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MULTI-BUNCH STABILITY ANALYSIS OF THE ADVANCED PHOTON SOURCE UPGRADE INCLUDING THE HIGHER-HARMONIC CAVITY*

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Abstract

Multi-bunch stability simulations were done for the very-low-emittance hybrid seven-bend-achromat (H7BA) lattice proposed for the Advanced Photon Source (APS) upgrade. The simulations, performed using `elegant`, were meant to determine whether the long-term wakefields of the higher-order modes (HOMs) of the main 352-MHz cavities will produce an instability. The multi-particle simulations include the important effects of the Higher-Harmonic Cavity (HHC) and the longitudinal impedance of the new vacuum chamber. These realistic simulations show that the HHC provides additional damping in the form of the Landau damping. Still, the HOMs may likely produce a multi-bunch instability which can be cured with more effective HOM damping or a longitudinal feedback system.

INTRODUCTION

The present Advanced Photon Source (APS) ring has sufficient damping to suppress multi-bunch instabilities in the longitudinal and transverse planes. The APS Upgrade ring, with the Hybrid MBA optics [1], will have a larger current of 200 mA, somewhat smaller synchrotron radiation damping, and reduced longitudinal focusing. This will result in a higher tendency for (particularly) longitudinal multi-bunch oscillations generated from the wakefields of the higher-order mode resonances (HOMs) of the 352-MHz single-cell cavities of the APS ring. Even though only 12 of the original 16 cavities will be kept, the HOMs tend to act individually and any one or two of them may cause an instability.

Another difference from the present APS is the presence of a higher-harmonic cavity (HHC) [2], which stretches the bunch to reduce the IBS emittance growth and to make the lifetime longer [3]. The longitudinal dynamics are significantly changed with the HHC, which will provide some Landau damping to any longitudinal centroid oscillations.

To accurately include the HHC, which changes the potential well and makes the motion anharmonic, a tracking simulation must be done. Though we realize that reference [4] gives some analytical predictions, tracking is the most straightforward way to approach this problem (see for example [5]).

The HOM spectrum of each cavity was modeled by [6] from frequency-domain finite element code CST [7]. The ten lowest modes below the cut-off (1640 MHz) of the cavity beam pipe were selected. The spectrum is dominated by one strong HOM around 540 MHz, which has been damped by a factor of 8 in four of the cavities at APS. We assume that for the APS Upgrade all cavities will have this mode damped by the same amount. The other HOMs in the aggregate contribute about the same effect as this damped mode. The cavities were constructed differently from each other to systematically stagger the HOM frequency by at least 210 kHz (a little less than one revolution frequency). However, the frequencies of the individual HOMs are not known exactly and can change during operation. Thus we have a huge parameter space of possible HOM frequencies to explore, which requires a Monte Carlo approach.

We have done preliminary calculations of expected multi-bunch mode growth rates using a normal mode analysis [8], which assumes single-particle bunches and harmonic motion. This calculation method cannot include the effect of the HHC and impedance, which is a severe limitation. However, because the calculation is very fast, one can apply a large number of realizations of the possible 120 HOM frequencies (10 HOMs for each of the 12 cavities), and thereby obtain a cumulative distribution of expected growth rate.

In the section that follows we report on multi-particle tracking that fully includes the HHC and impedance. Here we perform calculations for far fewer HOM-spectrum scenarios.

Multi-bunch beam modes in the transverse plane are considered stable because of the coherent damping from the short-range transverse wake and the deliberately-chosen positive chromaticity. This stability is unaffected by the presence of the HHC. Results from a Monte Carlo calculation with dipole HOMs of randomized frequencies are given in Table 2.

PRELIMINARY MONTE CARLO CALCULATIONS

The stability of the modes were first examined by assuming that each bunch behaves as a point charge. Though we know this is an approximation, we can quickly perform Monte Carlo calculations of possible maximum growth rates and assess the need to make further calculations.

The main lattice parameters that control longitudinal growth rate are given in Table 1 and appear in the following equation for the maximum growth rate of a multi-bunch beam mode due to a single HOM resonance:

$$G = \frac{\alpha_c I_{\text{total}}}{2(E/e)\nu_s}(R_s f_{\text{HOM}}) \exp(-\omega^2\sigma_t^2), \qquad (1)$$

where α_c is the momentum compaction, I_{total} is the stored current, E/e is the beam energy in eV units, ν_s is the synchrotron tune, R_s is the (circuit definition) shunt impedance of the monopole HOM, f_{HOM} is the frequency of the HOM

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Table 1: Comparison of Relevant Ring Parameters

Quantity	APS	MBA
No. of cav.	16	12
I_{total} (mA)	150	200
E (GeV)	7	6
α_c	2.82×10^{-4}	5.66×10^{-5}
Sync. freq. (kHz)	2.1	0.718[a]

[a] With HHC off.

resonance, and σ_t is the bunch length. The exponential is a bunch form factor, which is close to unity for the HOM frequencies of interest. The MBA parameters reduce G by 0.68. The growth rate must be countered by a damping mechanism, such as synchrotron radiation, Landau damping, or feedback, for the beam mode to be stable. The synchrotron radiation damping rate is reduced by a factor of 3 in the MBA, which will tend to make the multi-bunch beam more unstable.

The fast calculations use a normal mode analysis as implemented in `clinchor` [9], which involves finding eigenvalues from a coupling matrix with complex elements. Using `clinchor`, one can repeat the calculation for several seeds of random HOM frequencies sampled from a uniform distribution of $\pm f_0$, where f_0 is the revolution frequency [10].

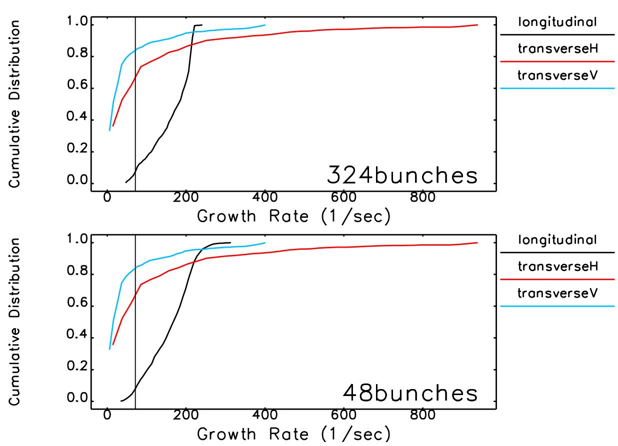

Figure 1: Cumulative distribution function of the maximum growth rate for symmetric bunch patterns. The black line shows longitudinal damping rate.

Table 2 summarizes the Monte Carlo calculation results. With the HHC off, the longitudinal plane will be unstable. Thus a feedback system would definitely be necessary for that operating mode. Included in the table is the expected Landau damping from the frequency spread calculated from ideal bunch lengthening using the damping formula in [5]. However, the bunch will be overstretched for lengthening stability [3], which may reduce the effective frequency spread.

Table 2: Summary of Monte Carlo Calculations

	Growth Rate[a] (s^{-1})	Damping Rate[b] (s^{-1})	Stability
Horizontal	690	4200	Yes
Vertical	250	11000	Yes
Long. with HHC off	260	71	No
Long. with HHC on	N/A	259	Not determined

[a] Worst 98th percentile of either bunch pattern.
[b] Expected synchrotron radiation, coherent and Landau damping.

MULTI-PARTICLE TRACKING

Tracking simulations were done with `elegant` [11] or `Pelegant` [12] depending on the size of the simulation. Much of the tracking methodology follows [3], where a few beamline elements were used for an efficient representation of the optics, rf elements, synchrotron radiation effects, and impedances. In particular the passive HHC and HOMs were both represented by the `RFMODE` element, where the voltage is generated by beam, while the main rf cavities for the present paper were represented by an `RFCA` element for simplicity. The HHC with $R_s/Q = 54\ \Omega$ was configured with $Q = 6\times10^5$ and $\Delta f = 13.5$ kHz, which [3] recommends for a 48 bunch pattern.

Included in the beamline were the short-term wake fields based on the conceptual vacuum system design (an older version of that presented in [13]) . To correctly represent the microwave instability the bunches need at least 30,000 macro-particles [14].

The baseline design for the APS Upgrade calls for bunch patterns of 48 and 324 bunches. For expediency we ran cases only for 48 bunches (1.44 million macro-particles). 324 bunches will be done later; similar results are expected.

To make the results easier to interpret, the HHC and HOM were sequentially ramped up. Initially, the HHC was ramped up over 1000 turns. Then 5000 turns (1.3 damping times) were tracked to achieve a steady state, after which the HOM(s) were ramped up over 1000 turns.

Our initial tracking was with a single particle per bunch with a single undamped 540-MHz HOM on resonance and HHC+impedance off in order to check the resulting growth rates with analytical calculation. The agreement for the growth rate and multi-bunch mode pattern was excellent. We tracked a total of 25k turns in order to ensure stability, which takes about 60 h on a single CPU, or proportionally less using multiple cores.

We then scanned the Q of a single 540-MHz HOM impedance while keeping $R_s/Q = 41\ \Omega$ constant to get a sense of instability thresholds and beam dynamics. Figure 2 shows the evolution of the momentum centroid error for a particular bunch for several of the Q values. We observed three regimes. For low shunt impedance (Q<12000) there was no growth in bunch centroid error or spread in coordi-

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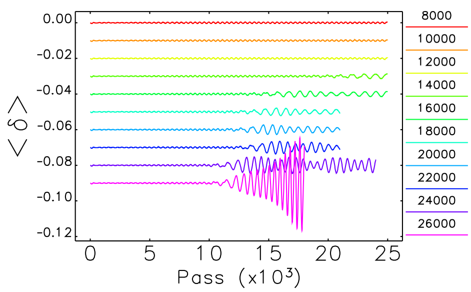

Figure 2: Momentum centroid oscillations for different Q values of the 540-MHz HOM. Data is staggered 0.01 units vertically for clarity. Time coordinate centroid oscillations would show essentially the same thing.

nates. Here the tendency to go unstable was countered by synchrotron radiation damping. Above some threshold in shunt impedance ($1200 < Q < 2400$), there were some complex centroid oscillations along with variations of beamsize and energy spread (not shown). This was Landau damping in action, we believe. The oscillation amplitude increases with shunt impedance. The energy spread projected for all bunches may be intolerable (up to 1%). Above a second threshold in shunt impedance ($Q > 2400$), the centroid rapidly grows linearly or exponentially and some particles eventually get lost. Using Equation 1 we find a rough numerical correspondence between the growth rates of the shunt impedance threshold values and the damping rates of synchrotron radiation and Landau damping.

Also of interest are the induced voltages in the HHC and HOM as shown in Fig. 3. Ideally the HHC voltage should be constant (and at the appropriate phase of course), and the HOM-induced voltage should always be low. Recall that

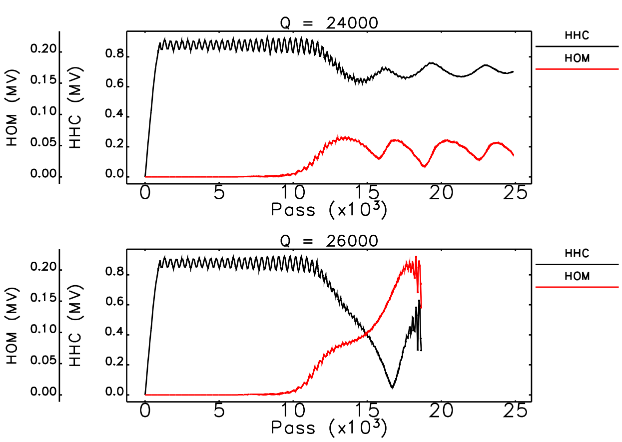

Figure 3: Induced voltages for Q of 24000 and 26000.

the HHC is driven passively by beam. If the bunch centroids are perturbed too much, then the HHC voltage can become suppressed, destroying the elongated potential and causing a loss of Landau damping. At high enough shunt impedance the beam will eventually become unstable and the beam may require a feedback system. Simulation with a feedback system is in preparation.

A small number of randomly-selected sets of HOM spectra from the single-particle bunch Monte Carlo calculation were tracked to get an idea of the possible stability. Figure 4 shows that out of 8 sets (certainly not a sufficient number), 3 were unstable and 5 have sustained oscillations of various amplitudes. We tentatively conclude from this that we are about 50% likely to have unstable beam due to the HOMs of the APS cavities.

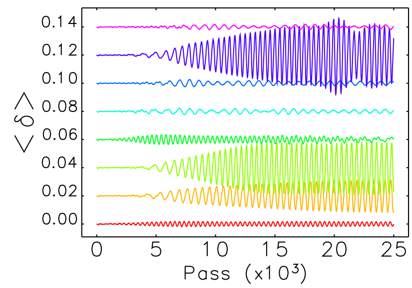

Figure 4: Momentum centroid oscillations for 8 realizations of 120 randomized HOMs. Data is staggered for clarity.

CONCLUSIONS

Tracking with `elegant` including the HHC, HOMs, and impedance shows two thresholds for multi-bunch instability, indicating the limits of synchrotron radiation damping and Landau damping. With the HHC off, the 12 APS cavities will produce a multi-bunch instability which will have to be cured with more effective HOM damping or a longitudinal feedback system, or by limiting the total current under that condition. With the HHC on, the HOMs may likely produce a multi-bunch instability which can also be cured with more effective HOM damping or a longitudinal feedback system for the design current of 200 mA. We tracked with only one HHC tuning setting and one bunch pattern. The Landau damping effect may differ for other conditions which should also be simulated. Future work will include feedback simulations as well.

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