Coupled-Bunch Instabilities in the APS Ring*

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Abstract

A study of coupled bunch instabilities for the APS storage ring is presented. The instabilities are driven by the higher-order modes of the fifteen 352-MHz single-cell RF cavities. These modes are modeled using the 2-D cavity program URMEL[1]. The program ZAP[2] is then used to estimate the growth time of the instabilities for an equally-spaced bunch pattern. The cavity modes most responsible for the instabilities will be singled out for damping.

I. INTRODUCTION

One of the eventual goals of the Advanced Photon Source (APS) main ring is the capability to store 300 mA in many bunches[3]. It is therefore valuable to investigate the current limits imposed by coupled-bunch motion instabilities which may jeopardize this goal. Instabilities of bunch motion in the longitudinal or transverse plane may occur when slowly decaying wakefields generated by a bunch passing through vacuum chamber discontinuities are felt by following bunches. Normally, the higher-order modes (HOM's) of RF cavities are the largest contributors of slowly decaying wakefields and, therefore, of coupled-bunch instabilities. The wakefields produced in cavities are usually described as high-Q resonator impedances for each HOM. The design of the APS cavities can be found in reference [3].

Computer calculations of the HOM impedances of the main ring single-cell RF cavity are presented. Then the current limit due to the impedances of the fifteen RF cavities is estimated. The results give a clear indication that cures against the instabilities are required for the operation of the ring. One cure is to attach tuned dampers to the cavity in order to reduce the shunt impedance of the strongest HOM's. To assist the dampers, one may implement systematic geometry differences (slight elongation of the cavities) in all or groups of cavities to spread the HOM resonant frequencies across a number of revolution harmonics. This reduces the chance that many cavity HOM's contribute to the same coupled-bunch mode instability. The required deQing effect of the tuned dampers is estimated.

II. CAVITY IMPEDANCES

In order to predict the longitudinal and transverse coupled-bunch instability limits, one would ideally make impedance measurements on all cavities to be installed in the ring. Since the cavities are not built yet, one can model the monopole and dipole cavity modes using URMEL[1], which uses a rectangular grid on the radial-longitudinal plane. An output file provides the resonant frequency f_r, the shunt impedance R_s, and the quality factor Q for each HOM. Tables 1 and 2 list the strongest modes below the cut-off frequency of the cavity beampipe.

Since the rectangular grid can't fit the spherical contour of the cavity exactly and since the real cavity is not cylindrically symmetric (due to the RF power coupling loop and various ports), one would expect the measured frequencies of an assembled cavity to differ from the URMEL calculation. The measured frequencies of a prototype cavity are reported in [4]. The URMEL frequencies should therefore be taken as uncertain to some extent. For conservative estimates of the coupled-bunch instability growth rates, the frequencies will be shifted to the closest positive revolution frequency harmonic synchrotron sideband.

Table 1
Longitudinal coupled bunch motion with one cavity.

f_{HOM} (MHz)	R_s (MΩ)	Q	$1/\tau_{300mA}$ (sec^{-1})	$I_{thresh.}$ (mA)
536.7	1.67	41000	790.	80.
922.5	0.62	107000	500.	130.
939.0	0.23	42000	190.	340.
1173.2	0.18	44000	190.	340.
1210.8	0.49	94000	510.	130.
1509.1	0.40	88000	510.	130.

Table 2
Transverse coupled bunch motion with one cavity.

f_{HOM} (MHz)	R_t (MΩ/m)	Q	$1/\tau_{300mA}$ (sec^{-1})	$I_{thresh.}$ (mA)
588.7	13.6	68000	390.	80.
761.1	25.6	53000	730.	43.
962.0	6.1	54000	170.	190.
1017.4	2.6	41000	73.	435.
1145.1	2.7	92000	78.	410.
1219.2	3.6	41000	101.	315.

In addition, the Q of each HOM may be lower in the real cavity due to the influence of the RF power coupling loop. It is expected however that the measured value of R_s/Q should not change appreciably from the calculated one.

This paper will include only HOM's with frequency lower than the cut-off frequency for the 7-cm radius beam pipe connecting the RF cavities. However, standing wave modes can be trapped in these sections. The TM mode cutoff frequency for 7-cm radius is 1.6 GHz while the cutoff frequency for the regular elliptical vacuum chamber is 4.5 GHz. All modes of intermediate frequencies can be trapped. URMEL can evaluate the impedance contributed by these, and they are by no means negligible.

Absorbing materials placed in these regions will damp these modes. I will assume that strong damping is much more easily acheived for these modes than for the lower HOM's, and no further study is required for the moment.

III. RING PARAMETERS

Table 3 lists the relevant ring parameters for the stability

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calculations. The bunch length used in the calculations takes

Table 3
Parameters used in Stability Calculations

Energy E	7 GeV
Revolution frequency f_0	271.55 kHz
RF frequency f_{RF}	351.931 MHz
RF Harmonic number h	1296
RF voltage V_{RF}	9.5 MV
Natural Bunch length σ_{l0}	5.33 mm
Bunch length σ_l	7.0 mm
Energy Spread σ_ϵ	9.6×10^{-4}
Momentum compaction η	2.28×10^{-4}
Synchrotron frequency f_s	1.49 kHz
Synchrotron tune ν_s	0.00549
Horizontal tune ν_x	35.2
Vertical tune ν_y	14.3
Longitudinal damping rate $1/\tau_\epsilon$	213 sec^{-1}
Longitudinal damping time τ_ϵ	4.7 msec
Transverse damping rate $1/\tau_\epsilon$	106 sec^{-1}
Transverse damping time τ_ϵ	9.4 msec
Total current I	300 mA
Number of bunches n_b	54
Bunch current I_b	5.6 mA

into account single bunch intensity effects for a bunch current of 5 mA according to a pseudo-Green function method[5]. The energy spread is not affected however. Since 5 mA is close to the transverse mode coupling limit[5], the number of bunches for a total current of 300 mA is set at 54, which must be a factor of h for the application of most calculational methods of growth rates of coupled-bunch instabilities.

IV. Coupled-Bunch Modes Growth Rate

The threshold current for instabilities in electron storage rings is determined by the partially cancelling action of instability growth and the synchrotron radiation damping rate. The instability growth is proportional to the stored current, while the radiation damping rate is constant. The current threshold is then defined as the current at which the instability growth is equal to the damping rate. All growth rates will be calculated for I=300 mA. The current threshold will be extrapolated from

$$I_{\mathrm{thresh}} = 300\mathrm{mA}\left(\frac{\tau_\epsilon}{\tau_{300\mathrm{mA}}}\right). \tag{1}$$

The coupled-bunch modes treated in this section are those produced by a symmetric bunch pattern, i.e. bunches that are equally spaced and equally charged so that the frame of reference of one bunch is equivalent to that of another. The coupled-bunch modes are then rather simple. The amplitude of all bunches is the same, and the phase separation of the motion of each succesive bunch is $\Delta\phi = 2\pi m/n_b$ where n_b is the number of bunches (n_b must be a factor of the RF harmonic number) and m is the coupled-bunch mode number where where $0 < m < n_b - 1$.

For the longitudinal plane the growth rate of each longitudinal mode m is determined by the values of all longitudinal impedances sampled at revolution harmonic synchrotron sidebands

$$f_p = (pn_b + m)f_0 + af_s \tag{2}$$

where p is an integer, f_s is the synchrotron frequency, a is the synchrotron mode number (for dipole mode, a=1), f_0 is the revolution frequency. For a conservative estimate of the current threshold, we consider the dipole synchrotron mode ($a \doteq 1$), since higher order synchrotron modes grow more slowly.

The positive revolution harmonic sidebands ($p > 0$) contribute to growth, and the negative ones ($p < 0$) contribute to damping. It follows from this that if a HOM causes growth for mode m, then it will cause damping for the $n_b - m$ mode.

Similarly for the transverse motion, the relevant quantities are the transverse impedances from dipole HOM's and revolution harmonic betatron sideband frequencies $f_p = (pn_b + m + \nu_\perp)f_0 + af_s$. The horizontal motion is considered here, therefore we set $\nu_\perp = \nu_x$. For zero chromaticity, the growth rate is greatest for the rigid bunch mode, a=0. Here positive p causes damping and negative p causes growth — the opposite of longitudinal motion.

A. Conservative estimates

If the resonant frequency of a monopole HOM happens to equal one of the positive f_p's, then the growth of a particular longitudinal coupled-bunch mode is maximal for that HOM. The growth rate formula in the Wang formalism[6] option of ZAP[2] reduces to approximately

$$\frac{1}{\tau} = \frac{If_{\mathrm{HOM}}\eta FR_s}{2(E/e)\nu_s} \tag{3}$$

with $F \approx 1$, and similarly for the transverse motion and dipole HOM's:

$$\frac{1}{\tau} = \frac{IcFR_t}{4\pi(E/e)\nu_x} \tag{4}$$

Since one cannot easily control the HOM frequencies, one must assume that some of the cavity HOM's will fall on such a frequency. The widths of the resonances ($\Delta f = f_r/Q$) are much narrower (of order 10 kHz) than the spacing between the harmful revolution harmonics (271kHz). Therefore it would seem that there is a only a small chance that a HOM from no more than one cavity will accidentally fall on or close enough to a harmonic sideband. Tables 1 and 2 show the worst-case growth rate for I=300 mA due to the strongest individual HOM's from a *single* cavity, as calculated by ZAP or equations 3 and 4. Unfortunately the desired 300 mA current is so large that the strongest mode (536 MHz) of a single cavity need only be 36 kHz away on either side of a revolution harmonic to cause instablity. Thus there is a 25% chance that the 536 MHz mode of any one cavity will cause instability. With 15 cavities, the growth rate for 300 mA will very likely exceed the radiation damping rate. Reducing the shunt impedance is necessary.

B. Systematic cavities modifications combined with deQing

If all or some of the resonant frequencies differ among cavities one can reduce the chance of two HOM's adding to the growth of the same coupled-bunch mode[7]. The HOM frequencies need to be at least f_0 apart. The cavities can be modified by inserting shims between the center equatorial ring of the cavity and the two nose cone sections. The proposed cavity elongation is along the beam axis. URMEL was used to estimate the rate at which resonant frequencies decrease as a function of shim thickness. Table 4 summarizes the results. The quantity $1/\tau$ does not include radiation damping, so the values shown should be compared to $1/\tau_\epsilon$=-215 sec^{-1}. Conveniently, the fundamental mode is hardly influenced. To spread the frequencies of the strongest HOM by a sufficient amount, I assume all cavities are shimmed in increasing thickness by steps of 1mm. This separates the 536 MHz modes by about $2.5 f_0$ from one cavity to the next. All the other mode frequencies are separated by about twice as much.

Table 4
Shimming the RF cavity and deQing monopole HOM's

f_{HOM} (MHz)	$d(f_{\mathrm{HOM}})/d(\Delta z)$ (MHz/mm)	$1/\tau$ for $Q = Q_0/10$ (sec^{-1})	Required Q/Q_0
351.93	-0.017	—	
536.7	-0.7	80	4
922.5	-1.1	50	2.3
939.0	-1.1	19	1
1173.2	-1.3	19	1
1210.8	-2.0	45	2.1
1509.1	-2.7	45	2.1

It would seem that the conservative estimate of growth rate in the previous subsection (shown in Tables 1 and 2) applies exactly to this situation since no two cavities have the same HOM frequencies. However, with 54 possible longitudinal modes for 54 bunches, and 15×6=90 individual HOM's it is likely that many coupled-bunch modes will be influenced by more than one HOM through aliasing, i.e., $f_{r1} = (p_1 n_b + m + \nu_s) f_0$ and $f_{r2} = (p_1 n_b + m + \nu_s) f_0$ with $p_1 \neq p_2$. But it is also likely that some HOM's will cancel each other in their damping and anti-damping effect on many modes. This statistical problem should be further studied. For this report I will assume that in this fifteen cavity system, there is only one HOM fully exciting some coupled-bunch mode.

Installing dampers to lower the shunt impedance and Q of individual modes can greatly reduce the growth rates. However, a lower Q means a wider impedance function, and a larger probability that a HOM will contribute significantly to some coupled-bunch mode growth even if the HOM is not centered on a revolution harmonic sideband. Table 4 lists the maximum growth rates for the cavities with a deQing factor of 10. The HOM's are considered individually. The basic result is that the growth rates are scaled by exactly the deQing factor. Coupled bunch modes associated with adjacent revolution harmonics (not shown) were calculated to have a growth rate of 10% or less than those corresponding to the main excited coupled bunch mode. One can specify the minimum deQing by comparing the growth rate with the radiation damping rate, and one finds that the largest deQing factor for longitudinal HOM's is 4. These low deQing factors may well occur naturally due to the input RF coupling loop without the aid of dampers.

The transverse HOM treatment gives similar results except that the 588 MHz mode does not shift appreciably with shims. This is because the electric fields of this HOM have no longitudinal variation. The spread of the 588 MHz HOM for fifteen cavities with 1mm incremental shim thickness is about 1.2 MHz, enough to cover 5 revolution harmonics. When deQing this mode one should consider each coupled-bunch mode to be fully excited by three cavities. Table 5 shows that the HOM needing the most deQing is the 588 MHz mode.

Table 5
Shimming the RF cavity and deQing dipole HOM's

f_{HOM} (MHz)	$d(f_{\mathrm{HOM}})/d(\Delta z)$ (MHz/mm)	$1/\tau$ for $Q = Q_0/10$ (sec^{-1})	Required Q/Q_0
588.7	-0.08	117.0	11
761.1	-0.7	73.0	4
962.0	-1.2	17.0	2.3
1017.4	-1.7	7.3	1
1145.1	-1.5	7.8	1
1219.2	-1.9	10.	2.1

Instead of making all cavities different one can make groups of cavities with the same shimming. However this will increase the required deQing of the modes by a factor between 1 and the number of cavities in the group. The exact deQing factor depends on the statistical distribution of frequency shift due to construction tolerances and other imponderables.

V. Conclusion

The growth rate for instabilities were evaluated for reasonably pessimistic cases. The deQuing requirements for most of the HOM's are modest if all cavities are shimmed differently.

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