Upgrade Opportunities at the Advanced Photon Source Made Possible by Top-Up Operations

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Top-up Injection

- Inject a little beam at a time to maintain constant total current
- Default operation mode since Oct. 2001
- Schedule 75% of user time
- Report from users: very positive and anecdotal, i.e. No need to adjust x-ray optics during week of running.

SR Improvements

- Past improvements were easy, no physical trade-offs.
  - Reduced β_y from 10 m to 4.5 m
    - Increased brightness
    - Increased vertical acceptance for 5 mm ID VC
    - Reduced single bunch instability threshold
  - Low-emittance optics (3.9 nm-rad, effective)
  - Top-up

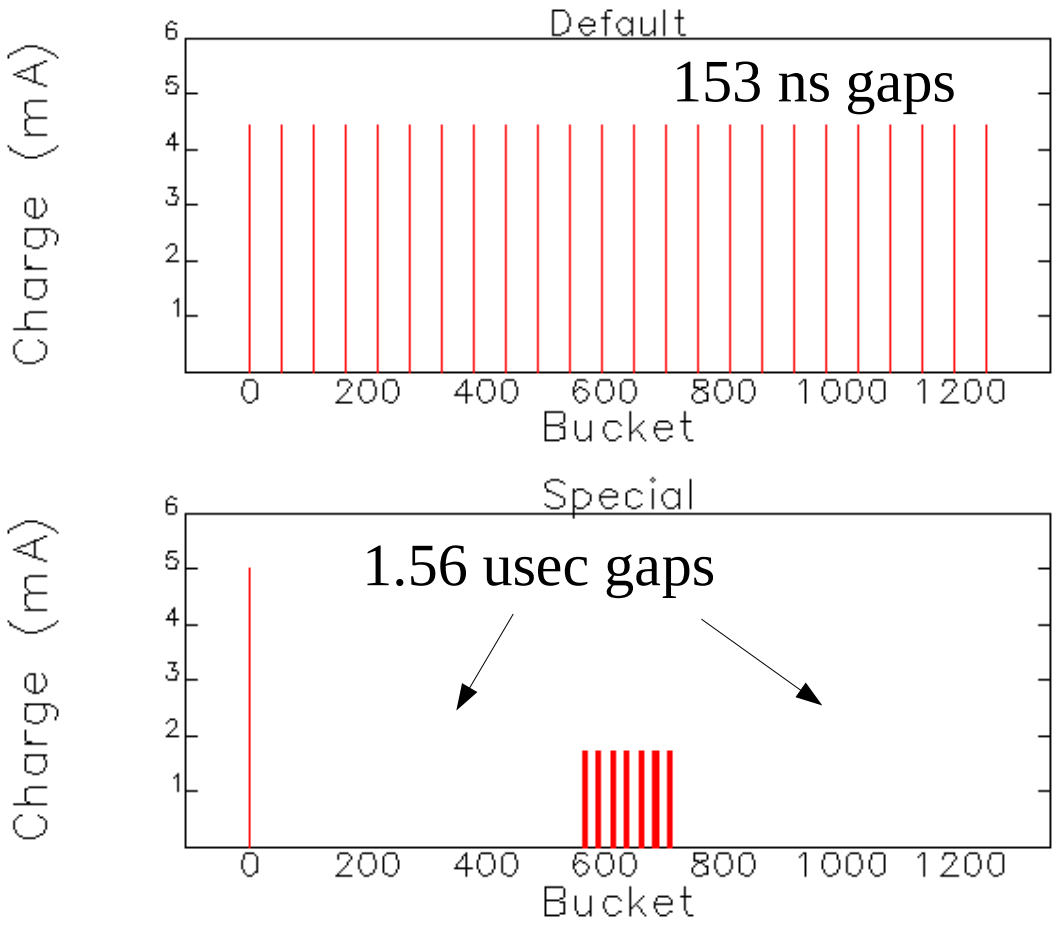
Next Improvements in Brightness

- Emittance and current
  - Want to keep same bunch pattern of low number of bunches
  - Will reduce lifetime

Present Running Parameters

Energy	7 GeV
Current	102 mA
Bunch pattern	23 bunches
Injection interval	2 min
Injector bunch	One bunch, 3.7 nC max.
Injector emittance	130 nm-rad (i.e.,large)
Injection efficiency into SR	80%-100%
SR optics	Low-emittance
SR effective emittance	3.9 nm-rad
Lifetime	7 h for 2% emittance ratio

Present Bunch Patterns in Top-up



Used in last week of each run

Lifetime for Given Optics

- Values measured for different optics (low- nand high-emittances) consistent with calculations
- Bunch pattern
  - Rigidly set by management for now (for timing experiments)
- Vertical emittance
  - Adjusted with using skew quadrupoles whole keeping x-y coupling low.
  - Determined by length of filling cycle, e.g. 12-h or 24-h cycle, gives about 20 h

Lifetime for Given Optics

- Vertical emittance (cont'd)
  - Higher value: increases lifetime
  - Lower value: increase brghtness and decrease injection losses
  - Beamlines can't use potential decrease in vertical beam size $\Rightarrow$Very low value not needed.
- Bunch length
  - Bunch charge dependence
  - Optimize lifetime slightly with rf voltage to match momentum aperture.

Operating Lifetime Limit

- Non-top-up:
  - Determined by length of filling cycle, e.g. 12-h or 24-h cycle, requires at least about τ of 20 h.
- Top-up:
  - Determined by injection interval, charge per injection cycle, e.g. 5 h for APS

$$\tau_{limit} = 6.25 \Delta T\,[min] / \eta_{inj} Q_{max}\,[nC]$$

Fundamental Trade-offs

- Injection loss and radiation damage
  - High emittance ratio (for lifetime) means higher losses
  - If we operate with minimum ε_y, or close to it $\Rightarrow$ Increase injector charge, decrease injector interval or increase number of bunches
  - Idea to eliminate trade-off: Adjust lifetime with vertical planar wiggler to increase while keeping xy coupling small with skew quadrupoles.

Fundamental Trade-offs

- High bunch density means low lifetime
  - $\tau \sim \sigma_x \sigma_y \sigma_z / Q$
  - Further reduction in lifetime:
    - Non-top-up mode, must be countered with increase in number of bunches
    - Top-up mode, increase injector charge, decrease injector interval, increase number of bunches, e.g.,

$$Q_{inj}[nC] = 6.25\,\Delta T[min] / \eta_{inj}\,\tau[h]$$

SR Improvement Enabled by Top-up

- Reduction in ε_x
- Higher total current
- Higher bunch current

Lower Emittance I

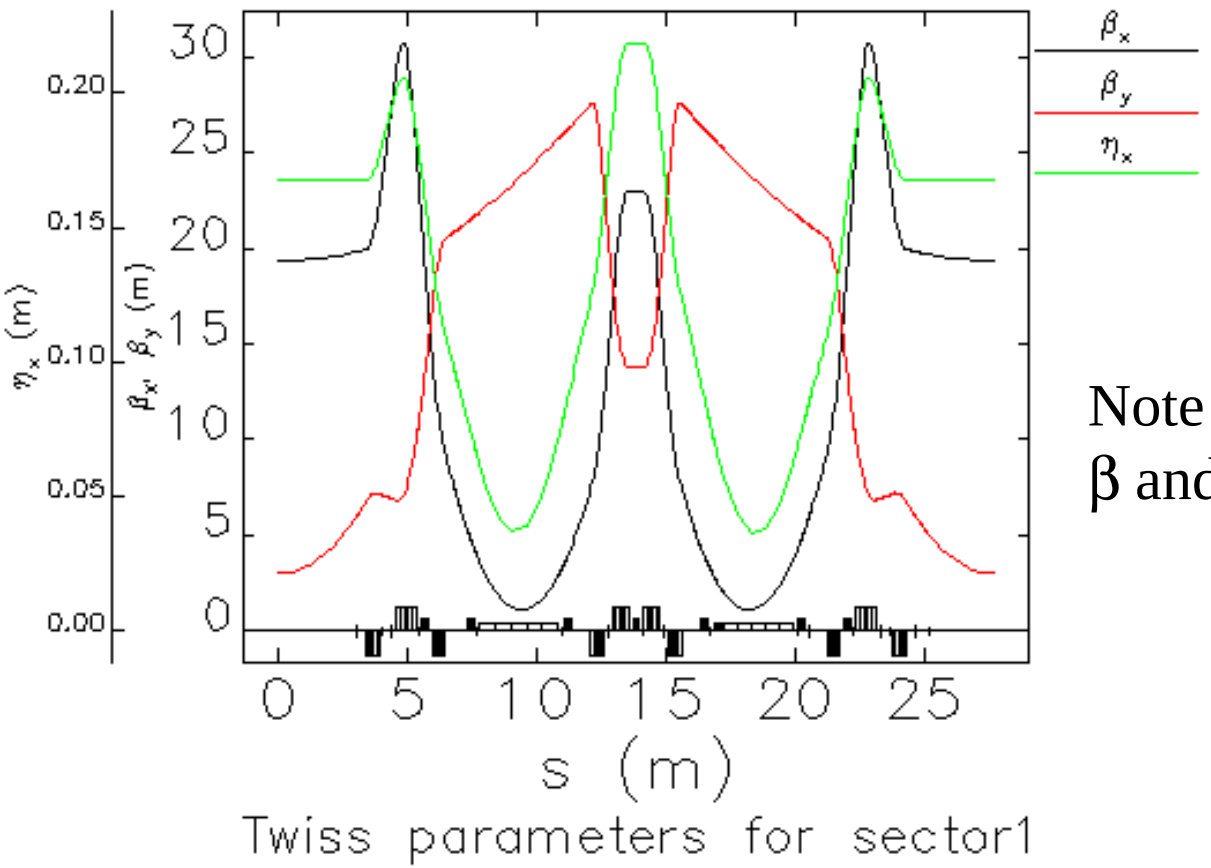
- Simply rematch for minimum effective ε_x with present power supplies and magnets as constraints

$$\epsilon_{x,eff} = \sigma_x \sigma_{x'} = \sqrt{\epsilon_x \beta_x + (\eta_x \sigma_E)^2}\sqrt{\epsilon_x / \beta_x}$$

- Program elegant optimizes effective ε_x directly

Model emittance	2.5 nm-rad
Measured emittance	2.5 nm-rad
Model effective emittance	3.0 nm-rad
(nux, nuy)	(36.2, 19.27)

Lower Emittance I



Note symmetric
β and η in dipole

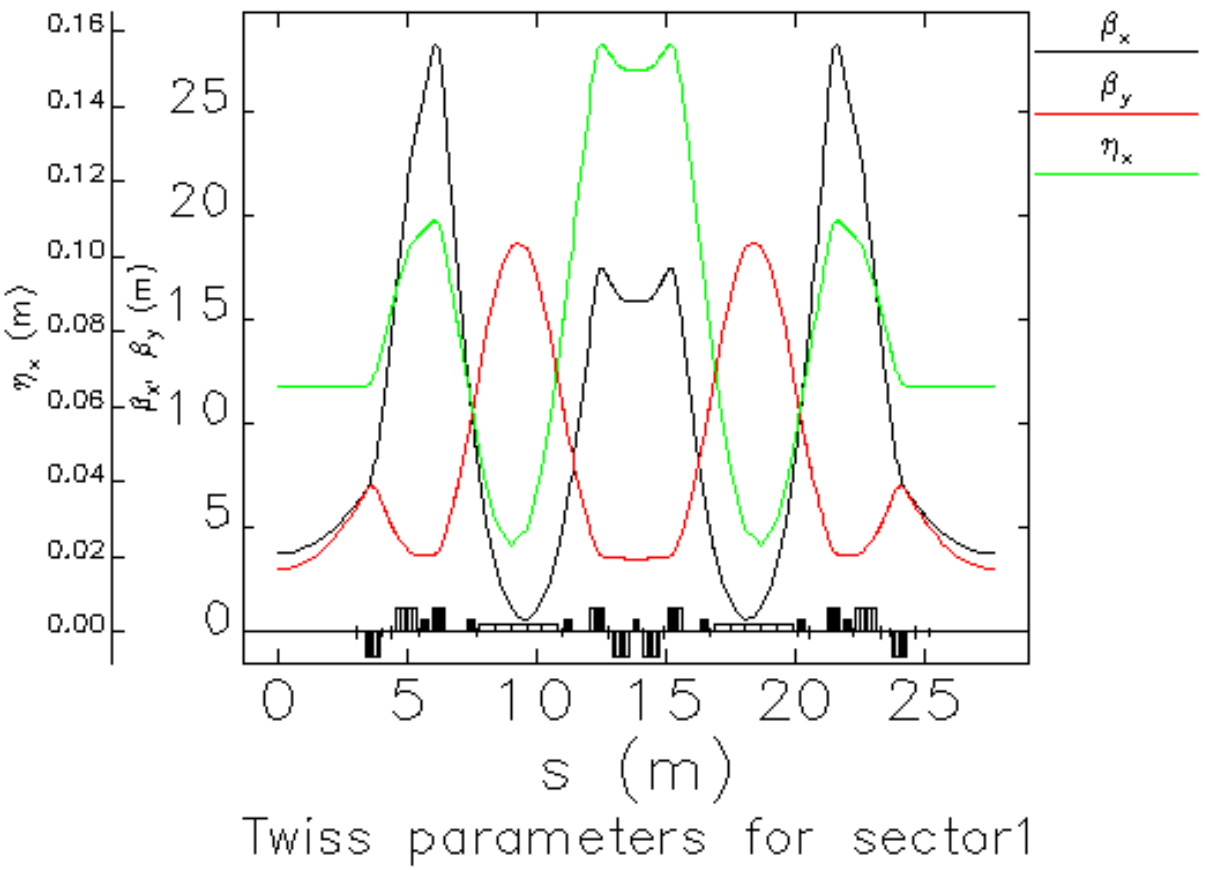
Lower Emittance II

- Add gradient to dipole with pole face windings. No other magnets or power supply require change.

Model emittance	1.2 nm-rad
Model effective emittance	1.8 nm-rad
(nux, nuy)	(46.2, 32.27)

- Lifetime for 23 bunches and 2% emittance ratio will be about 2.5 h.

Lower Emittance II



Higher Beam Current

- SR photon absorber limited at 300 mA
- ID front end handles 130 mA for undulator A at 10.5 mm gap.
- Run once with gaps open and many bunches at 200 mA with no serious problems.
- Need limit on peak current for the ceramic chambers of injection kicker magnets $\Rightarrow$ change bunch patterm
- Delivered beam for users during machine studies: 130 mA, 23 bunches, 5 h lifetime,
  - Limited by injector charge

Increased Bunch Current

- Single bunch instability threshold is about 8 mA. Use 5 mA in special bunch pattern.
- In special bunch pattern, 5 mA is all that is available for timing experiments.
- Get higher bunch charge by getting stronger sextupoles, feedback system, or accepting a higher emittance.
- Lifetime differs from rest of bunches.
- Top-up maintain bunch pattern by injecting more times in single bunch $\Rightarrow$ Much lower lifetime for one bunch is acceptable