Automated Commissioning Plans for the APS Upgrade

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Beam Tests and Commissioning of Low-Emittance Storage Rings
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Automation is a key to fast commissioning

- APS-U will have to be commissioned is 3 months
- We see automation as a key to fast commissioning
- We have simulated lattice commissioning and are testing it now at present APS
  - 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 feedback, etc.
- Simulations have helped us identify required steps and algorithms
- Experimental tests are being used to validate algorithms and prepare actual software for APS-U commissioning
Lattice commissioning simulation

- Lattice commissioning consists of
  - Establishing first turn
  - Multi-turn trajectory correction
  - Orbit correction
  - Beta function and coupling correction
- Commissioning is simulated by tracking a bunch of particles with parameters corresponding to the extracted beam form the Booster
- Early simulations showed that sextupoles should be turned off during first steps of the commissioning to simplify multi-turn trajectory correction

<table>
<thead>
<tr>
<th>Errors used in commissioning simulation:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Girder misalignment</td>
<td>100 µm</td>
</tr>
<tr>
<td>Elements within girder</td>
<td>30 µm</td>
</tr>
<tr>
<td>Dipole fractional strength error</td>
<td>$1 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Quadrupole fractional strength error</td>
<td>$1 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Dipole tilt</td>
<td>0.4 mrad</td>
</tr>
<tr>
<td>Quadrupole tilt</td>
<td>0.4 mrad</td>
</tr>
<tr>
<td>Sextupole tilt</td>
<td>0.4 mrad</td>
</tr>
<tr>
<td>Corrector calibration error</td>
<td>5%</td>
</tr>
<tr>
<td>Initial BPM offset error</td>
<td>500 µm</td>
</tr>
<tr>
<td>BPM calibration error</td>
<td>5%</td>
</tr>
<tr>
<td>BPM single-shot measurement noise</td>
<td>30 µm</td>
</tr>
<tr>
<td>BPM orbit low-current noise</td>
<td>3 µm</td>
</tr>
<tr>
<td>BPM orbit high-current noise</td>
<td>0.1 µm</td>
</tr>
<tr>
<td>BPM and corrector tilts</td>
<td>1 mrad</td>
</tr>
</tbody>
</table>
Sector configuration

- APS consists of 40 identical sectors
- Each sector contains 14 BPMs and 10 correctors
  - Presently, only 10 BPMs per sector are planned to have turn-by-turn capability
- Insertion Device (ID) vacuum chambers (vertical gap $\pm 3$ mm) will be installed before commissioning
- Minimum horizontal aperture is $\pm 6.5$ mm in the photon absorber upstream of ID chamber
Correction of incoming beam trajectory

- Based on simulations, if the beam makes it through the long narrow vacuum chamber of the septum magnet, it will make it through the first sector too.
- BPMs in the first sector are used to correct trajectory of the incoming beam.
- The expected accuracy of the trajectory correction:
  - 0.5 mm and 0.1 mrad rms
  - Limited mainly by the BPM offset errors
- The energy error cannot be determined yet.

<table>
<thead>
<tr>
<th>Static errors (rms)</th>
<th>Jitter (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal position 2 mm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Horizontal angle</td>
<td>0.5 mrad</td>
</tr>
<tr>
<td>Vertical position</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Vertical angle</td>
<td>0.3 mrad</td>
</tr>
<tr>
<td>Energy</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>
First turn trajectory threading

- Even after correcting incoming trajectory, the beam will not get to the end of first turn without correction with 100% certainty due to
  - Small apertures
  - Very strong quadrupoles (1 mm offset in Q8 gives 2.3 mrad kick)
- Due to limited corrector strength and nearly guaranteed loss position (at ID chamber), the first-turn trajectory correction is done using sector-by-sector multi-corrector threading
  - 3 BPMs on each side of ID are used to calculate position on a virtual BPM in the middle of ID straight section
  - All correctors in the sector upstream of the virtual BPM are utilized to correct beam position and angle using ideal trajectory response matrix
- Threading fails occasionally, then simplex optimization of transmission is performed in this sector
**Injection energy correction**

- When threading reaches half turn, the energy error of injected beam is measured using average horizontal BPM error:
  \[
  \frac{\Delta E}{E} = \frac{\langle x \rangle}{\langle \eta_x \rangle}
  \]

- Expected accuracy of the energy error determination is 10\(^{-3}\)

- After adjustment of the booster extraction energy, the threading starts from the beginning
BPM verification

- BPM performance is crucial to the success of the automated commissioning
  - Bad BPMs significantly complicate calculations that rely on small number of BPMs like threading

- Extensive tests and checks of magnet and BPM connections and polarity will be performed
- Wrongly connected or damaged BPM cables will result in large BPM gain, tilt, or offset errors
- Parallel with sector-by-sector trajectory threading, crude BPM verification will be done
  - 4-corrector trajectory response matrix will be measured using all BPMs in the sector (4x10 matrix in each plane) and trajectory response matrix fit will be performed
  - This measurement allows the determination accuracy of BPM gain error of 15% rms and BPM tilt of 10 deg rms

- This accuracy should be enough for determination of BPM connection problems
  - The main limitation on the accuracy if the injection jitter and BPM noise

- If needed, BPM timing scan can also be performed in parallel with sector-by-sector threading

- Magnet verification is not tested yet – extensive pre-commissioning testing of magnets is the main approach
Threading results

- After threading is complete, the beam barely goes beyond the first turn
- Ideally, if you make trajectory at the end of first turn equal to the trajectory at the beginning of the first sector, you create closed orbit condition
- In reality, you only improve your transmission slightly but not really create closed orbit
  - Median transmission improves from 1 to 5 beam-turns
- Using simplex at the end of the ring to try to find closed orbit does not give any better results

\[
\frac{1}{N_{p0}C} \int N_p \, ds
\]
RF setup

- Beam energy as a function of turn is measured using average horizontal orbit error
- Ignoring synchrotron motion ($\nu_s \approx 0.003$), one can write for the beam energy as a function of turn $n$:
  $$\frac{\Delta E_n}{E} = -\frac{eV}{E \cdot \Delta \omega T_0} \left( \cos(\Delta \omega T_0 n + \phi_0 + \Delta \phi) - \cos(\phi_0 + \Delta \phi) \right) - n \frac{U_0}{E}.$$

  This expression is used to determine phase and frequency error of RF
  - Relative phase of cavities is ignored presently
  - RF setup is run after every iteration of trajectory correction since it does not require additional measurements

Example of RF error determination
  $\Delta f_{RF} = 8$ kHz, $\Delta \varphi = 35^\circ$
Simulations show that tune correction is important for achieving multi-turn transmission. When transmission achieves 15 beam-turns tune correction is started. Tune is determined from trajectory response:
- Few-turn trajectory response is analyzed using NAFF for each BPM family on a sector-by-sector basis.
- Achieved tune accuracy is 0.05 rms.
- Enough for this stage of commissioning.

No above-below integer and integer ambiguity since NAFF determines per-sector tunes.

Other methods can be used.
Global trajectory correction

• Early on, it was realized that corrector strength required to correct trajectory could easily exceed the maximum corrector strength

• To minimize corrector strengths, the correction is run gently in 3 nested loops:
  - Outside loop – increases number of correctors in use from 2 to 8 per sector in some steps
  - Second loop – increases number singular values in the matrix inversion
    - Inner loop – just repeats correction with one SV until convergence

• RF setup and tune correction is run every few iterations

• Simulations are only run for 20 turns
  - 50% of cases achieve 20 beam-turns (no losses)
  - 90% of cases achieve more than 10 beam-turns
Orbit correction

- Orbit correction is run using the same 3 loops only with orbit response matrix
- In addition to RF setup and tune correction, sextupole ramp is run every few iterations
  - Keeping tunes away from integer and half-integer is crucial
- After sextupole ramp is completed, the expected median lifetime is 15 minutes
- BPM offset measurement will be done at this point; then orbit correction will be repeated with new BPM offsets
  - Usual offset measurement relative to nearby quad
- After orbit correction is completed, the expected median lifetime is 30 minutes – enough to start response matrix fit based lattice correction
Lattice correction

- Automated lattice correction is a routine exercise in present light sources
  - We will use response matrix fit based correction
    (20 correctors per plane, <10 minutes)
  - Performed in several iterations with increasing SV number
- Expected accuracy of beta function correction is 1-2%, with X being about a factor of 2 worse than Y
- Design emittance is achievable, and minimum achievable emittance ratio is about 1%
Conclusions

- Automated commissioning is key to fast lattice commissioning
- Automated commissioning simulations are routinely performed for every lattice candidate and used to evaluate and compare lattice performance
- Commissioning simulations are used to figure out correction algorithms that work well enough for our lattice
  - Presently, simulations predict ~800 injections to establish closed orbit
    - ~300 injection cycles for trajectory correction
    - ~500 injection cycles for BPM verification and tune measurement
- Commissioning program testing is ongoing at the existing APS
  - Is used to verify algorithms and to ensure that all effects are taken into account