Automated Commissioning for the APS-U

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APS brightness will be increased by a factor of 500 after upgrade

- APS is an 1104 m-long synchrotron light source in operation since 1995
- APS operation was stopped in April 2023 for 1 year to perform an upgrade of its storage ring
  - Everything in the SR tunnel will be replaced with exception of rf cavities
  - Injectors are not being upgraded
- SR lattice is changed from 2-bend achromat to hybrid 7-bend achromat[1] with reverse dipoles[2,3]
- 5-fold stronger quadrupoles and 7-fold stronger sextupoles

Quantity	APS Now	APS MBA Timing Mode	APS MBA Brightness Mode	Units
Beam Energy	7	6		GeV
Beam Current	100	200		mA
Number of bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Horizontal Emittance	3100	32	42	pm·rad
Emittance Ratio	0.013	1	0.1	
Horizontal Beam Size (rms)	275	12.6	14.5	μrad
Vertical Beam Size (rms)	11	7.7	2.8	μrad
Betatron Tune	35.2, 19.27	95.1, 36.1		
Natural Chromaticity	-90, -43	-130, -122		

[1]L. Farvacque et al., IPAC'13
[2]J. Delahaye and P. Potier, PAC'89
[3]A. Streun, NIM-A 737, 148

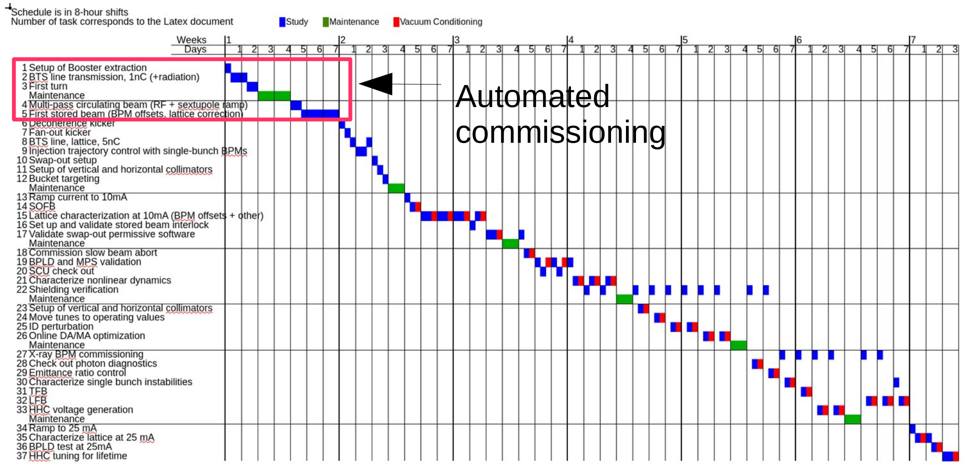
Automation is key to fast commissioning

- Total “dark time” length is 1 year; APS-U will have to be commissioned in 3 months
- We have extensively simulated lattice commissioning
  - Lattice commissioning is everything from first injection to lattice correction
  - Lattice commissioning is commissioning with low beam current – does not include bunch lengthening cavity, bunch-by-bunch feedbacks, etc.
- Simulations are crucial to identifying required commissioning steps and algorithms
  - Initial goal of simulations was to demonstrate that the actual commissioning is possible
  - Statistical plots later are typically based on commissioning simulation of 200 error sets
- Automated commissioning stemmed from automated commissioning simulations
- We see automation as one of main keys to fast commissioning

Automated commissioning covers only a small part

- APS-U commissioning is a multi-step process that will take 7 to 13 weeks and involve a lot of people
  - The result of the commissioning will be 50 mA operation with user acceptable parameters – lifetime, swap-out, orbit stability and control, IDs, etc
- Automated commissioning software will perform only a first few steps of the commissioning:
  - Transfer line, first turn correction, stored beam
  - Lattice correction
- The tasks covered by automated commissioning take the first week of the commissioning schedule
- I will describe steps that are used in this automated commissioning

APS-U commissioning plan



Major lattice commissioning steps

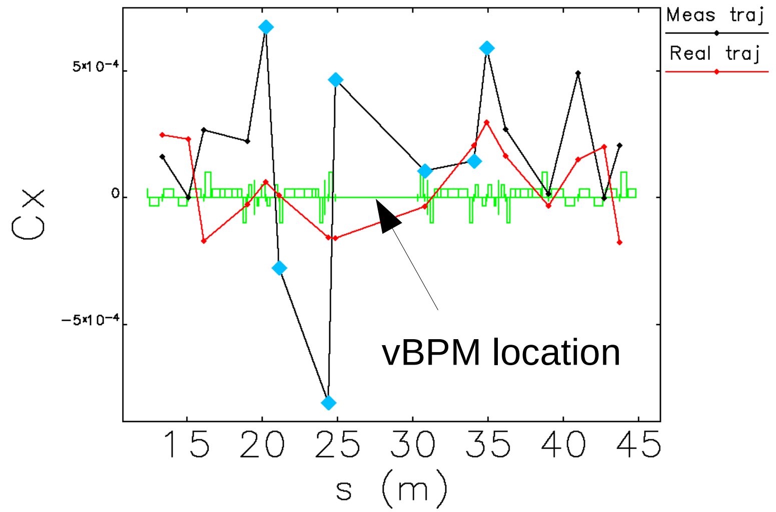
- Initial settings: lattice is set to (95.18, 36.23) instead of design (95.10, 36.10), sextupoles are turned off, RF turned off
- BTS trajectory correction (including first SR sector)
- First-turn trajectory threading
- Global trajectory correction to get a few dozens of turns
  - RF is turned on
- Sextupole ramp
  - Results in stored beam
- Orbit correction
- Lattice correction, coupling minimization
- Coupling adjustment to 0.1 emittance ratio, tune shift to 0.10

Many more sub-steps, will elaborate later

Virtual BPM is used in many cases

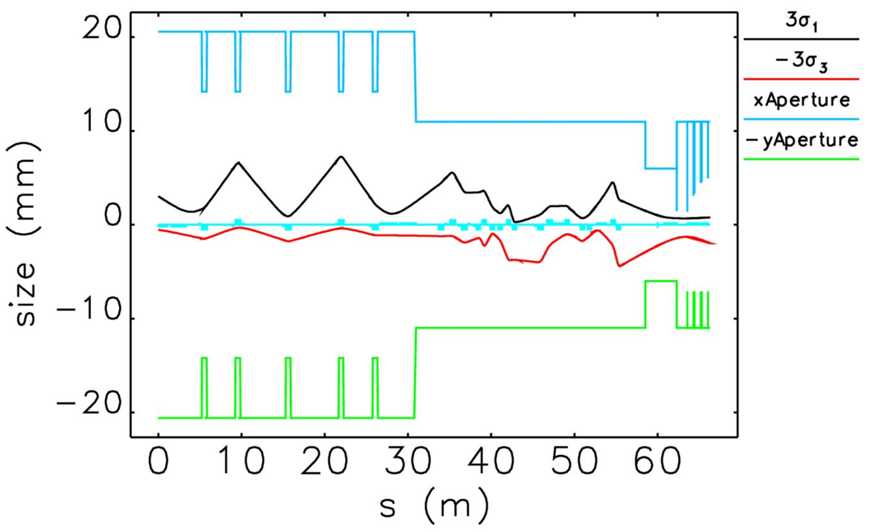
- vBPM-based threading is introduced because traditional corrector-to-BPM threading didn't always work
- Uses several real BPMs and ideal transfer matrices to derive position and angle at a location in the lattice (virtual BPM)
  - Takes lists of X and Y BPMs and their readings, returns coordinate vector (x, x', y, y')
- Uses a number of correctors upstream to correct position and angle on vBPM
- vBPM approach is used in:
  - Trajectory threading (in BTS and SR)
  - Injection coordinate corrections (into BTS, into SR)
  - Transmission optimization when threading fails to advance (in BTS and SR)
  - Equalizing end-of-first-turn coordinates to injection coordinates (in SR)

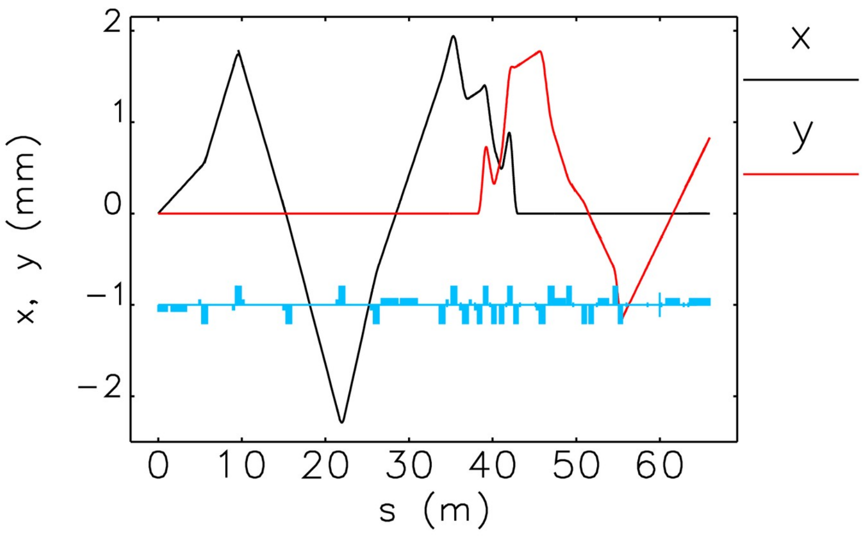
Large expected BPM offset errors (500 μm rms) in combination with very strong quadrupoles complicate trajectory correction



Booster-To-Storage ring (BTS) trajectory correction

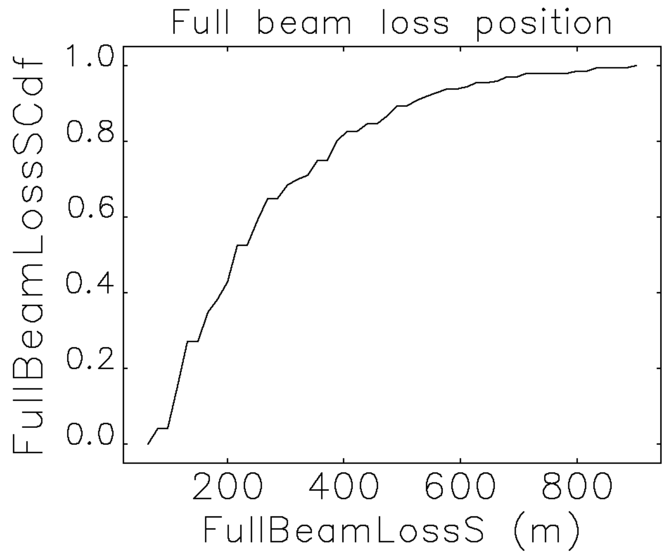
- Exciting new BTS features: 2.86 mm full horizontal gap at the exit and emittance exchange
- Start with SR kickers turned off (pulse is 22 ns-long)
- Global trajectory correction in large-aperture old BTS part
- vBPM threading along the rest of BTS
  - If needed, transmission optimization
    - Maximizes BPM sum signal on first 2 SR BPMs
  - Results in beam reaching first 2 SR BPMs
- Turn kickers on and scan timing of each kicker
- vBPM correction on first 2 SR BPMs
  - The beam goes through the first SR sector
- BPM timing scan for the first SR sector





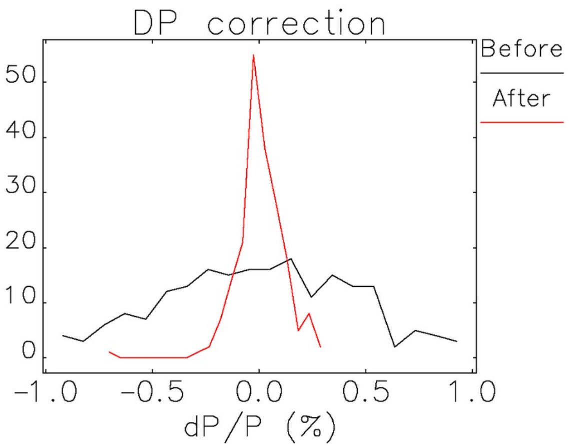
First-turn correction

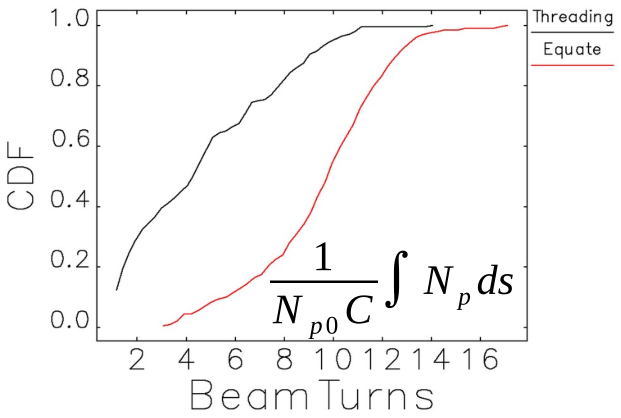
- Correct injection coordinates
  - vBPM at SR entrance using BPMs of the first SR sector
  - Correction uses correctors in BTS and SR kickers
- vBPM threading along the ring
  - vBPMs placed in the middle of Insertion Device straight sections (smallest gaps, 40 straight sections)
  - Correction on a vBPM is performed using a number of H and V correctors upstream (usually 10 correctors per plane, SVD)
  - As beam transmission extends to next sector, runs BPM timing scan for that sector
  - Analyzes trajectory for bad BPMs on every correction iteration
    - Looks for spikes/zeros in position/sum signals
    - Compares expected trajectory change due to applied correctors with measured trajectory change and looks for spikes



First-turn correction (continued)

- Beam energy error is calculated using **x·η/η·η** when the beam reaches half the ring
  - Booster extraction energy is adjusted
- If vBPM threading fails, uses optimization program to pass through a sector
  - vBPM failure could happen for very unlucky BPM offset error combination
- After first-turn threading is completed, the beam goes through ~5 turns
- Equalizing end-of-first-turn trajectory to injection trajectory allows to double transmission
- First-turn correction results in ~10 turns



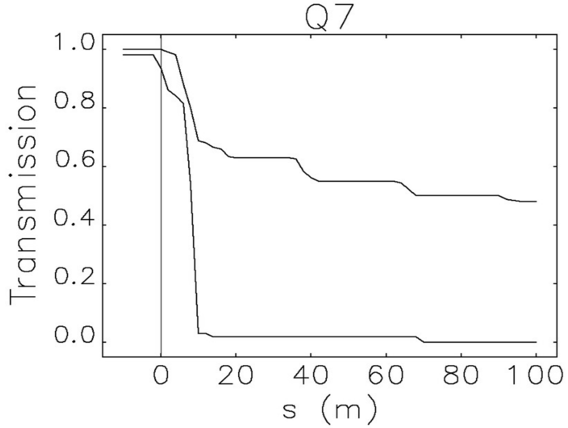


First-turn correction – extra steps

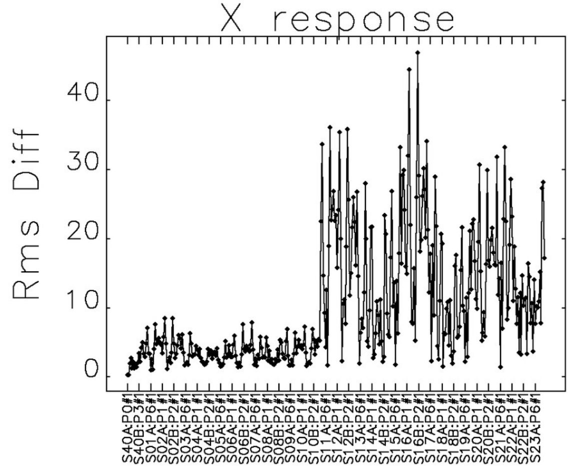
- Collect 10 repeated trajectories to look for bad BPMs based on trajectory noise
- Check corrector polarity one by one using correlation with ideal response (400 correctors per plane)
- Measure BPM offsets using trajectory, if requested

- If first-turn correction failed or transmission is below 80%, analyze for bad quadrupoles/obstructions:
  - Measure trajectory response using 6 correctors per plane in first sector (averaging needed), then abort
  - Manually review trajectory response, fix magnets/obstructions, restart the entire program
  - Detects a reversed quad within half a sector with 90% certainty

25th and 75th percentile transmission in case of reverse polarity quad



Rms response difference from ideal response



Tunnel shielding verification

- While first-turn correction studies are performed, user beamline upgrade work is suspended, because no personnel allowed on the experimental floor without shielding verification
- Shielding verification is dumping the injected beam at various locations and measuring radiation outside the tunnel
- Shielding verification will be performed after the first-turn correction is completed
  - Sextupoles are still off – the lattice is linear
  - Allows the beamline upgrade work to resume as early as possible

Global trajectory correction

- Trajectory/orbit correction is performed by a program with input parameters (among many)

  “-measMode <traj|orbit> -correctionMode <traj|orbit>”

- “-measMode traj -correctionMode orbit” means quasi-closed orbit correction
- Loops over singular values and corrector configurations from small to large
- Every few iterations the following steps are performed:
  - Check for stored beam
  - Adjust injection coordinates towards closed orbit (-correctionMode orbit)
  - Adjust tunes
  - Adjust RF settings (phase and frequency)
  - Ramp sextupoles if requested

Getting to stored beam

- Global trajectory correction:

  ```
  trajCorrection -measMode traj -correctionMode traj -targetBeamTurns 20
  ```

  - Turns on RF and performs initial setup (Booster to SR phase scan)
  - Measures and adjusts tunes (trajectory response-based, 0.05 rms accuracy)
- Quasi-closed orbit correction to increase number of turns:

  ```
  trajCorrection -measMode traj -correctionMode orbit -targetBeamTurns 80
  ```

  - Adjusts RF frequency and phase; adjusts tunes
- Sextupole ramp:

  ```
  trajCorrection -measMode traj -correctionMode orbit -rampSextupoles 1
  ```

- Quasi-closed orbit correction until stored beam is found:

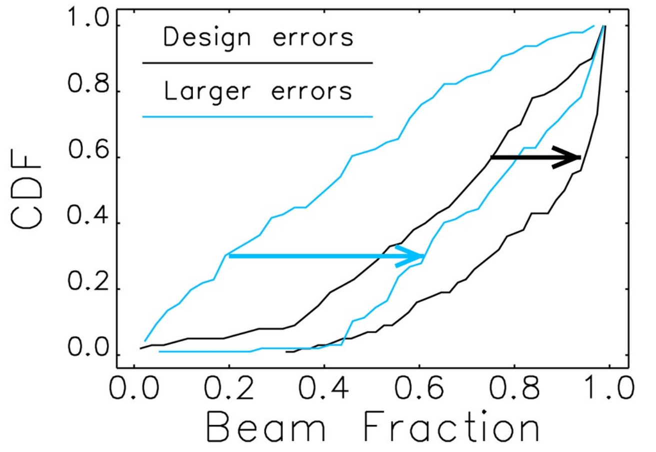
  ```
  trajCorrection -measMode traj -correctionMode orbit -targetBeamTurns 200
  ```

- In most cases, this procedure results in stored beam

If failed to reach stored beam:

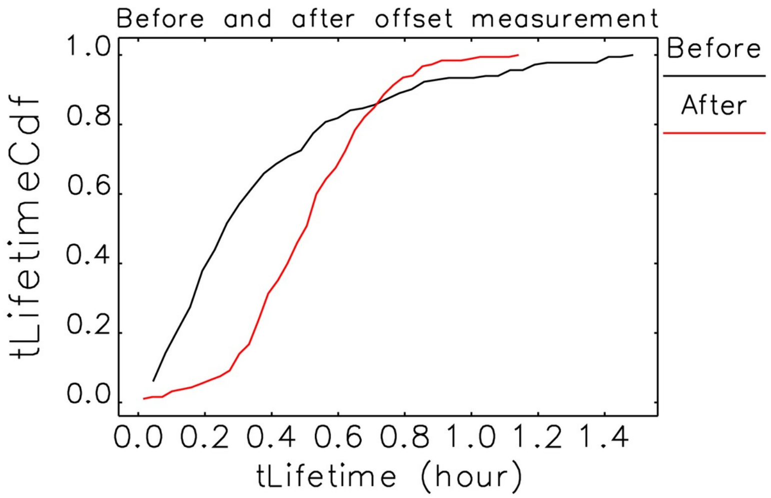
- Increase magnet errors in simulations to increase probability of failure
- Small dynamic aperture is the main reason in failing to get stored beam; to improve DA:
  - 1. Transmission optimization using first 2 singular vectors of the quadrupole-beta function response matrix
  - 2. Lattice correction using quasi-closed orbit response matrix fit
  - 3. Measure BPM offsets using trajectories, repeat entire correction from beginning (only a fraction of BPMs around sextupoles)
- For rather large errors, the program fails to ramp sextupoles
  - Measure BPM offsets using trajectories, repeat entire correction

Improvement of surviving beam fraction after 5000 turns after optics correction



Closed orbit correction

- Closed orbit correction with tune adjustment between iterations
  - Keeping tunes away from integer and half-integer is crucial
  - After closed orbit correction converged, the expected median lifetime is 15 minutes
- Orbit-based BPM offset measurement for all 560 BPMs
  - Simulations show that 3-4 iterations are needed to achieve required 30 μm rms accuracy
  - Total measurement time is ~30 hours
- After orbit correction is converged with new BPM offsets, the median lifetime is 30 minutes – enough to start lattice correction

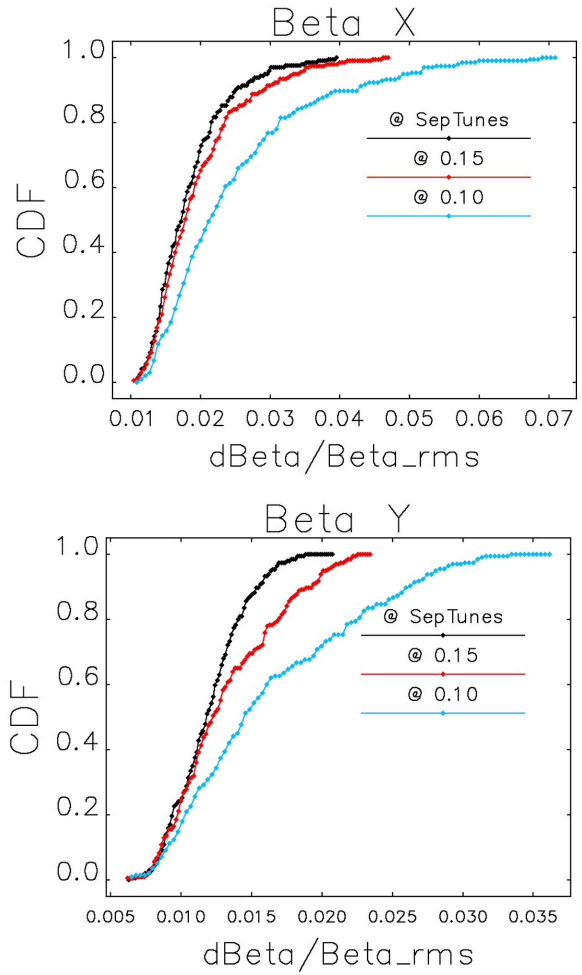


Lattice correction

- Lattice correction is response matrix fit based
- Correction is performed in several iterations with increasing number of singular values
- Uses existing APS programs
- Last step of the automated lattice commissioning with single bunch

- Lattice correction and BPM offset measurements will be repeated later with multibunch fill that would provide lower BPM noise
- Tunes will be moved from (95.18, 36.23) to (95.10, 36.10)
  - Lattice correction accuracy depends on working point

Lattice correction accuracy for different tunes



Conclusions

- Automated commissioning is key to fast lattice commissioning
- Automated commissioning is a natural extension of the automated commissioning simulations
- Commissioning simulations are crucial in MBA-based light source design:
  - At design stage, commissioning simulations are used to evaluate various lattices, magnet/support designs, tolerances, etc
  - At pre-commissioning stage, commissioning simulations are used to prepare for possible surprises: reverse-polarity magnets, vacuum chamber obstructions, malfunctioning BPMs

- While you can never be prepared for everything, the more time you spend on commissioning simulations, the less need you will have to invent some corrections during actual commissioning