Automated Commissioning for the APS-U

Vadim Sajaev
Argonne National Laboratory

Optics Tuning and Corrections for Future Colliders workshop
June 27, 2023
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

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

\(^1\) 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
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 $x \cdot \eta / \eta \cdot \eta$ 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

V. Sajaev, “Automated Commissioning of APS-U”
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
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