ALTERNATE HYBRID MODE BUNCH PATTERNS FOR THE ADVANCED PHOTON SOURCE*

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Abstract

The Advanced Photon Source is operated for five weeks per year in a special bunch (hybrid) pattern of one large 16-mA (74-nC) bunch in a gap of 3 microseconds, and the remaining 86 mA in 8 trains of 7 consecutive bunches, forming a 500-microsecond-long bunch train. We are developing variations of this bunch pattern, which might have 3 large bunches equally spaced in the 3-microsecond gap in a 4-mA, 16-mA, and 8-mA distribution. The 500-microsecond-long bunch train could be changed to 2 or 3 bunch trains of 7 bunches. We report on the difficulties in bringing these into future operations: impedance-driven injection losses, sextupoles in injection section, lifetime and top-up injection limit, and beam diagnostics responses to the patterns.

INTRODUCTION

The Advanced Photon Source (APS) storage ring has a flexible bunch timing structure. We normally operate a stored beam of 102 mA with 24 4.2-mA single bunches symmetrically arranged around the circumference. With a revolution period of 3.68 μs and harmonic number 1296, the bunch spacing is 153 ns or 54 buckets. For APS users that require a much longer time gap around a bunch, we operate a particular bunch pattern where one 16-mA bunch is stored in the center of a time gap of 3.2 μs, and the rest of the charge, 86 mA, is stored in a train of 8 groups of 7 bunches covering 500 ns. We call this bunch pattern "hybrid" because it is a mixture of a (high-intensity) single-bunch operating mode and a general bunch train.

We received a request from APS x-ray users to study the feasibility of various alternate hybrid mode bunch patterns. One group of users wants multiple strong bunches in the 3-μs interval: 16 mA, 8 mA, and 4 mA spaced by 0.8 μs. A different group of users wants a variation of the 500-ns bunch train. These hopefully can be satisfied simultaneously, and studies were done to investigate any limitations; we eventually operated for select users for a few hours in March 2008 in one of the alternate hybrid bunch patterns.

The bunch patterns we considered are listed in Table 1 and shown in Figure 1. We divide the revolution period into two intervals: a long 3.2-μs time interval in which we inject the intense bunches, and a short 500-ns period where we inject bunch trains. The nomenclature of the bunch patterns is $n + l \times m$, where n is the number of intense bunches, with a value of 1 or 3, and $l \times m$, meaning l trains of m consecutive bunches. It is understood that the trains are spaced equally to fit inside 500 ns, or close to it.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

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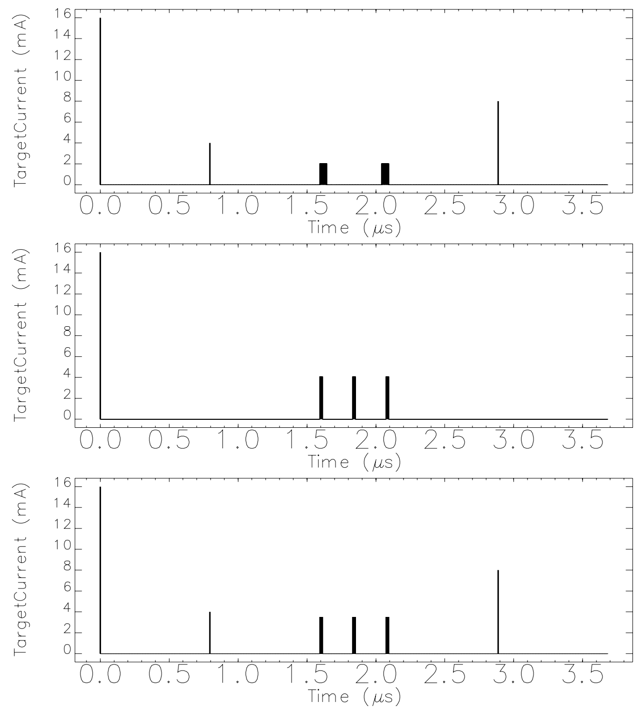

Figure 1: Bunch patterns tested.

CHROMATICITY AND LIFETIME

The main concern in the standard $1 + 8 \times 7$ hybrid-mode bunch pattern is the single-bunch injection limit. We must operate at high enough chromaticity to maintain the stability of the 16 mA. New bunches of 8 mA and 4 mA would normally be stable, obviously.

The chromaticity for hybrid bunch pattern is +11 for both planes compared to about +6 for the 24-bunch symmetric pattern. These settings do not change for the alternate hybrid patterns.

The next concern is the lifetime of the bunch pattern. The injector charge limit, top-up injection interval, and lifetime determine whether 102-mA stored current can be maintained. With constraints of 3 nC per pulse, and 60-second top-up interval, the minimum lifetime is 125 minutes.

In general we strive to improve lifetime for any bunch pattern and chromaticity. We first empirically optimize the working point by scanning the two-dimensional fractional tune space, which is a relatively quick process. This results

Table 1: Bunch Patterns Considered

Bunch patterns	Intense bunches (mA)	Bunch train current (mA)	Bunch train length (ns)	Weaker bunches (mA)	Lifetime* (minutes)
$1+8\times 7$	16	11	17	1.5	350
$3+2\times 18$	16, 8, 4	37	48	2.1	315**
$1+3\times 7$	16	29	17	4.1	215
$3+3\times 7$	16, 8, 4	25	17	3.5	260**

*Emittance is 2.5 nm-rad and coupling is set to 1.5%
**Estimate explained in the text

in a working point (ν_x, ν_y) = (36.185, 19.225) for high-chromaticity lattice that differs from that of the standard chromaticity lattice (i.e., +6 in each plane), which has an optimum lifetime at (36.14, 19.20). We can then optimize the sextupole families (and working point optionally) using simulation models with errors [1], which we have done.

Most of the studies on alternate hybrid patterns occurred during a time when there was a reversed sextupole in the ring [2], making the lifetime shorter than what would normally be possible. Thus we report either the lifetime measured after the sextupole problem was fixed, or, if the measurement is unavailable, an estimate of what the lifetime would be. The estimates are based on the measured lifetime of the 16-mA bunch under nominal conditions of Table 1 (130 minutes) and the $I^{2/3}$ scaling law for Touschek scattering rate including bunch lengthening.

EMITTANCE

A variation of emittance ratio between bunches occurs from transverse wakefields or impedance. The transverse impedance induces a charge-dependent tune depression, largest in the y-plane. Thus the bunches with different charge will have different tunes, and therefore different emittance ratios. The higher-charge bunches will have closer x- and y-tunes and therefore, higher emittance ratio. Our photon diagnostics and the general user see the weighted average of all bunches.

INTENSE BUNCHES

At a chromaticity of +11 the bunch limit is 22 mA — the limiting instability is in the vertical plane. We set the single bunch current target value at 16 mA for reliable operation. When injecting an equivalent current of 0.8 mA (3 nC) into the 16-mA bunch, the losses are about 0.2 mA (0.8 nC) or 25%. The losses are due to the horizontal wakefields produced by the 16-mA stored bunch executing some residual horizontal betatron oscillation during the injection process. Some motion is transfered to the vertical plane, and losses occur on vertical apertures. Ideally, we would set the injection kicker to produce a closed bump in which the stored beam is not perturbed. Because of the somewhat small dynamic aperture, we set the injection kickers to reduce the oscillation amplitude of the injection beam, which, regrettably, induces betatron oscillations in the stored beam. The operational settings of the injection kickers is thus a compromise between the dynamic aperture limit, which causes loss of injection particles, and wakefields produced by the stored bunch, which causes losses of both injection particles and stored particles.

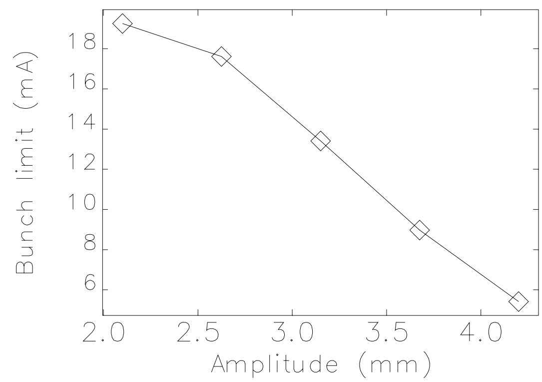

Figure 2: Bunch charge limit as a function of imparted horizontal betatron oscillation.

Figure 2 show the bunch-charge limit as a function of betatron oscillation during injection. This is measured by repeatedly pulsing the injection kickers with no incoming beam and determining the value of the largest bunch charge for which the loss per pulse remains lower than, say, 0.1 mA. According to this data the betatron oscillation for the 16-mA bunch must be limited to less than than 2.7 mm.

Early on we were surprised to find that injection into the intense bunches suffered when the 8-mA and 4-mA bunches were added. It turned out that the injection kicker bump was imparting excessive betatron oscillations to non-targeted bunches.

Some amount of oscillation is expected in our injection process because the kicker bump is along two sectors and passes through the nonlinear fields of 14 sextupoles. The original high-chromaticity sextupole settings caused the problem, with the effect unseen in the standard hybrid pattern. Figure 3 shows the measured betatron oscillation imparted on a non-targeted bunch as a function of time relative to the target bunch. Two settings are shown, one for the original sextupoles and one after a quick optimization of a pair of sextupoles in the injection sectors. For the original sextupoles, some of the bunches ahead of the targeted bunch would suffer 3.3-mm betatron oscillation, which had a bunch limit of about 12 mA, according to Figure 2. The largest effect occurs on the leading edge of a kicker waveform, where the slope is greatest. Thus the total effect is a combination of kicker waveform mismatch and nonlinear

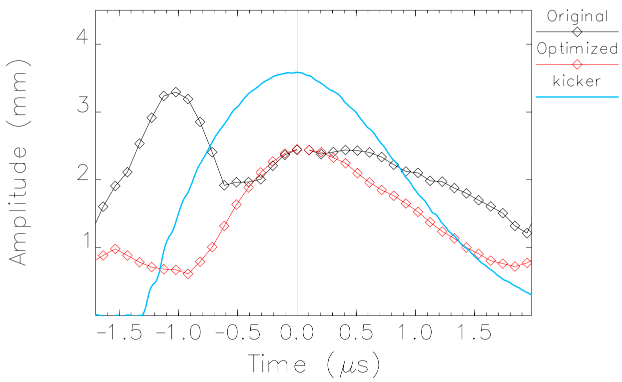

Figure 3: Betatron oscillations on non-targeted bunches as a function of time about the targeted bunch for two sets of sextupole settings. Ideal kicker waveform is superimposed.

optics.

For operations, one might optimize the sextupoles in the injection sectors to minimize the betatron oscillation amplitude. However, it is better to optimize the four sextupole families symmetrically around the ring with the criterion of maximizing dynamic aperture and momentum aperture (as mentioned in an earlier section). Fortunately, these optimized settings pose no problems for non-targeted bunches.

HIGH-CHARGE BUNCH TRAINS

We rely heavily on Bergoz narrow-band beam position monitors (BPMs) near insertion device straight sections for readings that are accurate and relatively bunch-pattern independent. However, some noise is generated internally for very non-uniform bunch patterns from the bunch train, not the intense bunches; evidently these BPMs prefer uniform bunch patterns.

The standard $1 + 8 \times 7$ hybrid-mode bunch pattern is relatively smooth compared to the alternates. For the alternate patterns we observed noise in the spectrum at particular frequencies, which varied across BPMs. These BPMs are used in orbit feedback and in monitoring orbit rms motion. We typically observe 50% higher rms orbit with the shorter bunch trains as shown in Table 2. The origin of the noise is believed to be the absence of synchronization of the button signal switching with the revolution period. An upgrade of the switching may correct the noise.

Table 2: The rms Motion as Measured by Narrow-Band BPMs in Bandwidths of 30, 100, and 767 Hz

Bunch patterns	rms motion (μm) x	y
$1 + 8 \times 7$	1.2 / 3.9 / 5.7	0.6 / 1.5 / 4.2
$1 + 3 \times 7$	1.7 / 6.5 / 19	1.1 / 2.5 / 8.9

An early concern was the amount of charge concentrated in a short time duration and the disrupting wakefields that might be produced. Fortunately this did not materialize for the bunch patterns attempted. For example, filling 50 mA in a single train of 18 bunches (part of the $3 + 2 \times 18$ pattern), which is 48.3 ns long, would increase the average density of charge by five relative to the normal hybrid bunch train. No increases were observed in the beam sizes and emittance. Also, no current-dependent instabilities or accelerator component heating were observed.

As far as transient beam-loading is concerned, most of the ring's charge (74 mA or 86 mA) is located in a time block of 500 ns. One would expect the same gap voltage variation in the 3-μs time gap for all the hybrid patterns. For the $3 + 2 \times 18$ pattern, however, we saw elevated rf cavity vacuum activity due to higher-order mode excitation. We didn't pursue the matter, because we moved on to other patterns.

Filling the 3 bunch trains of 7 bunches each for $1+3\times 7$ produced the densest distribution of charge we ever had. The current per train was 28.7 mA and the gaps were 221.6 ns long.

We tested this bunch train at low chromaticity (about +5.5) and at high chromaticity. There were no collective instabilities or elevated emittances. At low chromaticity with 1.7% coupling, the lifetime was 7 h; at high chromaticity with coupling of 1.4%, the lifetime was 2 h, a sharp decrease, but not unexpected.

With the orbit feedback loops closed for either chromaticity case, the rms values were a lot higher (1.6 μm in each plane) than for the standard (low-chromaticity) 24-bunch pattern. Bunch trains of double the number of bunches and with half the bunch charge were well behaved. Thus the noise in the narrow-band BPMs emerge somewhere in between.

USER TIME

There were two short periods of user time with $1+3\times 7$ in January 2008 for 5 hours with 30-s top-up interval and in March 2008 for 6 hours with 60-s top-up interval. The lifetime in the first case was only 85 minutes due to an unknown sextupole problem. This lifetime didn't satisfy the 125 minutes requirement for 60 second top-up. Thus we needed a 30-second top-up interval. In the second run the sextupole was fixed and we ran normally with a good lifetime of 215 minutes.

SUMMARY

We tested some alternate hybrid bunch patterns that had variations on the single bunch and on the bunch trains. We discovered some potential problems for operations during studies. We delivered some beam time to a user interested in very dense bunch trains.

REFERENCES

[1] M. Borland *et al.*, these proceedings.

[2] L. Emery *et al.*, these proceedings.