

TRACKING STUDIES OF A HIGHER-HARMONIC BUNCH-LENGTHENING CAVITY FOR THE APS UPGRADE *

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Abstract

The Advanced Photon Source (APS) multi-bend achromat (MBA) lattice will require a bunch-lengthening cavity to decrease the effects of Touschek scattering on the beam lifetime and of intrabeam scattering on the beam emittance. Using `elegant`, we've performed tracking studies of a passive, i.e. beam-driven, fourth-harmonic cavity in the MBA lattice, including the longitudinal impedance of the ring. Studies include investigating optimal detuning, simulation of transients after loss of a bunch, simulation of effects of bunch population variation, simulation of possible non-uniform filling patterns, and simulation of filling from zero. Realistic amplitude and phase feedback of the main rf cavities is also taken into account.

INTRODUCTION

The APS MBA lattice [1] has an emittance of under 70 pm at 6 GeV. Because of the short (12.5 ps rms) zero-current bunch length, use of a higher-harmonic cavity (HHC) to lengthen the bunch is needed to reduce IBS-related emittance growth and improve the Touschek lifetime.

The HHC provides bunch lengthening by reducing the local slope of the total accelerating voltage. In the case of a passive HHC, the cavity is detuned to the positive side of harmonic n of the main rf system frequency. The voltage induced in the HHC by the beam then has a phase that reduces the slope of the time-dependent total voltage. The induced voltage and bunch shape can be computed in a self-consistent fashion as in [2].

However, such results ignore potential well distortion and the longitudinal impedance, which can best be included using a tracking code. Tracking can also include self-consistent, time-dependent interaction of the beam with the cavity mode, particularly important for a passive system, as well as higher-order beam transport effects.

SIMULATION METHODS

`Pelegant` [3, 4] was used for the tracking simulations. Although the needed features have existed in `elegant` [5] for over a decade, we took advantage of recent improvements to parallel performance [1], diagnostics, and implementation of rf feedback [6].

Eight beamline elements were used: `ILMATRIX` provides fast single-turn beam transport that incorporates longitudinal, chromatic, and transverse nonlinearities. `SREFFECTS` provides lumped simulation of synchrotron radiation. `WATCH` and `HISTOGRAM` provide bunch-by-bunch

diagnostic data. `CHARGE` provides the ability via the `modulate_elements` command to achieve a quiet start by slowly ramping the beam current. `RFMODE` simulates a beam- and (optionally) generator-driven cavity mode. This is used for both the 352-MHz ($Q_L = 9.1 \times 10^3$, $R_a/Q = 208\Omega$) main cavities and the 4th harmonic cavity. A feedback model is used to maintain the main cavity voltage [6]. This element implicitly includes the short-range wake resulting from the fundamental cavity modes. It can also be used for including cavity HOMs [7]. `ZLONGIT` simulates the short-range wake, using an impedance model based on the conceptual vacuum system design (an older version of that presented in [8]).

BASIC RESULTS

The passive HHC [9] has $R_a/Q = 108\Omega$ and two free parameters: the detuning $\Delta f_h > 0$ of the resonance from the harmonic condition and the loaded quality factor Q_L . Earlier studies showed that using $Q_L = 6 \times 10^5$ or greater gave improved stability in the presence of irregular fill patterns, so this value is used throughout.

Starting with $\Delta f_h \gg f_h/Q_L$ and progressively decreasing the detuning, increasing voltage is induced until the ideal bunch lengthening condition is achieved. Further reduction results in splitting of the bunch. Figure 1 shows the bunch duration and energy spread as a function of the detuning for two fill patterns. The difference between results for the two patterns stems from the microwave instability (MWI), which impacts 48-bunch mode significantly, lengthening the bunch to 35 ps rms even in the absence of the HHC. The MWI is also slightly suppressed by the lengthening of the bunch. Nominally, ideal lengthening to 50 ps rms occurs at about $\Delta f_h = 16.5$ kHz, which agrees well with the simulation results for 324 bunches.

Figure 2 shows the longitudinal profiles averaged over 2000 turns for two detuning values. For 48 bunches, Δf_h can be reduced beyond what is possible for 324 bunches without creating a strongly double-humped shape, a curious benefit of being well above the MWI threshold. Turn-by-turn longitudinal profiles can be used to compute the Touschek lifetime using the program `touschekLifetime` along with local momentum acceptance results [1], providing higher-fidelity results than would be obtained from using the rms bunch duration [10]. Since these show that $\Delta f_h = 13.50$ kHz is beneficial, subsequent simulations concentrate on that value.

TRANSIENTS FOLLOWING BUNCH LOSS

The inclusion of rf feedback in the simulations allows realistic modeling of fault conditions, such as a swap-out fail-

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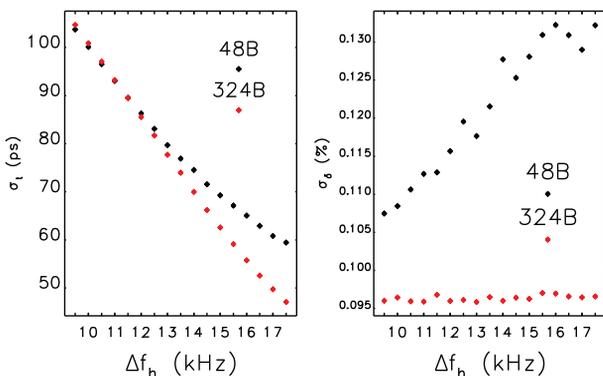


Figure 1: Rms bunch duration and energy spread vs HHC detuning for 200 mA in 48 and 324 bunch uniform fills.

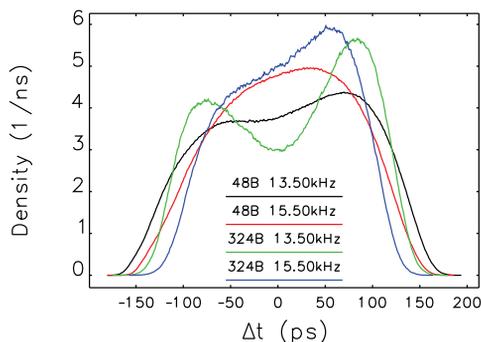


Figure 2: Longitudinal density for 200 mA in 48 and 324 bunch uniform fills, for two values of Δf_h .

ure that results in a single missing bunch from the bunch train. This was simulated by first allowing a 48-bunch fill to come into rough equilibrium, then kicking out the last bunch using the time-dependent BUMPER element. Figure 3 shows the resulting transient in the bunch durations, which are modest and do not result in any loss of beam, in spite of an artificially-low $\pm 2\%$ momentum aperture imposed on the simulations. As seen in Fig. 4 the peak-to-peak centroid shifts are 35 to 55 ps, somewhat less than the rms bunch duration, while the bunch durations themselves change by less than 10%. Overall, this should pose little problem to operations in the short time before the bunch is replaced. The transient in the main rf system (which is responsible for the phase shifts and hence the duration changes) may cause difficulties for injection of the replacement bunch, an issue that can be illuminated by simulations of filling from zero.

SIMULATION OF FILLING FROM ZERO

Because transients in the main rf system introduced by non-uniform fill patterns cause shifts in bunch timing, it is necessary to understand the beam dynamics as the ring is filled. We used the SCRIPT element to inject one bunch at a time, simulating both sequential (0, 27, 54, ..., 1269) and

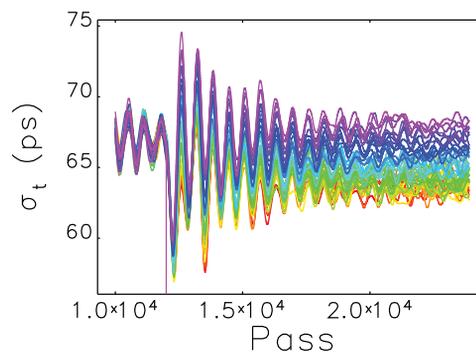


Figure 3: Time evolution of bunch durations for 47 remaining bunches after bunch 48 is kicked out at pass 12000.

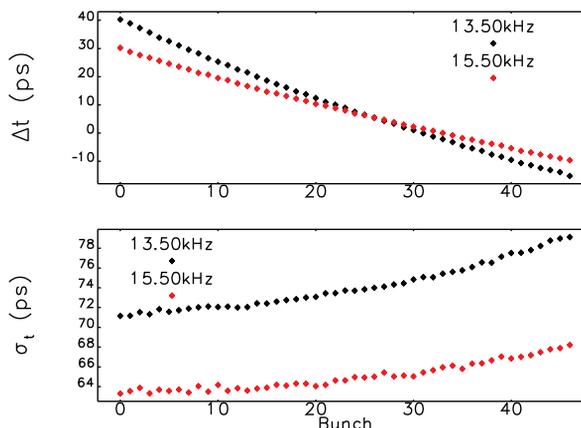


Figure 4: Centroid arrival times and rms bunch durations after re-equilibration following loss of one bunch from a train of 48.

balanced (0, 648, 324, 972, ...) fill methods. To reduce run times, bunches were injected at 10,000 turn intervals, which provides sufficient time both for damping of the bunch and settling of the rf feedback system. Given the long (100-ps rms) bunch expected from our booster, we sought to determine whether injected particles will be lost when injecting at the assumed synchronous phase rather than the synchronous phase imposed by the irregular, time-dependent rf envelope.

The sequential fill method exhibits large transients in the bunch timing, with observed shifts up to 10° (40°) of main (harmonic) rf phase. The balanced fill method is well controlled, as Fig. 5 shows. In both cases, losses are fairly small, even when imposing artificially-low $\pm 2\%$ momentum acceptance, with losses of 0.15% vs 0.06% for sequential vs balanced filling. With the HHC “fully” detuned to 136 kHz, these increased to 0.4% and 0.8%, respectively.

NON-UNIFORM FILL PATTERNS

Although the 48-bunch mode is intended to meet the needs of many timing users, non-uniform fill patterns are typically demanded as well. We explored three such pat-

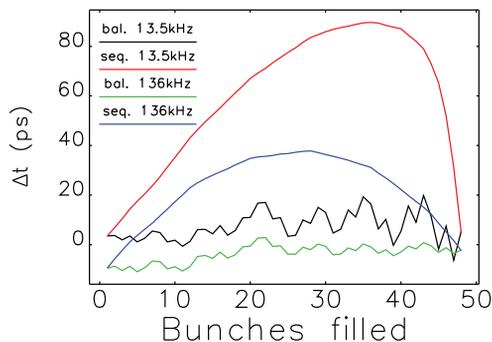


Figure 5: Timing shift of bunch 0 as other bunches are filled in sequential or balanced order.

terns using $\Delta f_h = 13.5$ kHz: 48-bunch hybrid mode 1, with one isolated bunch having $1.1\mu\text{s}$ gaps on either side; 48-bunch hybrid mode 2 with $0.66\mu\text{s}$ gaps; and 24-doublet mode, consisting of 24 uniformly-spaced pairs of bunches separated by 3 empty buckets (the same interval as in 324-bunch mode). For the hybrid modes, the large variation in the main rf voltage forces the bunches to shift in phase, resulting in greatly diminished effectiveness of the harmonic cavity, as seen in Fig. 6. In contrast, the 24-doublet mode shows highly uniform voltage and bunch durations that are fairly close to those seen in Fig. 1. The bunch shapes for 24-doublet mode, shown in Fig. 7, are significantly different for the leading and trailing bunches.

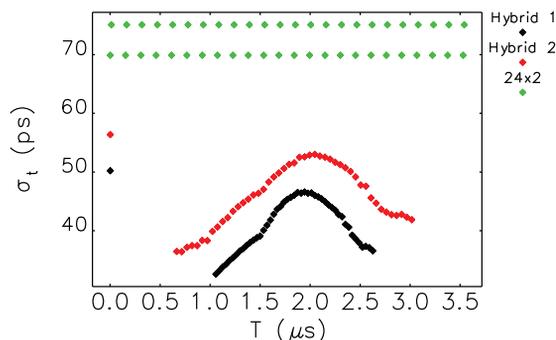


Figure 6: Rms bunch duration for each bunch in several candidate non-uniform fills.

CONCLUSION

In addition to the results shown here, simulations have been performed of the effects of insertion device gap variation, which forces the bunches to shift phase. This appears manageable but ultimately, due to several effects that change the beam phase, we may require direct measurement

and feedback on the beam phase in order to maintain the ideal phase for injection. We have also simulated the effects of bunch-to-bunch variation in charge at the 10% level

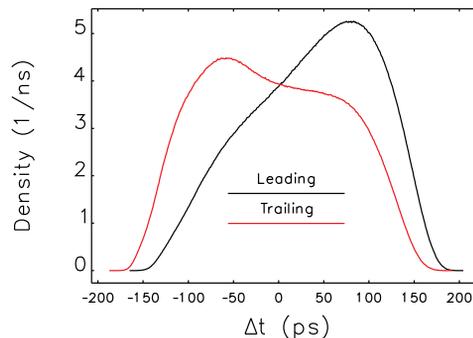


Figure 7: Longitudinal density averaged over 2000 turns for 24-doublet fill pattern.

and find that this does not cause any issues. Future studies will include re-examination of the choice of HHC harmonic (e.g., consideration of 3^{rd} and 5^{th} harmonic), as well as consideration of faster feedback to control voltage modulation due to non-uniform bunch patterns.

High-fidelity simulations were performed of a bunch-lengthening higher-harmonic cavity in the APS MBA upgrade. These included beam-loading in the main and harmonic cavities, rf feedback, and the longitudinal impedance. The HHC has the expected effect, allowing bunch lengthening to more than 65 ps rms. Simulations of a lost bunch, filling from zero, and bunch population variation showed no significant operational issues. Simulation of non-uniform fill patterns indicates that a 24-doublet pattern should be workable, but that hybrid mode is likely not.

Computations used the Blues cluster at Argonne's Laboratory Computing Resources Center.

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