Calculations of HOMs and Coupled Bunch Instabilities due to the RHIC rf Cavities*

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Abstract

The cavities for the two RHIC rf systems have been defined, a 26.7 MHz cavity developed by the RHIC rf group and the well documented CERN SPS 200 MHz cavity tuned to 196.1 MHz for operation in RHIC. Calculations of the shunt impedances and Q's of the higher order modes (HOMs) are summarized along with beadpull measurements of R/Q of selected modes. Estimates of coupled bunch instability growth rates are calculated with both analytical techniques and using the code ZAP and used to make projections of mode damping requirements.

1. INTRODUCTION

The Relativistic Heavy Ion Collider at Brookhaven consists of two counter-rotating beams of ions ranging from protons to gold colliding at up to six interaction regions. Major machine characteristics are given in Table 1.

Table 1 Machine parameters

Circumference	3833.852 m
Rotation Frequency	78.196 MHz
γ_{tr}	22.8
Horizontal Tune	28.19
Vertical Tune	29.18

The rf system must be capable of capturing, accelerating and storing for 10 hours 57 bunches of particles with an average current of up to 70 mA. Three rf systems will be used to perform these functions: An accelerating system to capture the injected bunches, accelerate through transition, and bunch shortening at top energy. It operates at harmonic number 342. An storage system which accepts the shortened bunches at top energy and provides sufficient longitudinal focusing to keep the bunches short during the 10 hour colliding mode in the presence of intra-beam scattering. It operates at a harmonic number of 2508. A wide-band system operates on a bunch to bunch basis to damp injection momentum errors and will also be used to damp longitudinal coupled bunch instablilities. Of these three systems, the accelerating and storage systems have narrow band cavities with high shunt impedances which contribute to coupled bunch instabilities requiring the design of passive HOM dampers to de-Q the high Q resonances.

2. CAVITY IMPEDANCES

2.1 *Accelerating Cavities*

The accelerating cavities consist of capacitively loaded quarter-wave structures with a close-coupled tetrode amplifier to minimize time delay to allow the implementation of local feedback. It has been changed from that of the prototype discussed earlier[1] by eliminating a capacitive step associated with coupling to a ferrite tuner that was replaced with a mechanical tuner. This has had the effect of raising the first HOM frequency from 64 MHz to 103 MHz. These higher order mode impedances were calculated with the codes SUPERFISH[2] and URMEL[3]. Bead perturbation measurements confirmed the calculated R/Q of the fundamental and will be used to measure HOMs, especially dipole modes as a function of asymmetries in the cavities, such as the power amplifier. The frequencies, shunt-impedances and Q's are given in table 2.

Table 2 Accelerating Cavity Modes

26.7 MHz Cavity Longitudinal Modes		
f_{rf} (MHz)	R_{sh} (MΩ)	Q
26.7	0.95	15750
103.3	0.129	26880
192.3	0.077	33430
276.5	0.174	28850
328.8	0.3069	23260
394.2	0.156	45160

* Work performed under the auspices of the Department of Energy

2.2 Storage Cavities

The storage system consists of 10 surplus CERN SPS cavities, the so-called SWC cavities, which are tuned from the SPS frequency of 200.1 MHz to 196.1 MHz for operation in RHIC. These cavities have HOM suppressors which consist of a quarter wave notch filter to reject the fundamental and terminate the HOM's in 50 ohms. The cavity is tuned to the new frequency by "squishing" it to decrease the gap from nominally 291mm to 278mm. The cavity was then modeled with URMEL to reproduce the new fundamental frequency. HOM data for the undamped cavity was obtained in this way. For calculating growth rates these new URMEL HOM frequencies were combined with the damped shunt impedances measured at CERN[4], and is given in table 3. Since the HOM damper is broadband in performance, and the modal fields in the cavity are not expected to change the damping effectiveness is expected to remain the same after the HOM damper is tuned to the RHIC frequency.

Table 3 Storage Cavity Modes

196.1 MHz Longitudinal Modes		
F_{rf} (MHz)	R_{sh} (MΩ)	Q
New Freq. (URMEL)	Damped Values from CERN data (*=undamped)	
196.1	8.4*	49260*
308.4	.0528	4400
445	.0084	1200
543.1	.0297	690
604.5	.0195	1500
844.5	.001	1000
993.4	.0458	9900

2.2 GROWTH RATE CALCULATIONS

Longitudinal coupled bunch instability growth rates were calculated analytically and compared with the results obtained by the code ZAP[5]. Since the fourier spectrum of the relatively long RHIC bunches falls off rapidly at higher frequencies the work was concentrated on the first few higher order modes of the cavity.

For the purposes of the growth rate calculations the worst case of cavity impedances falling directly on synchrotron sidebands of the revolution lines was used. This is justified in the case of a large circumference collider such as RHIC where the separation of revolution lines is only 78 kHz, and the cavity modes are very likely to cross slowly across the lines as the cavity is tuned with increasing beam-loading, and certainly as the cavity is tuned to keep up with the change in velocity of the beam during acceleration. They will also drift with temperature, although the tuning loop will keep the fundamental corrected for thermal detuning, the HOM's will still be affected. In addition, the 78kHz is beyond the accuracy of our knowledge of the actual mode frequency in the presence of cavity amplifier, vacuum ports, etc. and will be known only after the cavity is built and measured. Growth rates were calculated for proton and gold beams at three places in the cycle: At injection, close to transition, and at top energy, at the beginning of storage. It was found that the proton beam at injection was most sensitive and will be described here. The bunch parameters at injection are a bunch length of 6ns (95%), momentum spread of 3.95×10^{-4},a synchrotron frequency of 45 Hz 1×10^{11} particles per bunch, and 57 bunches.

The code ZAP was used with the Zotter formalism for parabolic bunches and growth rates found for each of the first few modes separately by flagging the input cavity frequency. The code then shifts the input mode frequency to lie on the nearest synchrotron sideband. Results are shown for the rigid dipole and quadrupole modes.

For the analytical approach the expression by Baartman[6] was used:

$$\frac{1}{\tau}=\frac{\omega_\phi}{r_\phi}\frac{I_0R}{V_T\cos\phi_T}F_m \tag{1}$$

where ω_ϕ is the angular synchrotron frequency, r_ϕ is the bunch half length measured in radians of f_{rf}, I_0 is the DC beam current, R the shunt impedance of the m^{th} cavity mode, $V_T\cos\phi_T$ is the total rf voltage seen by the beam and F_m is a form factor[3] given by

$$m\mu(\mu+1)\left(\frac{2}{\chi}\right)^{2\mu+1}\frac{(m+2k+\mu)\Gamma(k+\mu)\Gamma(m+k+\mu)}{k!(m+k)!}J^2_{m+k+\mu}(\chi) \tag{2}$$

where $\chi=\omega_{res}t_\phi$, the angular HOM frequency times the bunch half length in seconds. F_m is between 0 and 0.6 and is inversely proportional to ω_{rf} and the square of the bunch length. This expression was evaluated at $\mu=1.5$ for the non-degenerate case (m,k) equal to rigid dipole (1,0) and quadrupole (2,0) and the degenerate (long-range wakefields only) where all the radial modes are summed

$$F_m=\sum_{k=0}^{\infty}F_{mk} \tag{3}$$

The results of the three approaches are shown in table 3. The differences are due mostly to the variations in the form factor, e.g., the zeros are at the points the form factor goes to zero.

Table 4 Longitudinal Growth Rates

Growth Rates for Rigid Dipole (A=1) and Quadrupole Modes (A=2)				
HOM Frequency (MHz)		ZAP τ^{-1} (sec^{-1})	Non-Degenerate τ^{-1} (sec^{-1})	Degenerate τ^{-1} (sec^{-1})
103	A=1	11.3	12	12
	A=2	5.0	3.76	3.7
192	A=1	9.9	2.5	3.7
	A=2	0.9	4.47	4.9
276	A=1	2.1	0.23	3.8
	A=2	0.9	0.005	7.2
329	A=1	35	0	5.1
	A=2	13.5	1.3	8.9

All of the listed coupled bunch modes are unstable, and require either passive or active damping. RHIC will use a combination of the two to first reduce the growth rates to reasonable levels and active damping if required. There will be an active damper for correction of injection momentum errors which has a damping rate of $10s^{-1}$ and so even moderate passive damping will reduce the growth rates to within this range. The induced voltage in the storage cavities could be used to increase the synchrotron frequency spread and perhaps make the modes stable. The storage cavities have a damping loop which de-Q's the fundamental by a factor of 500 which is required at transition crossing, but could be withdrawn at injection if required. This will be explored in future studies.

These results are for a single rf cavity HOM, there are two accelerating and seven storage cavities per ring and so care must be used in applying these growth rates as they may be additive. In addition, the RHIC upgrade path of going to 114 bunches and $3x10^{11}$ means a factor of 6 increase in average current, and thus growth rate.

4. APPLICATION TO CAVITY HOM DAMPER DESIGN

The approach being taken for mode dampers on the 26.7 Mhz cavity are broad-band loop-coupled dampers located on the cavity to maximize the coupling to the few dangerous modes identified in the instability studies. Once a limit is placed on the impedance of the offending mode the required coupling can be easily determined.

5. CONCLUSION

Cavity impedances for the RHIC cavities have been calculated and confirmed with bead perturbation measurements of R/Q. These impedances were used to calculate longitudinal coupled-bunch instability growth rates using both the storage ring code ZAP and analytical methods and found to be in excellent agreement. These results are to be used to determine allowable HOM impedances and hence the coupling required for the HOM dampers, consisting of loop-coupled notch filters terminated in 50 ohms.

6. REFERENCES

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