COUPLED-BUNCH INSTABILITY STUDY OF MULTI-CELL DEFLECTING MODE CAVITIES FOR THE ADVANCED PHOTON SOURCE*

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Abstract

The short-pulse X-ray project at the Advanced Photon Source (APS) uses four room-temperature, three-cell, 2.815-GHz, deflecting-mode cavities in two consecutive straight sections. Undamped, these cavities' higher-order and lower-order resonator modes will cause multi-bunch instabilities in longitudinal and transverse planes for any bunch pattern of a 100-mA store. Damping of these modes must be part of the design of the cavities. We report calculations of instability growth rates that were essential in specifying and checking the rf design of the damping structures. We used various operating bunch patterns and scanned levels of damping of the cavities. Because one of the operating bunch patterns is not symmetric, we used a normal mode analysis implemented in the APS code `clinchor`. Our calculation included random sampling of resonator frequencies in a reasonable range.

INTRODUCTION

Several small but strong 2.815 GHz deflecting mode cavities will be inserted into the APS storage ring straight sections to create a p_y-t correlation on a high-charge bunch for short-pulse X-ray production [1]. The cavities have high shunt impedance for the main deflecting mode and have naturally strong higher-order mode (HOM) shunt impedances, which will be damped [2]. HOM impedances have the tendency to create multibunch instabilities through a resonant effect with beam frequencies. Thus we should determine whether the cavities will produce these instabilities, and if so, what level of damping of the modes is necessary for stable beam. The beam conditions to verify must include those when the cavities are not used.

The short-bunch project started out with a design of three nine-cell cavities with heavily-damped HOMs except for the modes in the working passband, because their frequencies were too close to the main one. Then a configuration with four three-cell cavities was adopted, which have potentially weaker HOMs because of the reduction of cells. A problematic but weaker vertical-plane HOM is present.

Multibunch beam stability calculations for both cavity designs will be reported. In an electron ring with no feedback, such as APS, the stability is determined by comparing the expected growth rates of various bunch patterns with the natural damping rate from synchrotron radiation. We neglect Landau damping (spread of frequencies along a bunch train) and head-tail damping from positive chromaticity, which usually provide much more damping. So we are being conservative here. A discussion will follow on whether to take credit for this extra damping.

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CALCULATION ASSUMPTIONS

Several aspects of the calculation will be discussed before getting to numerical results. The inputs to the calculations are the beam parameters, the bunch patterns, and the HOM data. The calculations can be done for a single dominant HOM of one cavity (for simple estimates) or with multiple HOMs and cavities with possible spread in frequencies. The calculation method could be a simple formula (which works only for symmetric bunches) or an eigenvalue solver for arbitrary bunch pattern.

The beam parameters are given in Table 1. The operating stored current of APS is 102 mA. Our calculations use 202 mA in order to add a safety factor of two for stability. The bunch length is used for bunch form factors that reduce the effect of high-frequency HOMs.

Table 1: Beam Parameters

Current I_0	202 mA
Energy E	7 GeV
Revolution frequency f_0	271.55 kHz
Synchrotron frequency f_s	2.1 kHz
Momentum compaction α_c	2.8×10^{-4}
Long. damping rate $1/\tau_s$	208 s^{-1}
H/V damping rate $1/\tau_{x,y}$	104 s^{-1}
Cavity β_x	20 m
Cavity β_y	5 m
RMS bunch length σ_t for 2 mA	37 ps

Two bunch patterns were treated: "24 singlets," which are 24 equidistant bunches, and "hybrid," which is a high-current single bunch of 16 mA plus a 56-bunch train occupying 500 ns on the opposite side. The 56 bunch train is actually eight groups of seven consecutive bunches spaced by 24 buckets. APS also operates with 324 equidistant bunches, but this instability case is essentially equivalent to the 24 equidistant bunch pattern.

The 3D HOM data (f, $R_{s,t}$ and Q) of the damped cavity with input coupler were provided by G. Waldschmidt [3]. The same was done for the nine-cell cavity design. Preliminary HOM data for the nine-cell cavity (before dampers were designed) were obtained with a URMEL 2D model

[4]. Calculating the growth rates with this data was useful for getting an initial estimate of required Q.

We did not include the HOMs of the sixteen single-cell 352-MHz cavities in the calculations. Though we do not expect a problem (because we do not have instability until we store 250 mA), future calculations will include them. We also observe head-tail damping in transverse oscillations (e.g., 600 s^{-1} for 0.5-mA single bunch at +3 chromaticity), which may be the reason we do not see instabilities. Thus it would be easy to increase this damping with chromaticity in the event of a higher-than-expected transverse impedance. In a hybrid bunch pattern where the chromacity is +11, the head-tail damping is probably very strong.

The shunt impedances in this paper are defined as $R_s = |V|^2/(2P_c)$ for the monopole HOMs, and $R_t = R_s(r)/(kr^2)$ for the dipole HOMs, where V is the special path integral of E_z through the cavity.

Crude estimates of possible growth rates (valid for symmetric patterns) are given by

$$G_s = \frac{\alpha_c I_0}{2(E/e)\nu_s}(R_s f_r)\exp(-\omega_r^2\sigma_t^2) \quad (1)$$

for the longitudinal plane and

$$G_{x,y} = \frac{f_0 I_0}{2(E/e)}(\beta_{x,y} R_t)\exp(-\omega_r^2\sigma_t^2) \quad (2)$$

for the transverse planes, where $\beta_{x,y}$ is the beta functions at the rf cavity, and the other quantities have the usual meanings. We used the notation G for the growth instead of the usual $1/\tau$ to prevent confusion with the damping rates symbols. Note the inclusion of the form factor, which reduces the expected growth rates a bit. The expression can be inverted to give a maximum limit for R_s or R_t for one HOM resonant with beam. Having a high R limit is a good thing because that allows a freer cavity design.

For a general bunch pattern, we used a normal mode analysis developed by Thompson and Ruth [5] and coded in program `clinchor` [6]. This gives the growth rates for only the centroid instability beam mode. We expect that the growth rates for higher-order beam modes will be lower. In the mode analysis, we included the effect of multiple cavities, possible spread in frequencies from construction errors, and possible design of staggering of frequencies. The spread in frequencies is treated as a Monte Carlo problem, where a sample of frequencies is made and a growth rate is obtained [6]. The distribution of the growth rate is then compared with the natural damping rate.

RESULTS

With equations 1 and 2 we obtain the limit of the shunt impedances for a single HOM. For the monopole HOMs, we use a resonant frequency of 2 GHz, giving an R_s limit of 0.25 MΩ. For the horizontal and vertical dipole HOMs, the R_t limits are 2 MΩ/m and 7.9 MΩ/m, respectively.

The nine-cell cavity 2D HOM data (not shown) indicated that the Qs should be in the range 100-400, depending on the plane (confirmed with Monte Carlo simulation).

Table 2 shows the HOM data for our three-cell cavity (with dampers). Fortunately the longitudinal and transverse shunt impedances are lower than the limits above.

The vertical dipole HOM R_t is within a factor of two from the limit. When including four cavities in a complete calculation there is a chance that the growth rate will exceed the damping rate by a factor of two. If it turns out that four cavities give instability, then the worst mode will have to be damped more or the cavity geometry will have to be modified to reduce the R_t/Q of the worst mode.

Table 2: Selected HOM Data for the Three-Cell Cavity

Monopole			
f (MHz)	R_s/Q (Ω)	Q	R_s (Ω)
1955	36	130	4700
2022	59	110	6610
2030	18	90	1600
Horizontal Dipole			
f (MHz)	R_t/Q (Ω/m)	Q	R_t (kΩ/m)
2620	1790	26	47
2663	500	25	13
Vertical Dipole			
f (MHz)	R_t/Q (Ω/m)	Q	R_t (MΩ/m)
2815*	3500	5900	21
2825†	475	10000	4.8

* Main deflecting mode.
† Most troublesome mode.

Table 3: Selected HOM Data for Nine-Cell Cavity

Monopole			
f (MHz)	R_s/Q (Ω)	Q	R_s ($k\Omega$)
1985	130	760	98
1998	230	710	160
2013	185	690	130
Horizontal Dipole			
f (MHz)	R_t/Q (Ω/m)	Q	R_t (MΩ/m)
2559	5700	85	0.49
2563	6560	85	0.56
2569	2837	85	0.24
Vertical Dipole			
f (MHz)	R_t/Q (Ω/m)	Q	R_t (MΩ/m)
2805†	2600	11800	31
2815*	10800	5500	59

* Main deflecting mode.
† Most troublesome mode.

Table 3 shows the results for the original nine-cell cavities. The 3D mode has a large R_t/Q for a y-deflecting mode that could not be damped. The R_t value for one cavity is about four times the maximum value allowed. This was one of the reasons why the nine-cell cavity configuration was rejected.

Since the frequency of the main mode is going to be under control using temperature, we do not have to include this mode in the calculation.

MONTE CARLO RESULT

The Monte Carlo simulation assumes the following conditions: the resonant frequencies are uniformly randomized over a $\pm f_0$ interval, frequency staggering is zero unless specified, and 100 cases are sampled.

The R_s and the horizontal R_t for the three-cell cavity were quite low and didn't expect to present a high growth rate in the Monte Carlo calculation with four cavities. This is seen in the histogram of growth rates in Figures 1 and 2. The histograms are very narrow because the Qs are so low. Perhaps the dampers in the horizontal plane do not need to be as strong as they are.

We found that the growth rates were generally greater for the hybrid mode pattern, probably because of so much charge within 500 ns out of the 3.68-μs revolution time.

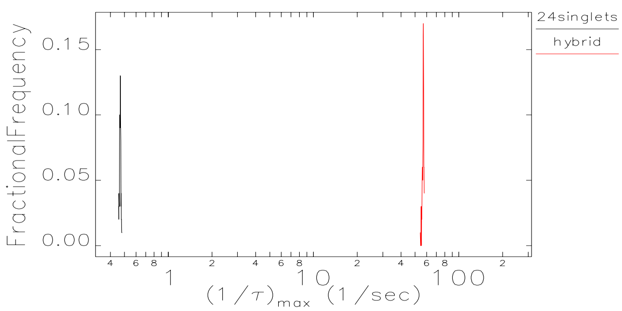

Figure 1: Histogram of possible longitudinal growth rates from four three-cell cavities. Stable limit is 208 1/sec.

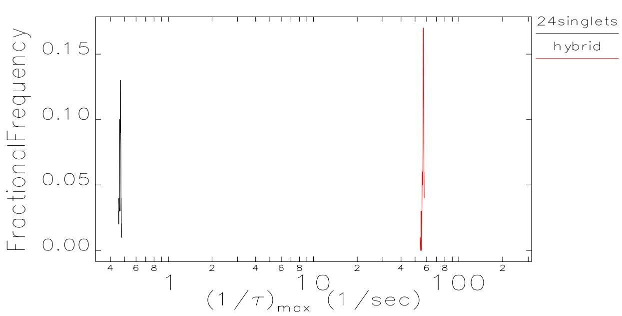

Figure 2: Histogram of possible horizontal growth rates from four three-cell cavities. Stable limit is 104 1/sec.

The vertical transverse shunt impedance was expected to be a borderline case since a single cavity could produce a growth rate equal to one half the damping time. When four cavities are combined we expect that sometimes their frequencies will line up to produce a higher growth rate. Figure 3 shows a growth rate of up to 200 1/sec, twice the damping rate. Thus the beam would be unstable for the 202-mA total current. At 100 mA the beam will be stable. It is not clear why both bunch patterns have similar histograms.

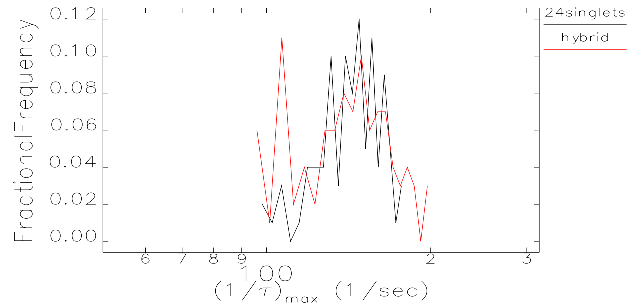

Figure 3: Histogram of possible vertical growth rates from four three-cell cavities. Stable limit is 104 1/sec.

A separate instability study was done for selecting the main deflecting mode operating frequency. Since only one bunch is to be chirped by the cavity, the fields only need to be synchronized at the bunch center and then turned off, thus the frequency could be arbitrary. We found that a range of 5 MHz around harmonics of 176 MHz prevented instabilities for the hybrid mode pattern. So we decided a working frequency of exactly 8 times 351.93 MHz, which is 2815.4 MHz.

CONCLUSION

Table 4 summarize the results of this paper. We must either work the cavity design to decrease the shunt impedance of the deflecting mode by a factor of two, which may cause a decrease in main mode shunt impedance, or we keep this design and ensure that head-tail damping in the vertical plane will work. We could look into designing a narrow-band feedback system to suppress the offending HOM field.

Table 4: Summary of calculations

Plane	Growth Rate	$1/\tau$	Comment
L	60 s^{-1}	208 s^{-1}	Stable
H	5 s^{-1}	104 s^{-1}	Stable
V	200 s^{-1}	104 s^{-1}	Stable only at 100 mA

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