HIGHER-ORDER MODES OF STORAGE RING RF CAVITIES AND THEIR INTERACTION WITH THE BEAM AT THE ADVANCED PHOTON SOURCE (APS)

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Abstract
The higher-order modes (HOMs) of APS storage ring (SR) rf cavities and waveguides were measured under various operating conditions. The HOMs of the 352-MHz rf cavity can be one of the major contributors to the coupled bunch (CB) instability. The distribution of HOMs under various conditions of beam current, cavity temperature, cavity tuning, single-bunch and multi-bunch operation, and fill patterns, are presented. The HOMs' shunt impedance of the loaded cavities were also measured. The effect of stagger tuning of the 16 cavities and their waveguide system is compared, and the HOM dampers are examined.

1 INTRODUCTION

To provide stable and useful x-rays from insertion devices such as undulators and wigglers from the APS, the main storage ring (SR) has to supply a positron beam of 100 mA with a lifetime of at least 10 hours at the nominal operation. Some CB-related APS SR parameters are found in Table 1.

Table 1: Some CB-related APS/SR Parameters

Beam Energy	7 GeV
Maximum Beam Current	300 mA
Revolution Frequency	271.55 kHz
Harmonic Number	1296
RF Frequency	351.927 MHz
Synchrotron Frequency	1.8 kHz
Longitudinal Damping Rate	213 sec^{-1}
Transverse Damping Rate	106 sec^{-1}
Cavity Coupling Factor for nominal current (100mA)	2.5
Cavity Tuning Range	3 MHz
Cavity Water Temperature	75 to 95 ^{o} F

In previous work, calculations were performed to determine the deQing requirements of cavity HOMs to ensure that the growth rates for CB instabilities do not exceed the synchrotron radiation damping rate [1]. The results for the monopole modes are summarized in Table 2, where the fundamental mode is included for comparison. HOM dampers were designed, and bench measurements of their effectiveness were reported [2]. The HOM dampers are tested and will be installed in the SR in the near future [3].

Experimental observations show that for specific bunch fill patterns, a longitudinal CB instability is encountered for beam currents around 100 mA [4]. The instability could be suppressed by changing the temperature of the rf cavities. Detailed measurements were performed on the rf cavities in situ in order to characterize the influence of temperature and tuner position on the HOMs. The beam-HOM interaction was also studied in order to identify the driving impedance for the instability.

Table 2: Required Q for Frequency-Staggered Cavity HOMs (only monopole modes are shown)

Monopole HOMs (MHz)	Q_o (1000)	R_s (MΩ)	DeQing Factor Q_o/Q	Calculated Staggering (kHz/mm)
352	49	5.60	*	5.1
538	41	1.67	64	210.
922	107	0.62	16	330.
939	42	0.23	6.4	330.
1172	44	0.18	6.4	390.
1210	94	0.49	16	600.
1509	88	0.40	16	810.

2 HOM MEASUREMENTS

2.1 Measurement Setup

The rf system consists of four power supplies, four klystrons, and four rf cavity sectors (S36, S37, S38, and S40). Each cavity sector has four single-cell cavities, each of which is connected to a WR2300 waveguide by an H-loop type of input coupler. Measurements were made on the cavities and waveguides in sectors 38 and 40. There are various types of field probes: H-loop for the low-level rf feedback, E/H-type HOM probes, E-detector probe for the electron-emission current, and the directional coupler in the waveguide.

2.2 HOMs vs. Cavity Length--Staggering Effect

The frequency, Q-values, and amplitudes of HOMs were measured for a total of ten cavities (eight from S38 and S40, and two spare cavities). Sample results for both unloaded and loaded cavities are shown in Table 3. These are also compared with the URMEL calculations. Most of the HOMs do not appear to couple to the waveguide through the input coupler, except two monopoles at 922 and 1210 MHz and one dipole at 1145 MHz. Due to the asymmetry of the cavity, one of the degenerate dipole modes was significantly deQed. When the frequencies of a typical HOM for eight cavities are plotted, one can see a staggering effect, as shown in Fig. 1 for the 0-M-1 mode at 536 MHz. The frequency linearly decreases with the cavity center

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length. There are some HOMs, however, for which the field configuration/strength is not simply correlated to the cavity center length.

Table 3: Comparison of HOMs in Three Cases: URMEL Calculation, Unloaded Cavity, and Loaded Cavity

Mode	URMEL Calculation		Spare(#4) 201.88 mm		S38 C3(#5) 202.18 mm	
	f(MHz)	Q_o	f(MHz)	Q_o	f(MHz)	Q_L
0-E-0	353.6	49000	351.93	47500	351.93	25900
0-M-1	536.7	41000	539.23	37700	539.19	34600
1-E-1	588.7	68000	582.09	55500	582.45	58500
			584.64	48200	584.24	51000
0-E-2	744.9	43000	735.26	22500	735.26	22200
1-M-2	761.1	53000	756.83	8700	756.49	6800
			761.67	too small		too small
0-E-3	922.5	10700	914.92	51600	915.76	21700
0-M-2	939.0	42000	933.06	1200	931.29	600
1-E-3	962.0	54000	955.71	34000	955.21	8600
			957.73	8600	957.01	16200
1-M-4	1017	41000	1020.5	20000	1020.74	40300
			1020.90	17000	1021.31	10800
1-E-5	1145.1	92000	1143.65	84000	1142.42	35900
			1144.79	61800	1143.16	too small
0-E-4	1173.2	44000	1166.82	61000	1166.76	57200
0-M-3	1210.8	94000	1205.86	31900	1207.14	26200
1-E-6	1219.2	41000	1231.07	19000	1230.40	31100
			1231.30	28500	1231.00	41300
0-E-6	1509.1	88000	1508.73	58800	1503.76	N/A

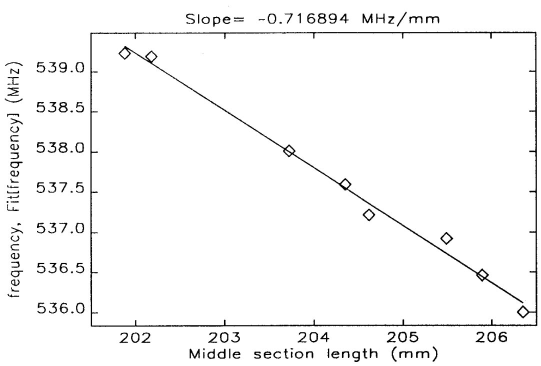

Figure 1: Cavity staggering effect at 536 MHz.

2.3 *HOMs vs. Cavity Temperature*

The S38 cavity water temperature was changed from 95° F to 73° F in 3-degree increments by mixing the cavity return water with the chilled water. The frequencies of the HOMs shift due to the change of the cavity's volume. The cavity body temperatures follow the water temperature change, which includes fluctuation of the order of +/- 1 C. The bunch current is constant at 0.8 mA. Figure 2 shows the beam-excited HOM amplitudes as a function of cavity temperature. The amplitude changes in most of the HOMs due to temperature variation appear to be significant, except at 744 and 1509 MHz.

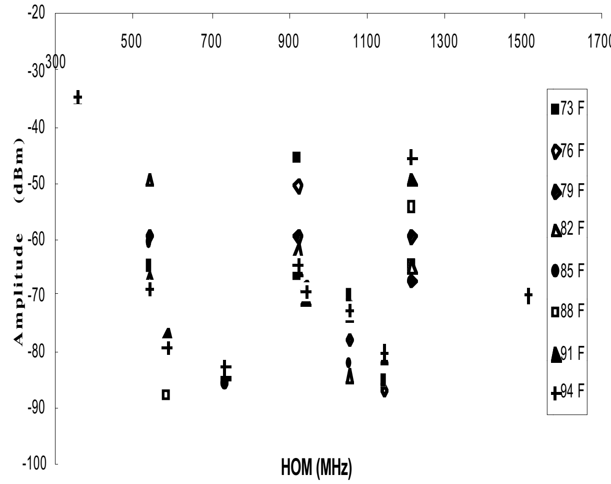

Figure 2: Amplitude variation of the HOMs vs. S40 #2 cavity temperature.

2.4 *HOMs vs. Cavity Detuning*

At a low bunch current (1 mA) the excitation of HOMs was measured while S38 cavities 1 and 2 were detuned, one at a time, by changing the tuner setpoint. There is a cavity temperature change associated with the cavity detuning, probably because the reflected power increases and less power is getting into the cavity. This may make the HOM amplitude results more difficult to interpret. These setpoint changes are rather large, resulting in phase shifts greater than 45° in the fundamental mode relative to the source frequency, and do not represent normal cavity operating points. Later, the threshold detuning on all the rf-sector cavities to sustain stability was carried out with a beam current of 100 mA. The beam spectrum center at an rf harmonic for the unstable case is shown in Fig. 3.

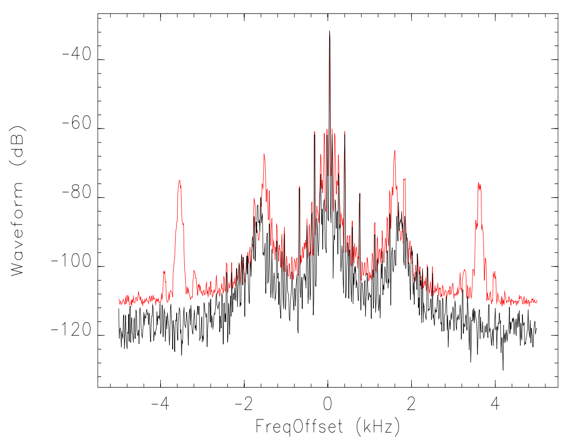

Figure 3: Beam spectrum from S35 BPM, while detuning the cavity; the solid line is the stable and the dotted line is the unstable beam.

In this figure the beam spectrum from a dispersion BPM for an unstable beam is plotted with a spectrum for a stable beam. The synchrotron frequency is about 1.7 kHz. Both dipole and quadruple synchrotron sidebands appear in the unstable beam.

3 DISCUSSION

When the beam is unstable, it oscillates longitudinally at the synchrotron frequency, which modulates specific revolution harmonics in the spectrum corresponding to the specific CB mode. The resonant frequency of the driving HOM determines which CB mode is observed. For each unstable fill pattern, the same CB mode was observed in the beam, implying that the same HOM is responsible. Each particular bunch fill pattern has a characteristic set of revolution frequencies which are then detected by the cavity probes. Of interest are those frequencies which show an increased cavity response when the beam becomes unstable.

Presented first are measurements at a resolution bandwidth of 300 kHz to show a large frequency span. Figure 4 shows the spectrum in one cavity for four groups of 12 bunches when the beam is stable. In this case, the 12 bunches are in a train of adjacent rf buckets, and the four groups are placed symmetrically around the ring. Figure 5 shows the cavity spectrum with the same bunch pattern, when the beam is unstable. The HOM near 1210 MHz shows an increase.

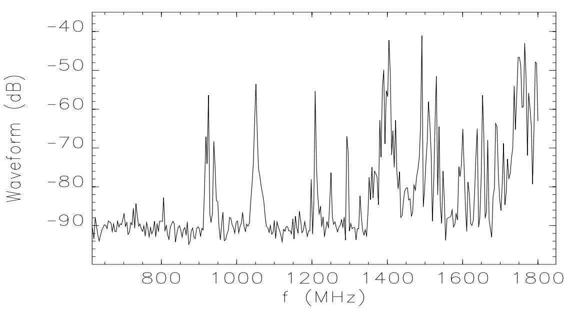

Figure 4: RF cavity HOM spectrum for stable beam.

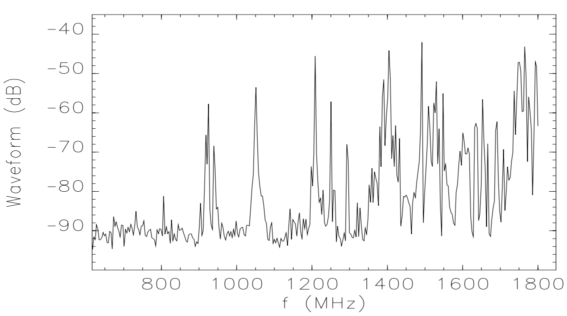

Figure 5: RF cavity HOM spectrum for unstable beam.

A narrowband measurement in Fig. 6 shows that the excitation occurs mainly in the upper synchrotron sideband. The two traces in the figure compare the cases for the unstable and stable beam, respectively. The single-sided response is as one would expect for a CB instability. Based on the measurement of the beam-induced power, one can calculate the shunt impedance of the cavity HOMs, which is summarized in Table 4. The equation used to calculated the shunt impedance is

$$P_{HOM} = P_c + P_{rad} = 2< I_b >^2 (R/Q_o)Q_L,$$

where P_{HOM} is the HOM power induced by the beam, P_c is the HOM power lost to the cavity wall, which the field probe sees, P_{rad} is the HOM power radiated to the waveguide, I_b is the average beam current, R is the shunt impedance, Q_o is the unloaded Q, and Q_L is the loaded Q. There are some discrepancies between the measurement and the calculation, but they are of the same order of the magnitude. More analysis is required to understand the differences.

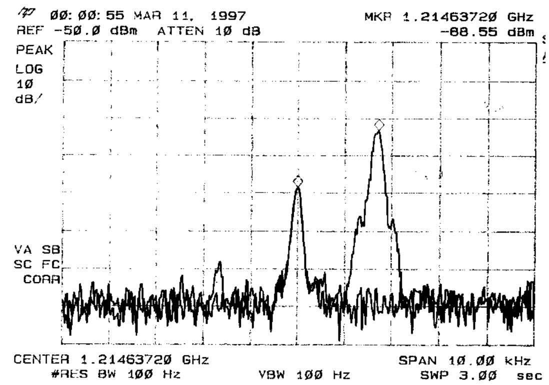

Figure 6: RF cavity signal centered on a revolution harmonic at 1214.64 MHz.

Table 4: Shunt Impedance of the S38 C3 HOMs

Freq (MHz)	Power (W)	Q_o	Q_L	Coupling Factor	Shunt Imp(MΩ)
351.75	24400	47500	18700	1.54	5.60
536.00	85.63	37700	34600	0.10	0.21
733.13	0.39	22500	22200	0.02	0.01
912.28	0.26	51600	21700	0.38	0.01
939.00	7.54	1200	600	1.00	0.33
1173.20	0.30	44000	35900	0.23	0.02
1210.80	7.16	31900	26200	0.22	0.62
1505.93	4.71	58800	3300	16.8	0.82

4 ACKNOWLEDGMENTS

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