UPGRADE OPPORTUNITIES AT THE ADVANCED PHOTON SOURCE MADE POSSIBLE BY TOP-UP OPERATIONS*

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Abstract

The default running mode of the storage ring at the Advanced Photon Source is top-up injection with a horizontal emittance of 3.0 nm-rad and a coupling of 2.0%. For a stored current of 100 mA in 23 bunches the lifetime is 7 h. The ability to run in low beam-lifetime conditions gives us the opportunity to make upgrades that would otherwise be futile. Some of the possible upgrade paths are presented here, such as lower emittance and higher-current operation.

1 INTRODUCTION

The Advanced Photon Source (APS) has been providing beam for x-ray users in top-up mode since October of 2001. The top-up running mode is scheduled for 75% of the time, while non-top-up mode is scheduled the other 25%.

In the past four years we have increased the brightness of the user beam through three major changes. First, the β_y of the storage ring (SR) straight section was reduced from 10 m to 4.5 m (this also increases the vertical acceptance of a 5 mm internal vertical aperture insertion device (ID) chamber and reduces transverse instabilities from the narrow gap impedance). Then a low-emittance optics was developed by introducing a non-zero dispersion in the straight section, as the European Synchrotron Radiation Source did earlier [1]. And finally, top-up [2] was implemented as the default operating mode. Top-up not only increases the average brightness but makes the beamlines more stable by reducing thermal transients of the usual 12-h or 24-h refill cycles.

Those were relatively easy improvements to the storage ring brightness and operation, and brought no serious trade-offs in other aspects of operation. Future storage ring enhancements may involve trade-offs, however. For example, a further reduction in emittance or increase in total current may significantly reduce the lifetime. Though this may be countered with an increase in the number of bunches, we would like to make the present few-bunch operation available in the future as much as possible, with top-up pushing the practical operating lifetime limit downward.

We present a list of possible SR improvements with their possible trade-offs and show how top-up can help shift the trade-off balance.

Other improvements under consideration at APS, such as longer straight sections, orbit stability, and beam size stability, are not related to top-up and won't be mentioned any further.

Not all of these improvements will necessarily be implemented, as APS and its users continue to prioritize their needs.

2 PRESENT RUNNING PARAMETERS

We maintain a total current of 102 mA by injecting a single bunch from the 7-GeV injector into the ring every two minutes. The 2-min interval is fixed during operation to allow the users a consistent warning time for an upcoming injection.

Automatic processes control the timing of the injection and select the bucket in which to inject the single bunch to maintain a desired pattern as much as possible. The bunch pattern we have been using since June 2001 is a train of 23 bunches spaced 150 ns apart with a gap of 300 ns before the first bunch. We occasionally run a special operating mode where we fill one bunch with 5mA and fill the rest of the charge in 56 bunches in a 500 ns window opposite the single bunch, leaving a 1.5 μsec gap on either side of the 5 mA bunch. Figure 1 illustrates the bunch patterns.

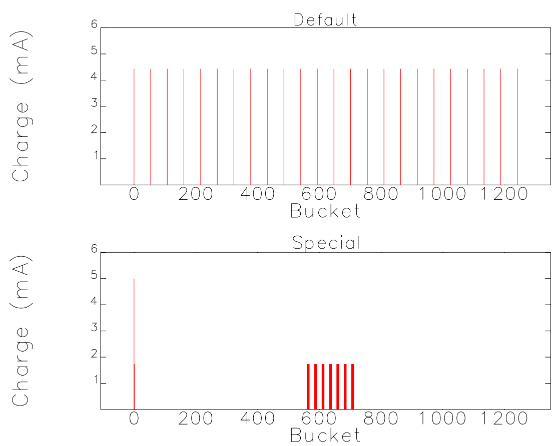

Figure 1: Default and special bunch patterns.

We have the choice of operating two focusing optics, the high-emittance optics (i.e., the original lattice) and the low-emittance optics. Once an optics is selected, the lifetime of the beam can only be adjusted with the bunch pattern, vertical emittance (through vertical dispersion and skew quadrupole settings), and bunch length, given that the lifetime is dominated by the bunch particle density.

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The high-emittance optics, used for non-top-up operation, has an emittance of 7.5 nm-rad and zero-dispersion in the straight section. With 23 bunches and a coupling of 2%, the beam has a lifetime of 20 h, sufficient for non-top-up operation. The low-emittance optics, used in top-up operation, has a measured emittance of 3.0 nm-rad with gaps closed to user settings, and 0.12 m dispersion in the straight section, giving an effective emitance of 3.3 nm-rad, with effective emittance defined as $\epsilon_{\rm eff} = \sigma_x \sigma'_x = \sqrt{\epsilon\beta + (\eta\sigma_E)^2}\sqrt{\epsilon/\beta}$ where $\alpha_x = 0$. For the same bunch pattern and coupling, the beam has a lifetime of about 7 h. The lifetime reduction is consistent with calculations for those lattices using the observed momentum aperture.

The number of bunches in the standard bunch pattern is, for now, rigidly set by management. The vertical emittance could be set to lower values for higher photon beam brightness and smaller injection losses, but most users' beamlines cannot make use of the potential additional brightness. We presently use the vertical emittance as a knob to adjust the lifetime to a desired value. The bunch length is mostly determined by the charge in the bunch through potential well distortion. We can optimize the lifetime slightly with the rf gap voltage, so that the bucket height matches the nonlinear momentum aperture.

The 2-min top-up injection interval was determined by consensus with the users (top-up injection produces a short-lived perturbation on the stored beam).

The possible operating beam lifetime in top-up is limited by the top-up interval and the injector charge per injection cycle. The injector charge is limited by safety hardware for now, but could be improved in the future. If in the future we operate a lattice or fill pattern with much lower lifetime, the injector capacity will have to be increased.

3 FUNDAMENTAL TRADE-OFFS

The desired improvements basically require an increase in particle density in a bunch, keeping the bunch pattern constant. The lifetime will be reduced in inverse proportion to the density. At a low enough lifetime in non-top-up mode, we would no longer operate effectively and the bunch pattern would have to change to more bunches.

In top-up mode, we have the option of not only changing the bunch pattern, but increasing the injector charge and decreasing the injection interval. We adjust the injector charge first, since this doesn't require user approval. The required charge from the injector is given by

$$Q[\mathrm{nC}] = \frac{6.25\ \Delta T[\mathrm{min}]}{\tau[\mathrm{h}]\ \eta_{\rm inj}}, \qquad (1)$$

where ΔT is the injection interval, τ the stored beam lifetime, and $\eta_{\rm inj}$ is the storage ring injection efficiency, which may vary from 0.8 to 1.0, depending on the setup of the incoming trajectory and the coupling in the storage ring. At some point the injector will not be able to keep up with the beam decay. Then the injector interval ΔT could be decreased.

To reduce injection losses and ID radiation damage we should operate with a minimum coupling or close to it. A very low coupling will produce a lower lifetime, which can be countered in top-up with the trade-offs mentioned above. In non-top-up mode, we would have to inject into a very low coupling configuration, then change it to a higher coupling for the rest of the store.

We are considering adjusting the lifetime by increasing the vertical emittance with a vertical wiggler yet to be designed, which is a more direct method than perturbing the vertical dispersion with skew quadrupoles. This has the advantage of freeing up the skew quadrupoles for x-y coupling minimization only, which will improve injection capture. Thus injection losses and low lifetime don't necesarily have to be traded off.

4 SR IMPROVEMENTS

The possible improvements that could be pushed further, by top-up are reduction of horizontal emittance, higher total current, and higher bunch current.

Since top-up injection allows us to run at lower lifetime, we'll report mainly on SR improvements and operating modes that reduce the lifetime of the beam.

4.1 Lower emittance

The easiest type of upgrade is simply rematching the optics of the ring for a minimum emittance with present power supply and magnet constraints. During recent machine studies, we installed an optimized effective emittance optics, and measured a $\epsilon_{\rm eff}$ of 3.0 nm-rad for the straight sections. Other parmeters are ϵ = 2.5 nm-rad, ν_x=36.2, ν_y=19.27. (The current operating lattices have ν_x=35.2, ν_y=19.27.) The β functions in general were also given upper limits to minimize nonlinearity and impedance effects. The optics optimization was done using `elegant` [3], which can optimize $\epsilon_{\rm eff}$ directly. The lifetime was slightly lower than that of the standard "low-emittance" beam of the SR, but still within present top-up operating limits. This optics will probably be ready for default operation in September 2002. Figure 2 shows the lattice functions.

To reduce the emittance further one would have to install new hardware for the dipole magnets (pole face windings) for adding a gradient. The model emittance is significantly reduced (ϵ = 1.2 nm-rad, $\epsilon_{\rm eff}$=1.8 nm-rad, ν_x=46.2, ν_y=32.27.) The lifetime will certainly decrease because of the higher nonlinearity. Figure 3 shows the lattice functions.

4.2 Higher current

The photon absorbers in the storage ring and the rf system were designed for a 7 GeV stored current of 300 mA. Most of the ID front ends can handle 130 mA from an APS undulator A at a gap of 10.5 mA, though some front ends have been designed for double undulators, which makes

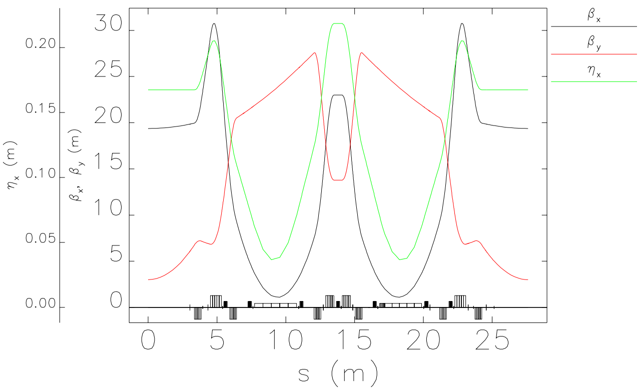

Figure 2: Machine functions of a lower emittance lattice cell for APS.

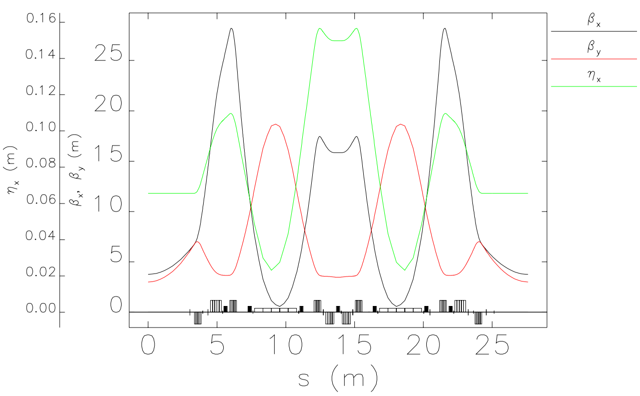

Figure 3: Machine functions of a much lower emittance lattice cell with gradients in the dipole.

these capable of much higher current from a single undulator. We have run the ring briefly at 200 mA, and found no serious problems with the accelerator systems. We recognize that a limit must be placed on the peak current of the bunches, as the ceramic vacuum chambers for the injector kickers heat up significantly and have a temperature limit of 200° C. The ceramic temperatures therefore limit the bunch patterns to those with many bunches, reducing the effectiveness of timing-experiment users.

We have delivered beam in 23 bunches at a lower total current of 130 mA in top-up mode for a few hours. Lifetime was 5 h, and the injector at times could not keep up with the required charge of 3.6 nC every two minutes. We could trade off the 2-min interval with a shorter one and comfortably operate with this bunch pattern at 130 mA.

4.3 Higher charge per bunch

We operate occassionally with a special bunch pattern with one bunch at 5 mA (below the instability limit), and many other bunches far away in time. The 5 mA bunch would be all that is available for the timing experimenter. We could reach a higher current limit than we presently have achieved by getting stronger sextupoles, by getting a feedback system, or even by accepting a slightly higher horizontal emittance. In any case, the lifetime of this bunch will differ from the rest by a large factor. The top-up process will ensure that the bunch pattern stays as uniform as possible by injecting more often in the high charge bunch.

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