity

The measured spectrum for two of the 28 MHz cavities for the Yellow and Blue rings are shown in Fig. 2 for the multibunch case. A closer look of the 28 MHz line is shown in

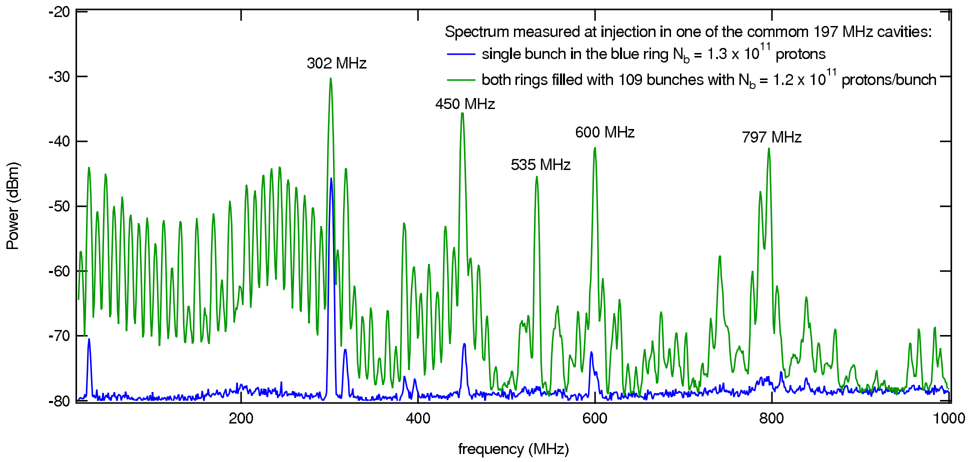

Figure 1: Measured spectrum at the HOM damper for the 197 MHz cavity.

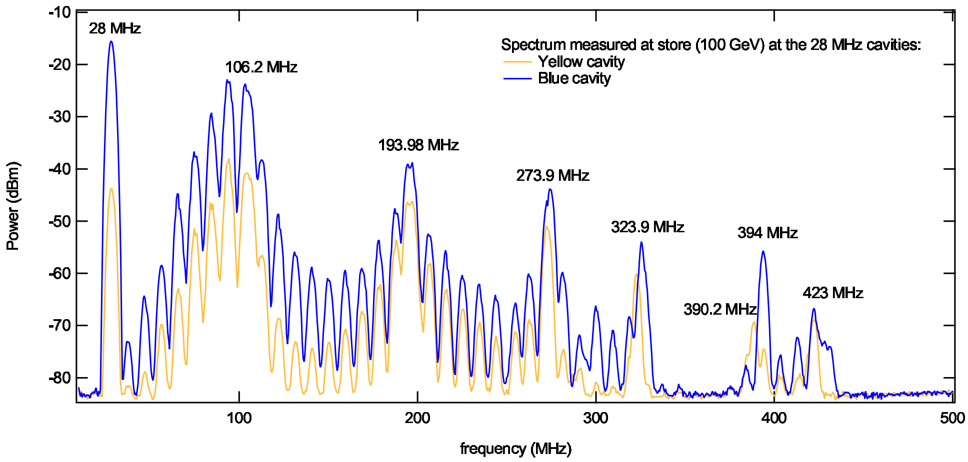

Figure 2: Measured spectrum at the HOM damper for the 28 MHz cavity.

Fig. 3. The fundamental frequency is 28.15 MHz and the sidebands are spaced by 78 kHz (beam revolution frequency). Beam revolution lines are much weaker than bunch lines, which are spaced by 9.383 MHz, as shown in Fig. 3. The power was measured by means of two different equipments, first we used a power-meter, which gives the integrated HOM power, then a spectrum analyzer, which gives an individual power content of each HOM. The total power in the 28 MHz cavities, measured using a power-meter, was -13 dBm for the blue cavity. Assuming that the cable loss is approximately 1 dB and that we were using a 20 dB attenuator attached just before the power-meter, the total power deposited into the HOM damper is 6.5 mW. The summed-up total power from the individual HOM's measured for each the spectrum line shown in Fig. 2 is around -15 dBm for the blue cavity.Both measurements give almost a consistent output power of around 6.5 mW. In the case of the Yellow cavity and extra attenuation of about 10 dB was used, that is why

Table 2: Summary of measured HOM frequencies for the 197 MHz and comparison with a previous measurement (196.1 MHz system) [1]

197 MHz	196.1 MHz	
f (MHz)	f (MHz)	Q_L
302	308.4	4400
452	445	1200
535	543	690
596	604.2	1500
797	844	1000

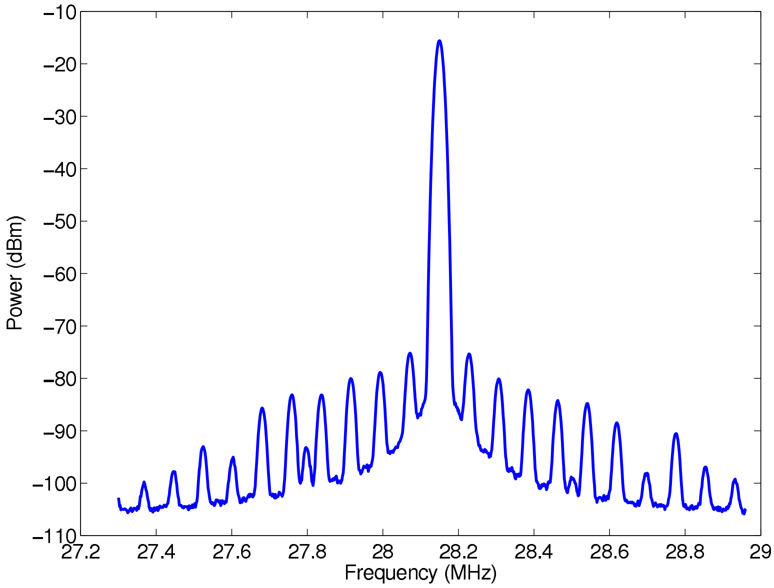

Figure 3: Blue ring spectrum near the fundamental mode of the 28 MHz cavity.

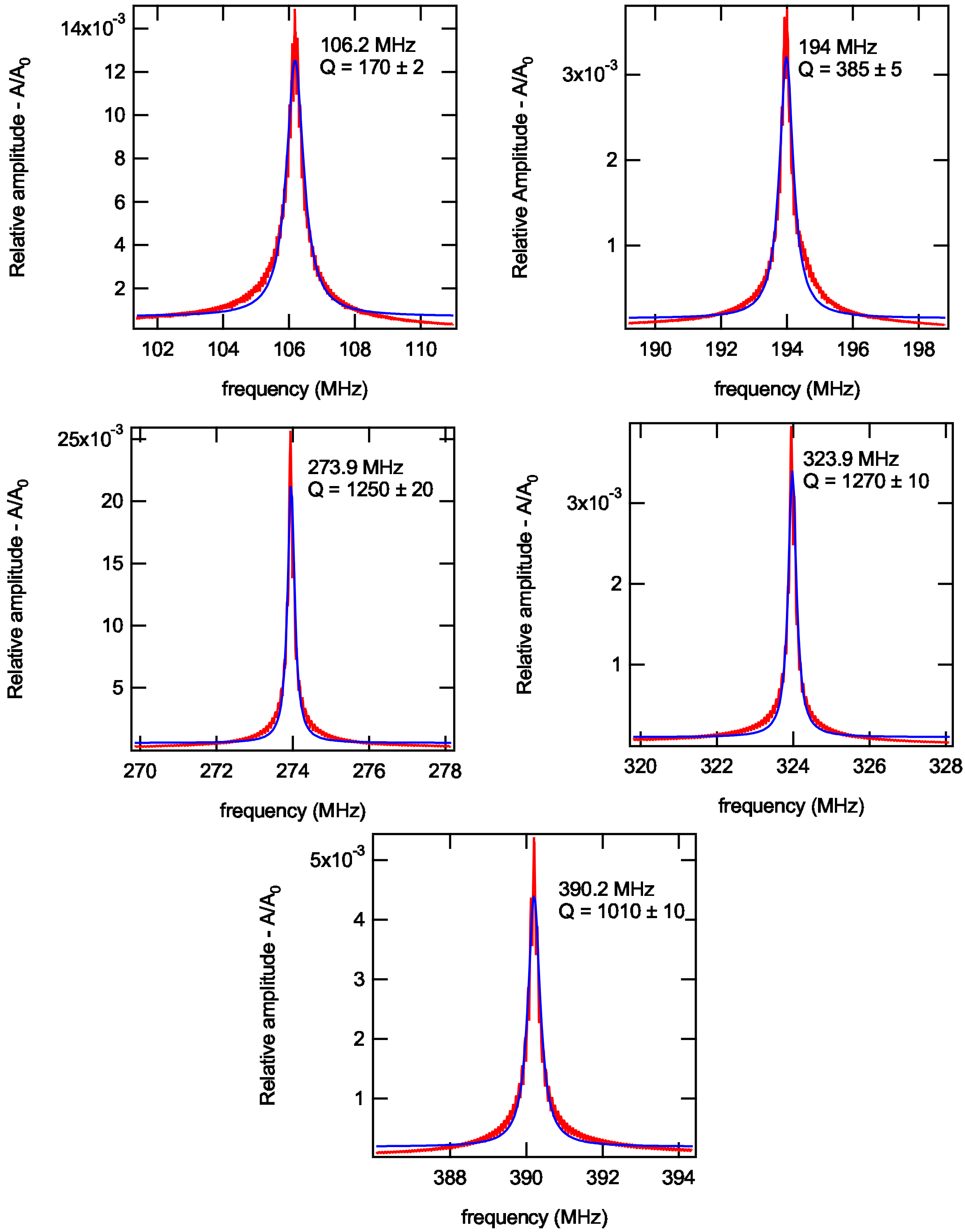

Figure 4: Measured loaded Q factor and center frequencies for the HOMs in the 28 MHz cavity. The blues line is the measured spectrum and the red line is the fitting.

Table 3: Summary of measured HOM frequencies for the 28 MHz and comparison with a previous measurement (26.1 MHz cavity) [2]

28 MHz		26.7 MHz	
f (MHz)	Q_L	f (MHz)	Q_L
106.2	170±2	98.8	190
193.98	385±5	216.3	460
273.9	1250±20	287.4	1500
323.9	1270±10	342.2	2100
390.2	1010±10	402.2	1100

the spectrum lines for the yellow case are always bellow the blue lines in Fig. 2

In order to get a cleaner spectrum we measured the HOM damper spectrum at injection energy with a single bunch in the machine with an intensity of $N_b = 1.5 \times 10^{11}$ protons. In order to measure the center frequencies and Q factors of the HOMs, we fitted this spectrum to the following Lorentzian formula

$$A(\omega) = A_0 \left[1 + Q_L^2 \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)^2 \right]^{-1} \tag{1}$$

where Q_L is the mode loaded quality factor and ω_0 the center frequency. The summary of the measured HOM frequencies and Q values is shown in Table 3 and are compared with a previously measured data. The HOM frequencies are identified to be very close to what had been measured and the Q vales are close to those reported on [2]. The measured and fitted data for each mode are in Fig. 4.

5 Analytic calculation of HOM power

In order to calculate the power in each HOM of the 28 MHz cavity first we have to take into account the frequency spectrum of the bunches at the moment of the measurement. For the proton run in 2008 the filling pattern used was: 109 bunches with a gap between buckets 38 and 41 and an abort gap from buckets 112 to 120. Also we have to consider that the intensity and bunch shape varies along the bunch train, as shown in Fig. 5 and 6. For simplicity we will consider that all the bunches have an average current of 1.6×10^{11} protons, with a rms bunch length of 5 ns with the exception of the Artus bunch that has one third of the intensity of the other bunches. Furthermore we will consider that all bunches can be approximated by a Gaussian shape, which turns out to be a good approximation as shown in Fig. 6.

In the time domain the beam current is given by:

$$I(t) = \sum_{k=-\infty}^{\infty} I_0(t - kT_0) = \sum_{k=-\infty}^{\infty} \sum_{h=1}^{N_1} \frac{q_h}{\sqrt{2\pi\sigma_t^2}} exp \left[-\frac{(t - kT_0 - hT_0/N_1)^2}{2\sigma_t^2} \right] \tag{2}$$

where q_h is the charge per bunch, T_0 is the revolution period and N_1 is the number of buckets which are 120 total in RHIC. The periodic current function can be expanded into

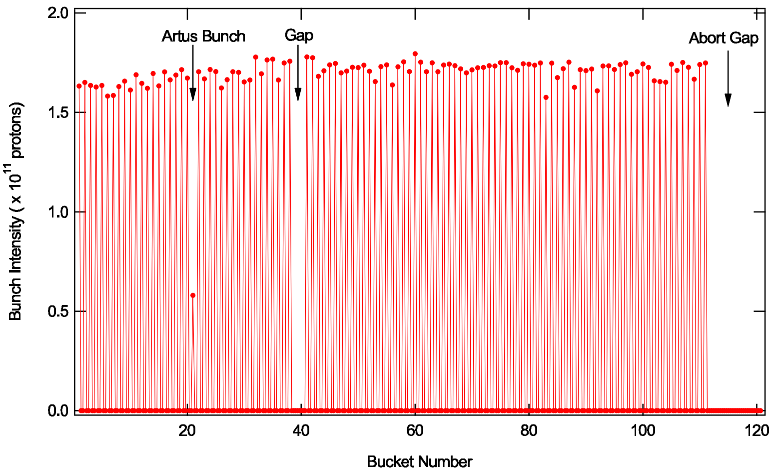

Figure 5: Filling pattern in the Blue ring during the measurement of the HOM power distribution.

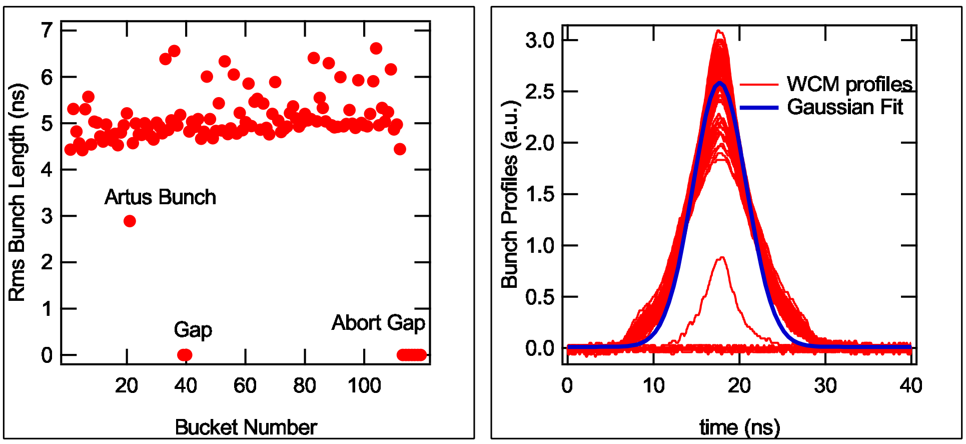

Figure 6: Filling pattern in the Blue ring during the measurement of the HOM power distribution.

Table 4: Summary of the measured 28 MHz cavity HOM frequencies with simulated R/Q [2] and the calculated beam frequencies at store. The dissipated power of each HOM is also calculated with two different assumptions: P(point charge) assumes trains of point charge bunches and P(Gaussian) assumes a train of Gaussian bunches. We considered 109 bunches with 1.2×10^{11} protons/bunch.

f (MHz)	f_{beam} (MHz)	R/Q (Ω)	P(Gaussian) (mW)	P (Measured) (mW)
28.149	28.149	67.6	3.35	4
106.193	103.215	2.8	0.36	0.4
193.923	197.046	0.12	0.0015	0.012
273.925	272.111	3.6	0.0062	0.004
323.93	319.027	9.4	0.0115	4×10^{-4}
390.187	384.709	2.8	0.003	2.5×10^{-5}
Total Power			3.7	4.4

a Fourier Series with the following spectrum components

$$I_n = \frac{1}{T_0}\int_0^{T_0} I_0(t)exp\left(j\frac{2\pi n}{T_0}t\right) \approx \sum_{h=1}^{N_1} \frac{q_h}{T_0} exp\left(j\frac{2\pi nh}{T_0}\right) exp\left[-\left(\frac{2\pi n}{T_0}\right)^2 \frac{\sigma_t^2}{2}\right] \quad (3)$$

The real part of the impedance of the kth HOM is characterized by the resonant frequency ω_k, the quality factor Q_k and the shunt impedance R_k and is given by

$$Real[Z(\omega)] = \frac{(R/Q)_k Q_k}{1 + Q_k^2\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)^2} \quad (4)$$

Then the beam power delivered by the nth beam harmonic in the kth cavity mode is

$$P_{n,k} = \frac{2(R/Q)_k Q_{Lk} I_n^2}{1 + Q_{Lk}^2\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)^2} \quad (5)$$

where Q_{Lk} is the loaded quality factor of the considered mode. The total power released by the beam due to a specific mode is the sum of the power released by each beam line

$$P_k = \sum_{n=0}^{\infty} \frac{2(R/Q)_k Q_{Lk} I_n^2}{1 + Q_{Lk}^2\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)^2} \quad (6)$$

Table 4 summarizes the HOM frequencies, their respective R/Q value which comes from a MAFIA simulation [2], the beam bunch frequency harmonics that are closer to the HOM frequencies and the calculated power dissipated in the HOM damper. The beam frequencies are calculated using the bunch frequency, which is 9.383 MHz, multiplied by integers and we considered a full machine (109 bunches) with and average intensity of 1.6×10^{11} protons/bunch (Fig. 5). The measured frequencies show that there is no significant overlap between the beam frequencies and the cavity mode frequencies. The individual power in each HOM is calculated using Eq. 6 and the 28 MHz mode is considered to be rejected by the HOM filter by -60 dB [1]. The summed-up HOM power is around 3.7 mW for the Gaussian bunch and the sum of the measured power in each HOM is 4.4 mW.

Comparing the measured HOM power of 6.5 mW with the calculated HOM power of 3.7 mW we see that the calculated HOM power in the HOM are about half of the total measured power, this difference could be explained by the power distributed in many bunches lines around each HOM line, as show in Fig. 3 which is around 2 mW if we consider the total power measured for each HOM (Table 4 - $6.5 - 4.4 = 2.1$ mW). The other 0.7 mW is due to a discrepancy between the calculated and the measured power for the fundamental mode. This is most likely due to the power rejection at the fundamental mode that was used based on the design value of the HOM damper [2]. In this case we considered that the fundamental had a 60 dB rejection from the HOM filter and a small difference (about 1 dB) in this value could account for the difference in the power calculated and measured.

6 Summary

We have measured the HOM power of the RHIC 28 MHz RF system and identified each HOM frequencies and respective Q_L factors. The total HOM power delivered to the HOM damper was measured to be around 6.5 mW. The values of the frequencies and Q factors for the 28 MHz and 197 MHz systems are comparable to the previously measured and simulated numbers reported in [1, 2] and show a very good agreement. The calculated HOM power is around 3.7 mW, which is smaller than the measured power of 6.5 mW. The discrepancy between the measurement and the calculation may be attributed to a slightly lower number in the rejection filter of the fundamental frequency than the original design value and the power dissipated in the bunch lines which is not taken into account in the calculation.

7 Acknowledgement

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References

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[2] S. Kwiatkowski et al., "HOM damper for RHIC 26.7 MHz accelerating system",RHIC/RF Technical Note No. 25, Jan. 1995.

[3] Padamsee book, p 338.