

Top-up Scenarios for SPEAR 3

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Summary: SPEAR 3 is scheduled to inject in the top-up mode with photon beam line shutters open in the near future. This note investigates top-up scenarios (top-up period, shots per cycle, etc) based on projections for the electron beam lifetime in the main ring and performance of the injector.

Storage Ring Parameters: 500ma, 5A-hr

$$\text{Electrons @ 500 ma} \quad N_t = It_{rev} = \frac{(0.5)(780 \cdot 10^{-9})}{(1.6 \cdot 10^{-19})} = 2.4 \cdot 10^{12} e^-$$

$$\text{Charge @ 500 ma} \quad C_t = 384nC$$

$$\text{Stored Energy @ 500 ma} \quad E = IV\Delta t = (0.5)(3 \cdot 10^9)(780 \cdot 10^{-9}) = 1.2kJ$$

$$\text{Average Power Loss} \quad P = \frac{\Delta E}{\Delta t} = \frac{1.2kJ}{(10)(3600)} = -32mW$$

Injection Parameters: 10Hz repetition rate, 1W in BTS, $\epsilon=100\%$ efficiency

$$\text{Fill Power (20 min fill)} \quad P = \frac{1.2kJ}{(20)(60)} = 1W \quad (25 \text{ ma/min/W})$$

$$\text{Electrons/Booster Pulse} \quad N_{inj} = \frac{P\Delta t}{eV * e} = \frac{1W \cdot 0.1s}{3 \cdot 10^9 eV * 1.6 \cdot 10^{-19}} = 2.08 \cdot 10^8 e^-$$

$$\text{Charge/Booster Pulse} \quad C_{inj} = N_{inj} \cdot 1.6 \cdot 10^{-19} = 33pC$$

$$\text{SPEAR Current/Booster Pulse} \quad I_p = \frac{N_{inj}}{t_{rev}} = \frac{(2.08 \cdot 10^8)(1.6 \cdot 10^{-19})}{(780 \cdot 10^{-9})} = 0.043ma$$

$$\begin{aligned} \text{Booster Pulses for 500 ma} \quad N &= 10 / s \cdot 60s / \text{min} \cdot 20 \text{ min} = 12,000 \\ N &= 500ma / 0.043ma = 12,000 \end{aligned}$$

$$0.1\% \text{ beam decay time (5 A-hr)} \quad t = 0.001\tau = 0.001(10)(3600) = 36 \text{ sec}$$

$$\text{Booster Pulses for 0.1\% decay} \quad 12,000/1000 = 12 \text{ pulse}$$

SPEAR 3 Top-up Nomograms

Figure 1 shows the percentage current ripple as a function of Amp-hr and top-up period. For a typical value of 5 Amp-hr, a top-up period between 60 and 180s produces current ripple similar to the ALS and APS (few tenths of a percent). Figure 2 shows the same data in a transposed form to yield top-up period as a function of Amp-hr and percentage current ripple. A 60 s top-of period yields a current ripple of about 0.2%.

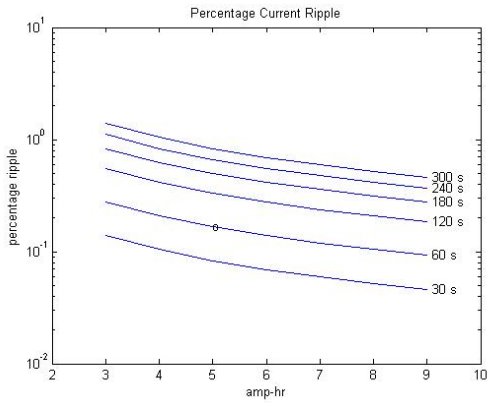


Figure 1: percentage ripple

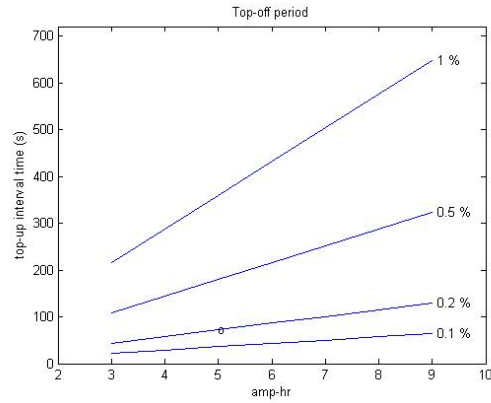


Figure 2: top-up period

Figure 3 shows the number of 10 Hz injector pulses as a function of Amp-hr and top-up period. The plot assumes 1W average power in the BTS (33pC@10Hz) and 100% injection efficiency. The injection time in the 10Hz injector mode is the number of injector pulses/10 sec. The point at 5 A-hr, 60 s top-up period is used in the example below (~25 pulses per top-up cycle). Figure 4 shows the total charge required to top-up for a given value of Amp-hr and top-up period (interval between injections). Top-up intervals on the order of 60 sec require <math><1\text{nC}</math> total injected charge.

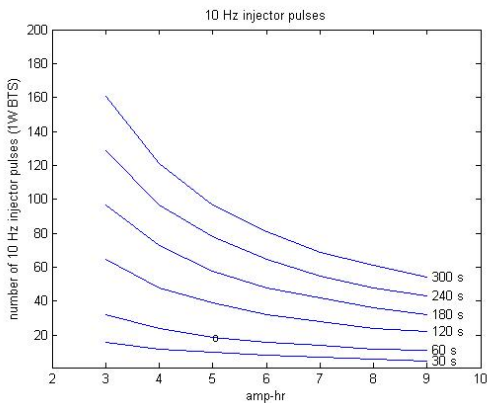


Figure 3: Number of 10Hz pulses

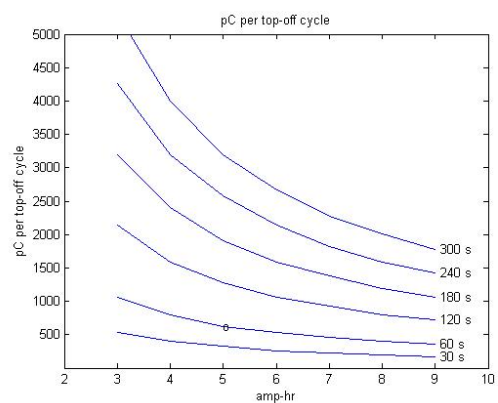


Figure 4: pC per top-up cycle

Example I: 10Hz Injector Top-up Scenario for SPEAR 3

Consider 500mA, 5 A-hr, 0.2% current ripple, 10 Hz injector and 1W in the BTS.

top-up period:	2*36s = 72 sec
current loss:	500*0.02=1 ma
charge loss:	768pC (4.8x10 ⁹ e ⁻)
charge per BTS bunch	33pC
bunches per top-up	~25
time per top-up:	2.5 sec
fractional injection time:	3.5%

Example II: Annual Electron dose in SPEAR 3

From above, a 500mA, 5 A-hr electron beam loses -32mW DC in the top-up mode. 32mW at 3GeV is a DC current of 0.032/3 x10⁹=10.6pA. (6.7x10⁷ e-/sec)

The annual electron loss is
 (6.7 x10⁷)*(3600)*(24)*(300)=1.7 x10¹⁵ electrons per 300 day year.

This is in line with previous electron beam loss estimates (few 10¹⁵ per annum).

Appendix I: Fill-on-Fill Top-up in SPEAR 3

A phase I top-up option keeps the photon beam line shutters open while periodically injecting ‘fill-on-fill’ at intervals of several hours to maintain high average current and constant heat load on the optics. The parameter space for this option is displayed in Figures 5 and 6 where the beam current decay curve has been approximated by

$$I_o(t) = \frac{I_o}{1 + \frac{I_o t}{Q}}$$

to take into account significant deviations from exponential. Figure 5 shows the injection top-up time with the 10 Hz injection scheme delivering 1 W power in the BTS. Figure 6 shows the same plot in terms of total injected charge per fill.

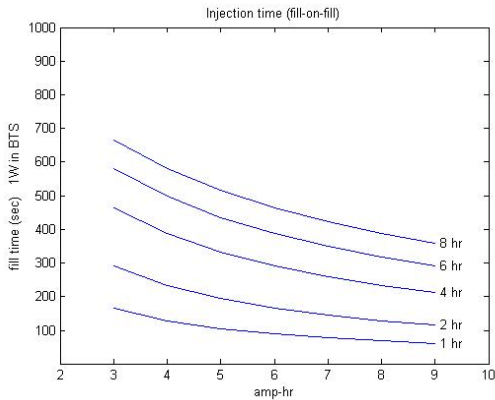


Figure 5: Top-up time

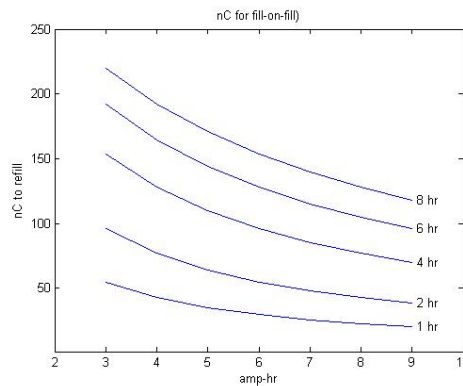


Figure 6: nC per top-up cycle

Appendix II: ALS Top-up (ALS Top-up Review, November 22, 2004)

The Advanced Light Source is engaged in a \$5M top-up upgrade that includes migration to higher currents (400→500 ma) and reduction in vertical beam size (150→30 pm-rad). 5 pm-rad has been achieved in beam studies. A bunch cleaning system will be installed in the booster to maintain pure bunches for the two-bunch timing mode of operation. The transition to top-up will have minimal negative impact on the users with all major upgrades occurring the nominal 2 month shutdown periods. The result of the top-up program will be a factor of 2 higher time-averaged current and less than half the present vertical beam size.

The nominal top-up parameters include 1.5 ma injected current in a train of 10 bunches on a 30 second top-up clock (0.3% current ripple). The 1.5 ma charge transfer will occur in 10 500 MHz rf buckets during a single booster cycle. Gating will be supplied for experiments sensitive to top-up transients. Injected currents exceeding 1.5 ma/shot have been observed but reduced efficiency is anticipated with IDs closed and vertical chamber half-gaps on the order 2.5 mm. Since the 1.9 GeV ALS beam is Touschek dominated (presently ~8 hr lifetime at 400 ma) it is expected the total injected beam current will increase in the top-up mode. The anticipated beam lifetime in the 500 ma top-up mode is 3 hr (1.5 A-hr). Estimates indicate that in an 8-hour period the total injected beam current will be on the order of 1.5 A as compared with 0.2 A in present operation.

Appendix III: APS Top-up (Emery, March 28, 2005)

With 100 ma circulating current in 24 buckets, the APS injects a 2.5 nC/0.5 ma top-up pulse once every 120 sec ($\tau=7\text{hr}$, $Q=0.7\text{ A-hr}$) in a single shot. The injected pulse keeps the peak current steady to about 0.5%. 1% would be adequate in terms of thermal effects on the optics in the majority of cases. A gate is applied 10 ms prior to the pulse and again 20 ms after the pulse (~2 damping times). Only one injection pulse is applied every 120 sec. If a second pulse were required, an additional 1.02 s delay would be needed (1 Hz booster). For SPEAR, the additional delay would be on the order 0.12 s (10 Hz booster). The rising edge of the APS septum magnet pulse (~5 ms before charge pulse) and the intentionally mis-matched kicker magnets perturb the closed orbit of the APS beam during each injection cycle.

The 2.5 nC injection pulses are formed by accumulating 3-5 linac macropulses in the positron accumulator ring (PAR). Each linac macropulse contains approximately 40 s-band buckets or ~0.9nC. The 0.9 nC/bunch figure could be used in the feedback loop on RF gun parameters but due to slow thermal settling times top-up rates are controlled by adjusting the number of linac macropulses in each injection cycle (3 or 4 or 5 macropulses/cycle). The PAR can deliver up to 6nC/cycle but runs into limitations above that level.

The 1,100 m APS storage ring can be filled in approximately 75 s. The BTS power level is $2.5\text{ nC} \times 1\text{ Hz} \times 7\text{ GeV} = 17\text{ W}$. Note that a SPEAR injector pulse has only 30pC/shot at 10 Hz and SPEAR can take up to 240 sec to fill with 1W in the BTS and 100% capture

efficiency. The difference lies the capability of the PAR to compress a ~10 m long s-band macropulse into a single 500 MHz RF bucket and capture efficiencies in the two systems. The PAR capture efficiency is about 70% due to limitations in momentum acceptance. The remaining APS transfer efficiencies (transport lines, booster, main ring) are near 100%.

It is interesting to note that initially each APS bunch has 4.5 ma current yet after the first 0.5 ma top-up pulse the first bunch goes to approximately 5.0 ma and so on. The picket fence gets out of sorts over time with any individual bunch currents varying in the range ~4-5 ma. In the 'hybrid' mode of operation, an 8 ma bunch is isolated by ~1.5 μ s but has a Touschek limited lifetime of only 3-4 hr. The resulting current variation in the 8 ma bunch is again considerable.

Injection efficiency is always a concern and must be compensated with feedback on the linac macropulses delivered to the PAR. If injection efficiency drops dramatically, it is usually possible to fix the problem by referring to history buffers rather than stop and tune. Hence, it is of utmost importance to have all systems running reliably with correct signal monitoring to keep top-up running smoothly. The booster supplies operate on a linear ramp. Top-up was first delivered to APS users in September, 2001 after accelerator development shifts and test runs with users. Since then there have been several full weeks of continuous top-up operation.

Motion of insertion devices continues through the 20 ms gate-out period.

The APS bunch pattern is measured with a fast digitizer with 750 MHz sampling rate. The master RF clock is used to control the ADC's and all buckets are sampled so charge spill can be detected. The entire pattern is calibrated against the DCCT measurement of total current. Buckets with $I_b \sim 0$ are neglected in the calibration procedure to eliminate the effects of noise and digitization error yet charge spill must be monitored. Although the RF clock is accurate, phase error can occur as the digitizer switches from bucket to bucket. Signal delay and amplitude variation through the variable attenuator can also change in time.

An EPICS sequencer is used to control the high-level system. The timer counts down from 120 seconds each injection cycle triggering various electronic and watchdog systems. The injector is activated 5 sec before each injection cycle and the bunch-clearing system in the PAR is activated. It is important to have many monitor systems and EPICS alarms active because you don't want to watch performance of the top-up system constantly. Top-up is 'quite high on the conscious' of accelerator physicists and engineers at the APS. Pulses can be missed and bunch clearing must be monitored on a regular basis. Process variables keep track of $\Delta I/I$, charge transport through the injection system, injection efficiency, etc. When injection efficiency goes to zero (it has at the APS) history buffers are used to monitor power supply performance. Usually the problem is steering.

It is important from an accelerator physics point of view to lobby for frequent top-up pulses. Users logically will want long intervals between top-up but by establishing a short top-up interval in the beginning it is easier to compensate for drift in system efficiencies. The storage ring operation scenario may also change in the future (low coupling, small gap devices, heavier beam loading, etc) requiring more frequent injection to minimize current ripple.

As an interim solution prior to delivery of pure top-up, the APS used frequent fill-on-fill with shutters open for approximately one year in advance of 'top-up'.

Appendix IV: SLS Top-up

The SLS started operations in August, 2001 with top-up from the beginning. With a beam energy of 2.4GeV and 4.8nm emittance the Touschek lifetime is on the order of 3-4 hr. ID chambers as small as 4 mm total gap have been installed in the main vacuum chamber.

The SLS injector starts with a 90kV DC gun followed by a buncher sequence to produce a 500MHz train of 1ns pulses. The pulse amplitude structure has about 1% purity. Following a 100MeV linac, charge is injected into a 270m concentric booster operating at 3Hz. At 2.4GeV, the booster emittance is 7nm-rad and the energy spread is 0.08%. Switch-mode power supplies are used to control the booster magnets. Digital power supply control allows single-cycle operation for top-up. A 400ma fill in the main ring can take as little as 3 minutes. Using the SPEAR figure of 25ma/min/watt, the booster must put out about 5W. On a single-shot basis, the booster injects 0.1-0.5ma, or 9-45nC (comparable to the 1W value of 33pC at SSRL).

A premium is placed on maintaining uniform bunch pattern to the level of a few percent in the SLS. In order to achieve this scenario, a precise timing system, flexible controls and sophisticated diagnostics are required. If the bunch pattern becomes 'ragged', the beam becomes unstable and non-linearities in the RF BPM processors compromise FOFB operation. Variable current levels in the bucket pattern also produces differences in bucket lifetime.

An APD has been installed on the optical diagnostic beam line to monitor filling patterns. The output of the APD is connected to a 2GHz digitizer without filtering or amplification in between. The fill pattern is averaged and the bucket numbers sorted according to charge. The SLS control system calculates the duration to the next top-up cycle and the timing system synchronizes all components and subsystems together. Low charge bunches are filled first in the subsequent top-up cycle. By maintaining clean 'picket fence' bucket patterns, orbit oscillations have been eliminated and the RF front end non-linearity reduced so that FOFB is more stable.

Two top-up modes have been tried at the SLS: (1) Frequent injection at 2-4 minute intervals. Frequent injection is triggered when the current falls below a prescribed level.

(2) Single bunch injection mode on a rapid-fire clock (rate not specified). The users appear to prefer the frequent injection mode.

Quote EPAC04 after 3 years of top-up experience: 'The requirements of top-up operation are rapidly changing with new ideas for experiments coming up'.