SIMULATION OF SWAP-OUT RELIABILITY FOR THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

The proposed upgrade of the Advanced Photon Source (APS) to a multibend-achromat lattice relies on the use of swap-out injection to accommodate the small dynamic acceptance, allow use of unusual insertion devices, and minimize collective effects at high single-bunch charge. This, combined with the short beam lifetime, will make injector reliability even more important than it is for top-up operation. We used historical data for the APS injector complex to obtain probability distributions for injector up-time and down-time durations. Using these distributions, we simulated several years of swap-out operation for the upgraded lattice for several operating modes. The results indicate that obtaining very high availability of beam in the storage ring will require improvements to injector reliability.

INTRODUCTION

An important reliability consideration for the APS Upgrade is whether the APS injector is able to provide pulses for swap-out [1,2] at an interval of 5 to 15 seconds. We can get some indication of this by looking at the top-up downtime performance of the injector This is an imperfect measure because the top-up interval is typically 60-120 seconds. Downtime shorter than this, e.g., a momentary trip that is quickly reset, may be invisible. However, we think it is relatively rare that trips are reset rapidly compared to the 8 s data logger interval for the relevant quantities.

Drawing on data collected since 2004, we computed three quantities: (1) The injector unavailability, defined as the ratio of the time during which the injector failed to provide beam for top-up to the total planned for top-up operation. (2) The durations of all top-up outages. (3) The durations of all periods of continuous top-up. The details of analyzing the data from the data logs to reconstruct the required probability distributions are highly APS-specific and may lack general interest. Hence, here we only quote some results of the analysis. As shown in Fig. 1, we found that the injector unavailability has been fairly constant over more than a decade, with occasional excursions to the high and low side. The median unavailability within a run is 1.1%. The worst is over 5%, while the best is below 0.2%.

The unavailability results are interesting, but they don't tell us whether we have many short-duration events or a few long-duration events. To analyze this, we perform additional analysis, which involves finding the duration of all continuous segments for which top-up is disabled when it should have been enabled. This is shown in Fig. 2. The

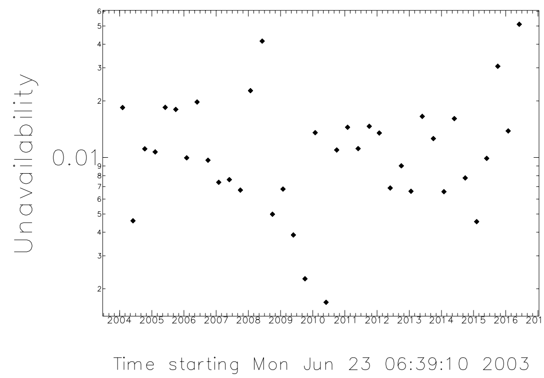

Figure 1: APS injector top-up unavailability over 3-month-long runs starting in 2004.

median outage duration is 150 s, much longer than the expected 5-15 s interval between swap-out injections needed for APS-U. Hence, with present performance we can expect to have to make up the beam current by injecting at a higher rate for a while after each outage. A typical 150 s outage will require injecting at 1 Hz for 10 to 30 s to make up the missed shots. A related quantity is the length of uninterrupted top-up, the distribution for which is shown in Fig. 3. Note that the archive has data sampled every 8s, so the cumulative distributions start there.

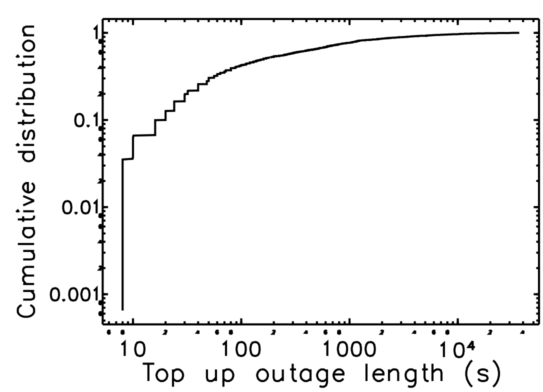

Figure 2: Cumulative distribution of top-up outage duration for all APS runs from 2004 to present.

SIMULATION OF SWAP-OUT

Combining the probability distributions shown in Figs. 2 and 3 allows simulating swap-out operation. To do this, we wrote a C-language program `swapOutSim`, with which

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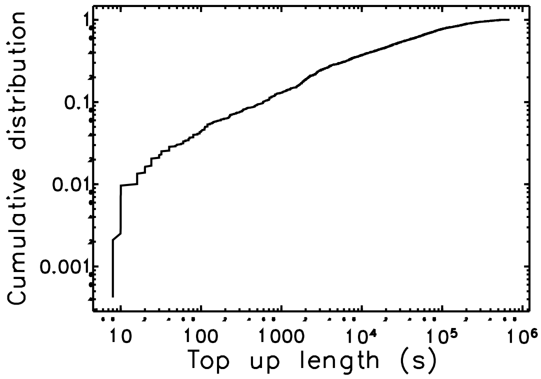

Figure 3: Cumulative distribution of continuous top-up duration for APS all runs from 2004 to present.

we were able to simulate several years of APS-U operations with various fill patterns and rf options. The program has a variety of commandline controls for parameters involved in the simulation, including (1) The target number of bunches N_b. (2) the target beam current I_T, which we set to 200 mA. (3) The desired fractional current regulation r. $r = 0$ would mean attempting perfect regulation at I_T. We used $r = 0.01$. Injection of bunches occurs when the current is below $I_T(1-r)$. (4) The allowed "droop" D in the current in any bunch before replacement. We used $D = 0.1$. (5) The beam lifetime τ, assumed to be independent of beam current. (6) The drop rate d, which defines what fraction of injection shots result in loss of the stored bunch without injection of a new bunch. We used $d = 0.01$, in rough agreement with the typical unavailability. (7) The fractional jitter level j for the captured bunch current. We used $j = 0.05$ [3]. (8) The simulated duration S. We used $S = 6$ days, corresponding to a 1 week run bracketed by machine intervention time (as in present APS operations).

In brief, the algorithm involves sampling the top-up uptime and downtime distributions in alternating fashion to simulate machine operation. Independent random number generators are used for sampling the uptime distribution, the downtime distribution, the drop-out distribution, and the injected charge jitter distribution. The algorithm is designed to inject at a 1-Hz rate until the target current has been reached. Thus, it fills rapidly when injector downtime ends and injects right away to make up for a dropped bunch.

We assumed 36 six-day user periods per year, giving 5184 h of user operation per year. We simulated 5 years of operation for each of the following cases, where τ_T is the lifetime and $\kappa = \epsilon_y/\epsilon_x$:

- 48-bunch mode
  - $\tau_T = 2.4$ h, for $\kappa = 1$ with 352-MHz rf.
  - $\tau_T = 5.0$ h, for $\kappa = 1$ with 117-MHz rf.
- 324-bunch mode
  - $\tau_T = 10$ h, for $\kappa = 1$ with 352-MHz rf.
  - $\tau_T = 33$ h, for $\kappa = 1$ with 88-MHz rf.
  - $\tau_T = 5$ h, for $\kappa = 0.1$ with 352-MHz rf.
  - $\tau_T = 17$ h, for $\kappa = 0.1$ with 88-MHz rf.

These values are from detailed simulations for the 67-pm APS upgrade lattice [4], using methods reported in [5] and [6]. Several rf frequency choices are under consideration; the low-frequency choices are of interest because of the long lifetime. In all cases, a higher harmonic cavity is assumed, at the appropriate frequency. The gas scattering lifetime was assumed to be 60 h [7].

Fig. 4 shows the first simulated week of operation for the two basic patterns, i.e., 324-bunch mode and 48-bunch mode with round beams. We note that the 48-bunch mode data is relatively noisy, a result of occasional dropped shots. The dropped-shot probability is of course the same for 324-bunch mode, but the contribution of each bunch is much smaller and harder to notice.

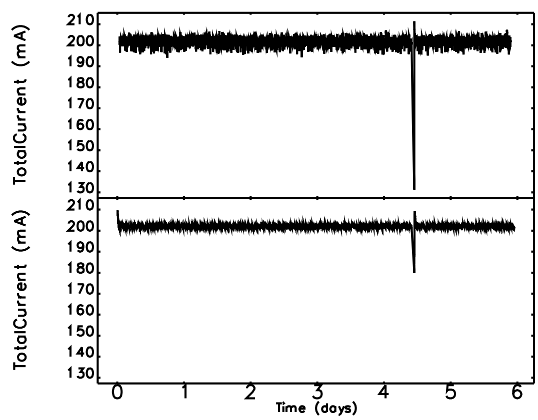

Figure 4: Total current vs time for the first week of simulated operation for 48-bunch (top) and 324-bunch (bottom) modes with round beams and existing rf systems.

With these results, we can evaluate various performance metrics. For example, it is interesting to determine the fraction of the time that the total current is below a specific fraction of the 200 mA target. Anecdotally, a reduction of more than 10% from the nominal current creates difficulties for sensitive users, so we can set 180 mA as a threshold below which we count the ring as unavailable. Figure 5 shows distributions of weekly unavailability for the operation modes described above. The data exhibit a consistent advantage for the cases with low-frequency rf or round beams.

In operations, we might set ourselves the goal of being above 180 mA 98% of the time. We can use the data in Fig. 5 to predict how likely this is to happen for each fill pattern and rf configuration. As shown in Table 1, the odds are greatly improved by the use of low-frequency rf and round beams. Even so, it is hard to get extremely high success rates. Note that we are only considering unavailability caused by the injector; the storage ring systems will make

Table 1: Fraction of runs for which predicted unavailability of 180mA is below 1% or 2%

Mode	Success fraction for 1% Unavail.	Success fraction for 2% Unavail.
324B-Round-88MHz	0.892	0.944
324B-Flat-88MHz	0.822	0.935
324B-Round-352MHz	0.772	0.897
48B-Round-117MHz	0.682	0.844
324B-Flat-352MHz	0.648	0.822
48B-Round-352MHz	0.611	0.789

their own contribution. Recognizing this, we might consider raising the requirement to 99% of the time for injector-related unavailability, which makes the relative advantage of low-frequency rf even more evident.

We can also use the data to compute the cumulative distribution of injection intervals, which is related to the probability that an experiment lasting *t* seconds can be performed without an injection event occurring. An injection event will be seen by the users as a 1-2% drop in brightness that recovers after about 50 ms. The data shown in Fig. 6 show a significant advantage for low-frequency rf and round beams.

It's particularly interesting that in the cases with the shorter lifetime or many bunches, injection takes place at 1-second intervals up to 20% of the time. This seems to be sensitive to the injected charge jitter in the few-bunch cases. In the many-bunch cases, it seems only weakly sensitive to the drop rate or charge jitter. More tuning and exploration of the algorithm might yield some improvements in this, but it seems likely that users will simply have to adapt to frequent irregular injections.

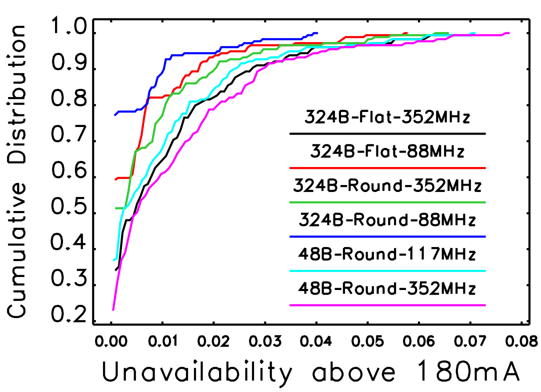

Figure 5: Cumulative distribution of unavailability of 180 mA for different fill modes and rf choices.

CONCLUSION

We analyzed 12 years of data from APS operation to determine trends in injector availability and distributions of injector up- and down-time durations. A new program,

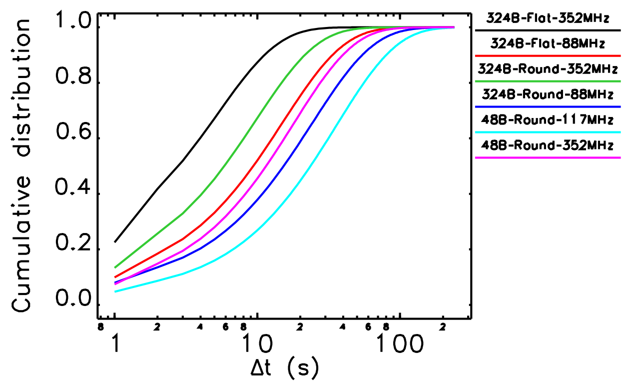

Figure 6: Cumulative distribution of interval between two swap-out shots for different fill modes and rf choices.

`swapOutSim`, was written that allows using these distributions to perform Monte-Carlo simulation of swap out. We find that it will be challenging to achieve the kinds of availability we have now, even ignoring the contribution of storage ring systems. Mitigating strategies include using round beams, improved lattice correction, relaxed beam current regulation, low-frequency rf, injector reliability improvements, and lowered expectations.

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