SIMULTANEOUS SIMULATION OF MULTI-PARTICLE AND MULTI-BUNCH COLLECTIVE EFFECTS FOR THE APS ULTRA-LOW EMITTANCE UPGRADE *

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Abstract

Next-generation storage ring light sources promise dramatically lower emittance due to the use of multi-bend achromat (MBA) lattices. The strong magnets required for such lattices entail small magnet and vacuum bores, which increases concerns about collective instabilities. In this paper, we describe detailed simulations undertaken for the APS MBA lattice using the parallel version of `elegant`. The simulations include short- and long-range geometric and resistive wakes, a beam-loaded main rf system including feedback, a passive harmonic bunch-lengthening cavity, higher-order cavity modes, and bunch-by-bunch feedback. Applications include insight into transients during filling, effects of missing bunches, evaluation of non-uniform fill patterns, and determination of feedback system requirements.

INTRODUCTION

Accurate modeling of instabilities is a challenging endeavor, yet it is vital if new accelerator designs are to deliver the expected performance. An example of a successful model of single-bunch effects in an existing ring is the impedance and instabilities model for the Advanced Photon Source (APS), a 7-GeV, third-generation storage ring light source. [1] Other noteworthy efforts are [2, 3].

Fourth-generation storage ring light sources are now being planned that will make use of multi-bend achromat lattices [4]. These lattices feature very strong quadrupoles and sextupoles, necessitating a significant reduction in the magnet bore and thus the vacuum bore radius r [5]. Since both geometric and resistive wakes scale like $1/r^2$ to $1/r^3$ [6], collective effects are expected to be more pronounced, although this is mitigated to some extent by the reduction in the beta functions. In the case of the proposed APS upgrade (APS-U) [7], the target single bunch current of 4.2 mA must be ensured (allowing 200 mA in 48 bunches). In addition, a passive higher-harmonic cavity (HHC) will be added to lengthen the bunch in order to reduce emittance growth due to intra-beam scattering and improve the Touschek lifetime. This cavity has difficult-to-determine implications for coupled-bunch instabilities [8]. Twelve of the 16 existing room-temperature 352-MHz rf cavities will also be retained. These considerations, coupled with the desire for a rapid return to user operations after the upgrade, motivate the creation of a model of collective instabilities that covers both single- and multi-bunch phenomena.

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To be more specific, the model we have created encompasses (1) Storage ring single-particle dynamics including chromaticity, nonlinear momentum compaction, and synchrotron radiation. (2) Short-range geometric wakes. (3) Short-range resistive wakes. (4) Long-range (multi-turn) resistive wakes. (5) Beam-loading and rf feedback for the 12 main rf cavities. (6) Higher-order modes in the 12 main rf cavities. (7) Single-cell passive (i.e., beam-driven) higher-harmonic cavity. (8) Transverse and longitudinal bunch-by-bunch feedback.

MODELING METHODS

In this section, we briefly describe the modeling methods used for each of the simulation components in the context of modeling collective effects for APS-U.

Addition of collective effects to `elegant` [9] began in the early 1990s, when short-range impedances and rf cavity modes were included to model the APS Positron Accumulator Ring [10]. Coherent synchrotron radiation [11] and longitudinal space charge were added in the late 1990s and early 2000's for linac modeling for free-electron lasers, e.g., [12, 13]. A time-domain implementation of short-range wakes was also added (though it is equivalent to the frequency domain impedance). In the mid-2000's, these features appeared in the parallel version, `Pelegant`, [14, 15]. More recent additions include space-charge in rings [16], intrabeam scattering [17–19], and Touschek scattering [20, 21], as well as more efficient simulation of long-range wakes and multi-bunch beams [19].

To control noise, modeling of collective effects requires many simulation particles. For the present case, the prominance of the microwave instability [22] motivates using at least 10,000 particles per bunch (10 kP/B). In addition, we must simulate all bunches to get accurate excitation of cavity modes, model feedback systems, etc., implying several million simulation particles in total. Given that the APS-U damping times are 3000~6000 turns, we must track for several tens of thousands of turns, and thus in excess of 10^{10} particle-turns. This would be very time-consuming if element-by-element modeling was performed. Hence, to the extent possible, both single- and multi-particle phenomena are simulated using lumped elements.

To accurately predict stability thresholds, simulations must include chromaticity, which can have a stabilizing effect. This is accomplished without element-by-element tracking using `elegant`'s `ILMATRIX` element, which computes a 6x6 linear matrix for each particle based on the particle's fractional momentum offset δ and transverse amplitudes. Path-length dependence on momentum, also im-

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portant in collective effects, is supported up to third order in δ. ILMATRIX can model any periodic unit of the lattice, including the entire ring. In the present simulations, we use a full-ring method that includes chromaticity up to third order in δ and momentum compaction up to second order in δ. Lumped synchrotron radiation including quantum excitation is modeled using the SREFFECTS element.

Short-range geometric and resistive longitudinal and transverse wakes are modeled using the frequency-domain ZLONGIT and ZTRANSVERSE elements. The geometric wakes are computed using the programs GdfidL [23] and ECHO2D [24], while resistive wake potentials are computed using well-known analytical expressions [25]; These are added with appropriate weighting by the beta functions to obtain the total wake potential.

The longitudinal wake field is computed by convolving the longitudinal density with the wake potential. For transverse plane, dipole and quadrupole wakes are included. In brief, for a dipole wake the kick to a trailing particle depends on the longitudinal density of the leading particles weighted by their transverse position. For a quadrupole wake, the kick to a trailing particle depends on the longitudinal density of the leading particles multiplied by the transverse position of the *trailing* particle. For further details, see [1].

The long-range part of the resistive wall wake, defined as the part that acts on subsequent bunches or turns, is modeled using the LRWAKE element [19] This element is configured by time-domain wake potentials computed from analytical expressions [25]. It treats the bunches like point particles, which is a valid approximation since the space between bunches is large compared to the bunch lengths and since the long-range wake varies slowly over the length of a bunch. In the APS-U simulations, we used a long-range wake extending over 10 turns.

In addition to non-resonant short- and long-range collective effects, we must also include rf cavity modes. Beam-loading of resonant modes is modeled using the loss factor coupled with phasor addition, rotation, and damping. elegant models both monopole (accelerating) and dipole (deflecting) modes, using the RFMODE and TRFMODE elements, respectively. (For cavities with many modes, the FRFMODE and FTRFMODE elements are used, since they allow specifying the mode parameters in a separate SDDS file.) The monopole modes are modeled by first creating a histogram of the particle arrival times for the first bunch. Stepping through the histogram allows computing the voltage induced in the cavity by each beam slice, as well as the time-dependent cavity voltage within the bunch, which acts back on the bunch. Once the bunch has passed, the cavity phasor is propagated in a single step to the start of the next bunch using the cavity frequency and loaded Q. Dipole modes are handled in a similar fashion, except the histogram is weighted by the appropriate transverse coordinate of each particle.

Each APS rf cavity was constructed with a slightly different length in order to ensure that HOMs fell at slightly different frequencies, thus reducing the potential multi-bunch instability (MBI) growth rates. Since the exact frequencies for the HOMs for each cavity are not known, we use a Monte Carlo technique to randomize the frequencies and determine the growth rates for each configuration [8, 26]. We then selected one of these configurations that was expected, in the absence of feedback, to be unstable longitudinally but stable transversely.

For the main rf cavities, the generator and feedback system must be modeled in addition to the beam-induced voltage, as described in [27]. For the present simulations, the user-specifiable phase and amplitude feedback filters are configured to match the feedback systems in use today at APS.

The last component is the bunch-by-bunch transverse feedback (TFB) and longitudinal feedback (LFB), modeled using pairs of TFBPICKUP and TFBDRIVER elements. elegant allows specifying FIR filters for both signal processing (TFBPICKUP) and drive generation (TFBDRIVER). For the TFB, these are configured to mimic the existing APS system [28, 29].

The simulated LFB works by measuring the mean fractional momentum offset, $\langle\delta\rangle$, for each bunch, presumably via a BPM in a dispersion location, whereas a more common choice is to use bunch phase measurements. Such ϕ-LFB has several disadvantages compared to δ-LFB. The correcting kick cannot be delivered until 1/4 of a synchrotron oscillation after the measurement, which reduces the ability to damp fast instabilities. With δ-LFB, the feedback system can act promptly, before a significant fraction of a synchtron oscillation has occurred. In the presence of a harmonic cavity, the synchrotron tune is ill-defined and depends strongly on amplitude, so it is not clear how to design the filter for ϕ-LFB. Finally, in non-uniform fill patterns (e.g., while filling), ϕ-LFB will need a pattern- and current-specific setpoint for each bunch to compensate for phase slewing due to transient beam loading. This is not required in δ-LFB, since the equilibrium value of δ is always 0.

UNIFORM FILL PATTERNS

We start with results for the nominal uniform 48-bunch pattern proposed for APS-U. (A uniform 324-bunch pattern is also proposed, but will not be covered in this paper.) We simulated both with and without the bunch-by-bunch feedback systems.

The simulations require some care to avoid spurious instabilities from shock-excitation of the rf systems and beam. Hence, the simulated beam current is fictiously ramped from 0 to 200 mA over 5,000 turns. This provides time for the main rf cavity feedback system to respond and provide sufficient voltage. Following the ramp-up, another 7,000 turns are allowed for the beam to damp close to equilibrium parameters, after which the beam is kicked in the longitudinal and transverse planes to assess the ability of the feedback system to respond.

Tracking without feedback shows instability in *both* planes and significant beam loss, even prior to kicking the beam, as

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illustrated in Fig. 1. It seems clear that feedback will be necessary. To confirm the feedback filter setup, we performed trial simulations with single-particle bunches, then tracked with 30 kP/B to confirm the results.

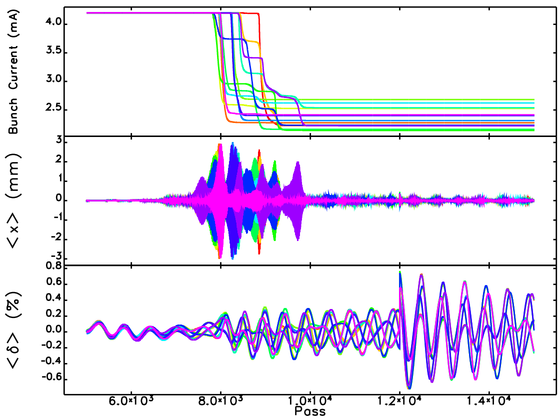

Figure 1: Multi-bunch instability resulting in beam loss in the absence of feedback. A selection of the 48 bunches is shown. See text for details. The beam is deliberately kicked at pass 12,000.

Turning on LFB alone is not sufficient to prevent instability. The cause appears to be the long-range transverse resistive wall wake, which is not covered by the mode-based analysis [8]. This was verified by removing first the transverse dipole modes, then the transverse long-range resistive wall wake. The former case still exhibited the instability, while the latter did not. This conclusion is confirmed by analysis of the bunch-by-bunch horizontal centroids for the unstable beam before particles are lost. This exhibits the expected horizontal tune signature [30], as shown in Fig. 2.

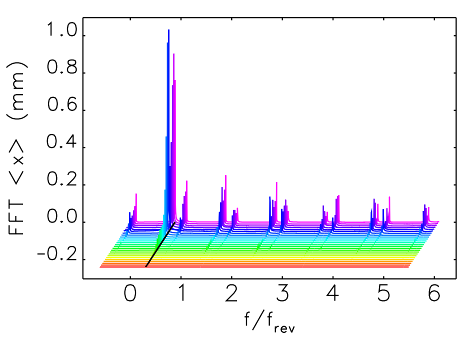

Figure 2: Evolution of Fourier transform of bunch-by-bunch horizontal centroids over 5000 turns, showing growth at $1 - \nu_x$ in the absence of transverse feedback.

With all effects included, the required peak (rms) feedback strength is 4.4 V (0.9 V) for horizontal, 1.6 V (0.3 V) for vertical, and 9.3 (2.6) kV for longitudinal. However, this is a relatively quiet situation and doesn't reflect the maximum effort that might be required from the feedback. Determining this requires looking at non-uniform fill patterns and transients during filling. As we'll see, it is possible to cap the longitudinal feedback strength and still preserve stability.

NON-UNIFORM FILL PATTERNS

Although uniform bunch patterns are the default, non-uniform patterns may be of value for some user programs. We've explored several alternatives in [31]. Here, we present a hybrid fill pattern created from the 48-bunch uniform pattern by removing two bunches on either side of a target bunch, creating an isolated bunch with twice the uniform gap on either side. Because of the low Q of the main rf cavities and the slow response of the main rf feedback, a voltage variation develops in the main rf cavities, causing the bunches to slew in phase. This impacts the induced voltage in the HHC and results in nonuniform lengthening of the bunches, as seen in Fig 3.

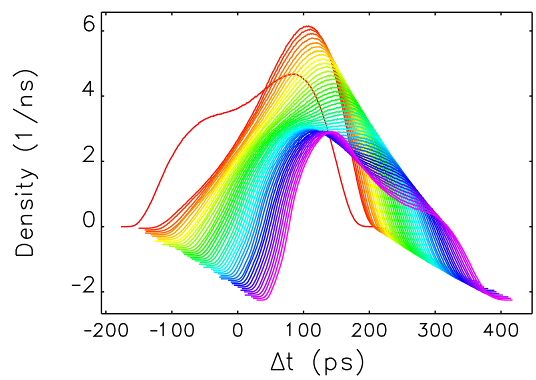

Figure 3: Bunch shapes for "1+45" hybrid mode pattern. Curves are offset in both dimensions for clarity. The isolated bunch is at the top.

As described above, the δ-based LFB employed in these simulations works without adjustment even in the case of nonuniform fill patterns. No stability issues are seen with LFB and TFB configured as for the uniform 48-bunch fill. With no strength limitations imposed and no disturbance to the beam, the peak (rms) feedback strength is 5.5 (1.0) V for horizontal, 0.5 (0.1) V for vertical, and 8.8 (2.4) kV for longitudinal. No particle losses are seen when limiting the longitudinal feedback strength to 1.8 kV (0.3 ppm of the 6 GeV beam energy). There is an increase in rms energy oscillation amplitude to 0.008%, which is negligible compared to the 0.1% energy spread of the beam. Reducing the strength cap to 0.1 ppm results in continuously growing longitudinal amplitude and partial beam loss.

IMPACT OF A LOST BUNCH

The injection method envisioned for APS-U is on-axis swap-out [32–34], which entails periodically extracting the weakest stored bunch and replacing it with a fresh, full-current bunch. It may well happen that a stored bunch will be extracted but the replacement bunch will not be injected. This will result in bunch phase, energy, and shape oscillations in the remaining bunches [31].

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This could prove problematical for the LFB as it will attempt to damp the large transient phase oscillations resulting from such an event. If overwhelmed, the LFB may be unable to ensure stability and more beam loss may occur. If no limit is imposed, the LFB peak kick corresponds to 480 kV, which is about the same as a storage ring rf cavity. Limiting the kick to 6 kV (1 ppm of the beam energy) does not adversely impact stability, even though the feedback output is "railed" following the loss of the bunch. If the limit is reduced to 0.3 ppm (which worked for the 1+45 pattern just described), there is continuous growth of the longitudinal oscillation and ~50% beam loss. Figure 4 shows HOM voltage data for both cases along with the momentum centroid for one of the bunches.

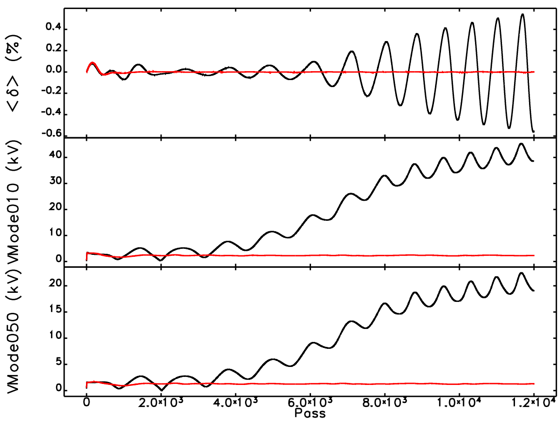

Figure 4: Centroid of bunch 0 (top) along with voltages in two monopole HOMs (923 MHz, 1.17 GHz), immediately following loss of one of 48 bunches. Black: LFB capped at 0.3 ppm. Red: LFB capped at 1 ppm.

SIMULATION OF FILLING FROM ZERO

Another situation in which transients may be important is when filling the ring from zero, particularly since on-axis injection requires injection of 15 nC shots. As in the case of a lost bunch, there will be transients whenever a new bunch is added. We previously simulated this [31] in the absence of bunch-by-bunch feedback and HOMs.

We simulated filling 48 bunches from zero using a "balanced" fill order to reduce transients [31]. The injection was accomplished using `elegant`'s `SCRIPT` element, which allows performing an essentially arbitrary periodic modification of the beam. In this case, at each injection time the beam is written to disk, modified by an external program, and then read back in for further tracking. A simple script using SDDS and Tcl/Tk was sufficient to add the next bunch with the appropriate time coordinates to simulate injection into a specific rf bucket.

Trial runs with 1 kP/B showed that the LFB strength was as high as 53 keV, which is about 15% of the voltage from one APS storage ring cavity. For production runs, we capped the LFB strength at 1 ppm (6 kV), which worked well in the simulations of a lost bunch reported in the previous section.

To economize computer time, we used 10 kP/B and injected a new bunch every 5,000 turns (~18 ms), which is about one damping time. (The damping times, for reference, are 12, 20, and 14 ms in the horizontal, vertical, and longitudinal planes.) This is also about the response time (~ 20 ms) of the feedback on the main rf system.

Results show that without sufficient transverse feedback effort, the initial bunch is partially lost. The results depend somewhat on the number of particles used in the simulation: for 100 kP/B and above, a feedback cap of 60 nrad is consistent with full capture. If the cap is below this the initial bunch will suffer a ~30% loss. This continues for subsequent bunches with slowly decreasing losses. Eventually, all bunches are fully captured.

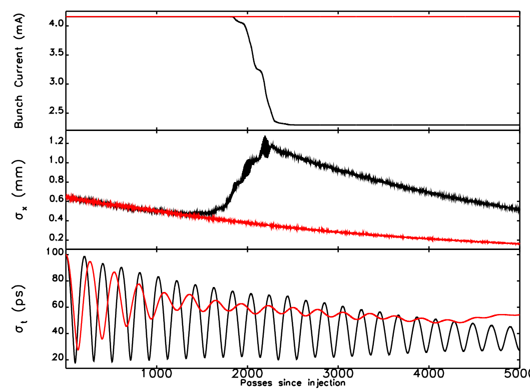

Figure 5: Turn-by-turn bunch current, bunch length, and bunch horizontal size for first (black) and 24^{th} bunches filled in a 48-bunch uniform fill, using 10,000 particles per bunch.

Although the required feedback effort is not a concern, it is interesting to simulate the behavior with marginal transverse feedback to understand the physics. As illustrated in Fig. 5, these losses apparently result from bunch-length oscillations that occur because of longitudinal mismatch of the injected bunch. As the early bunches tumble in the rf bucket in the absence of significant beam-driven harmonic-cavity voltage, they periodically become much shorter than normal, which amplifies the effect of the high-frequency part of the short-range dipole impedance. In particular, the horizontal beam centroid and size grow, resulting in particle loss. Inspection of the phase space data shows a clear head-tail instability, as shown in Fig. 6. As the harmonic cavity voltage builds up in response to the accumulation of beam, the minimum bunch length during these oscillations is increased, so the high-frequency part of the short-range impedance is not as influential.

The sensitivity of these results to the number of simulation particles suggests that the instability is seeded by noise. This implies that in a real system, jitter in the incoming beam position will be important. More simulations are planned to refine our understanding of this issue and the feedback requirements.

One possible solution is to fill in stages, i.e., fill to 100 mA in 48 equally-populated bunches, then to 200 mA by replac-

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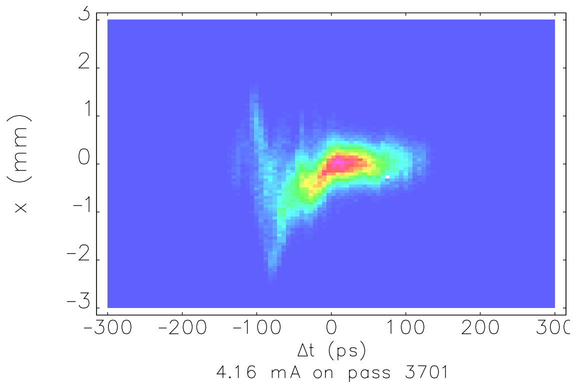

Figure 6: Tracking data from first injected bunch, showing head-tail instability.

ing each bunch with a bunch having twice the charge. With this approach we anticipate that the transients will be significantly reduced. Given that we intend injecting bunches at 1 Hz, this increases the fill time from 48 s to 96 s, which is a minor difference.

We modeled this using the same approach as described above, but with 10 kP per initial bunch and 20 kP per final bunch. We found no significant initial losses during the first pass of filling from 0 to 100 mA. Further, few losses were seen when replacing the damped 2.1 mA bunches with full-current 4.2 mA bunches. In one instance, injecting a bunch caused a loss in another previously-stored bunch, a phenomenon that remains to be understood.

CONCLUSIONS

Argonne is proposing to replace the APS storage ring with a multi-bend achromat lattice that would require much narrower vacuum chamber apertures. A sophisticated model of collective effects has been developed and is being used to understand issues related to single- and multi-bunch instabilities. The simulations include short-range longitudinal and transverse wakes, including the transverse quadrupole wakes; long-range resistive wall wakes; monopole and dipole resonant modes of the main cavities; beam-loading and rf feedback for the accelerating mode of the main cavities; a passively-driven higher-harmonic bunch lengthening cavity; and bunch-by-bunch feedback for the transverse and longitudinal planes.

So far, simulations have concentrated on the presumably more demanding few-bunch modes, primarily the 200-mA, 48-bunch uniform fill. Results include (1) The long-range transverse resistive wall impedance will result in beam loss in the absence of transverse feedback. (2) Non-uniform patterns, such as 1+45 hybrid mode, require considerable feedback effort to maintain longitudinal stability. (3) Even larger feedback effort is needed to prevent additional beam loss in the event of a failed swap out injection. (4) Filling from zero requires transverse feedback to suppress a horizontal head-tail instability. Filling to 100 mA in 48 bunches first, then going to 200 mA, will help reduce feedback strength requirements, although the latter do not appear onerous.

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