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

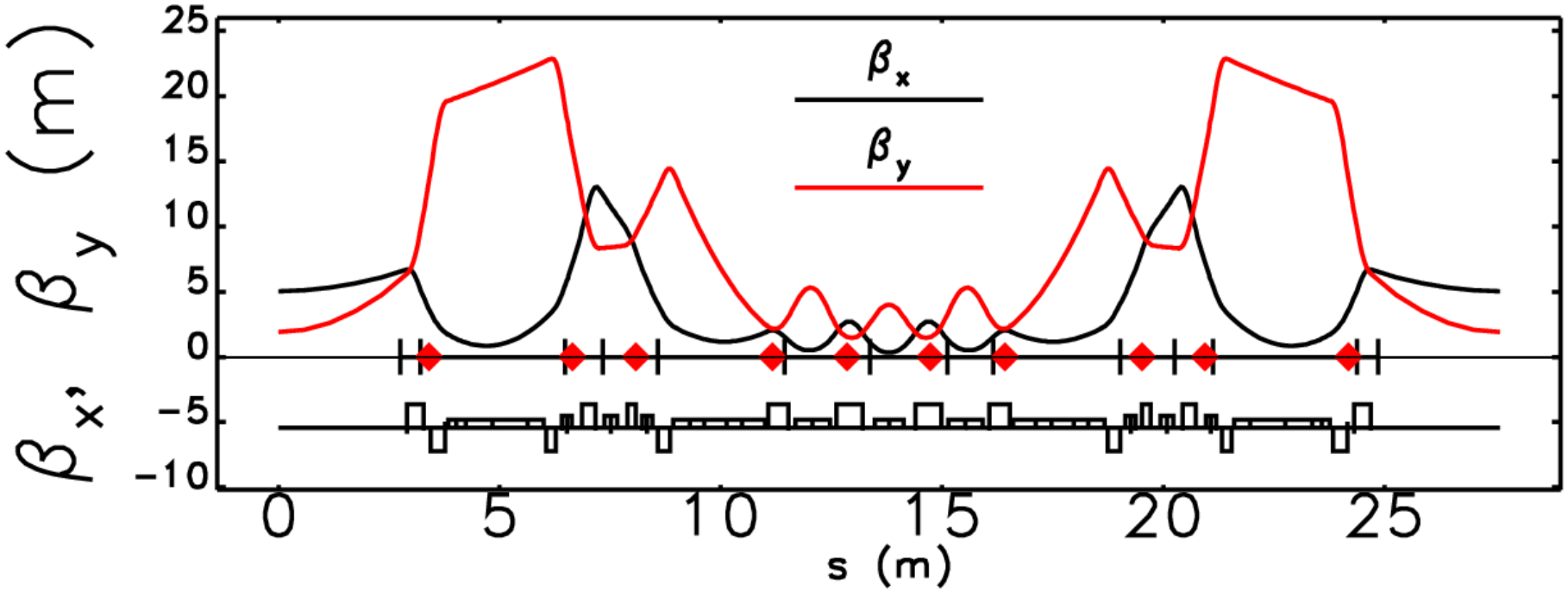
- Lattice commissioning consists of
  - Establishing first turn
  - Multi-turn trajectory correction
  - Orbit correction
  - Beta function and coupling correction
- Commissioning is simulated by tracking a bunch of particles with parameters corresponding to the extracted beam form the Booster
- Early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

Errors used in commissioning simulation:

Girder misalignment	100 μm
Elements within girder	30 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	0.4 mrad
Quadrupole tilt	0.4 mrad
Sextupole tilt	0.4 mrad
Corrector calibration error	5%
Initial BPM offset error	500 μm
BPM calibration error	5%
BPM single-shot measurement noise	30 μm
BPM orbit low-current noise	3 μm
BPM orbit high-current noise	0.1 μm
BPM and corrector tilts	1 mrad

Sector configuration

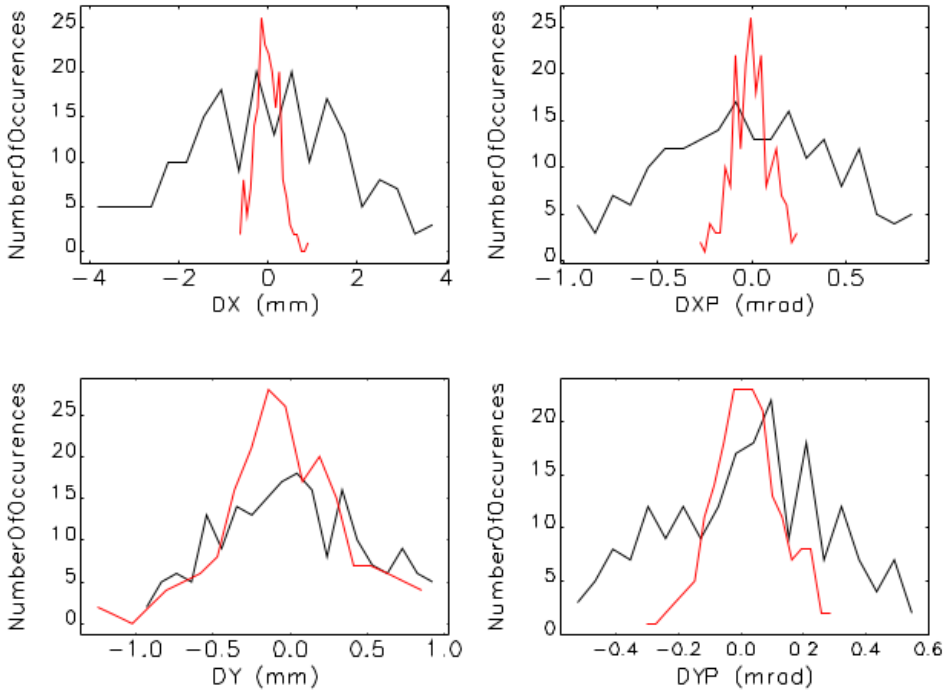
- APS consists of 40 identical sectors
- Each sector contains 14 BPMs and 10 correctors
  - Presently, only 10 BPMs per sector are planned to have turn-by-turn capability
- Insertion Device (ID) vacuum chambers (vertical gap ±3 mm) will be installed before commissioning
- Minimum horizontal aperture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



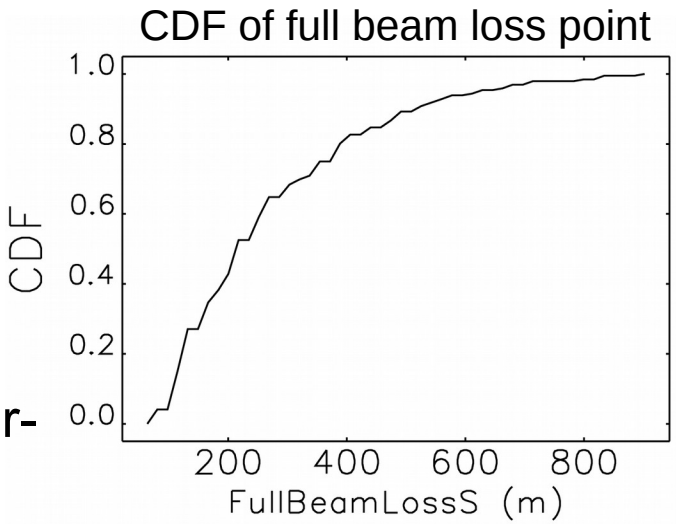
Correction of incoming beam trajectory

- 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

	Static errors (rms)	Jitter (rms)
Horizontal position	2 mm	100 μm
Horizontal angle	0.5 mrad	10 μrad
Vertical position	0.5 mm	25 μm
Vertical angle	0.3 mrad	15 μrad
Energy	0.5 %	10^{-4}



First turn trajectory threading



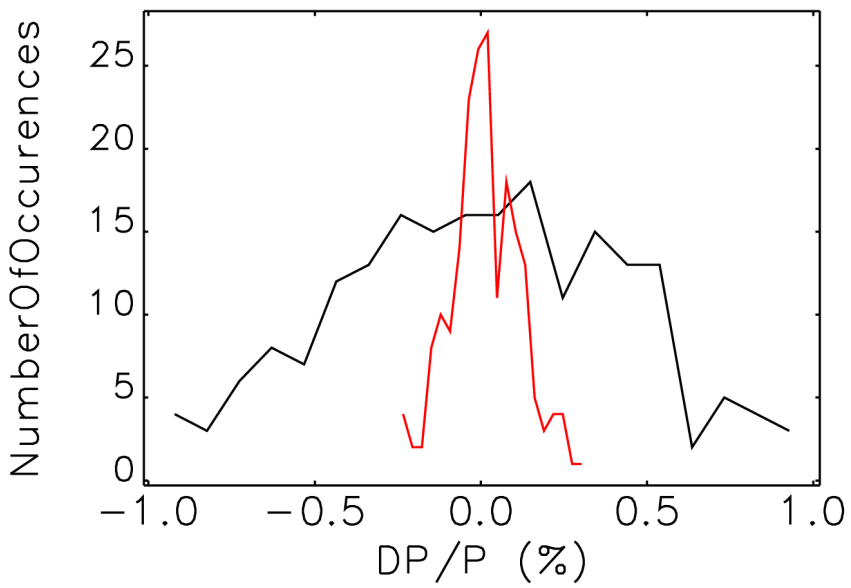
- Even after correcting incoming trajectory, the beam will not get to the end of first turn without correction with 100% certainty due to
  - Small apertures
  - Very strong quadrupoles (1 mm offset in Q8 gives 2.3 mrad kick)
- Due to limited corrector strength and nearly guaranteed loss position (at 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



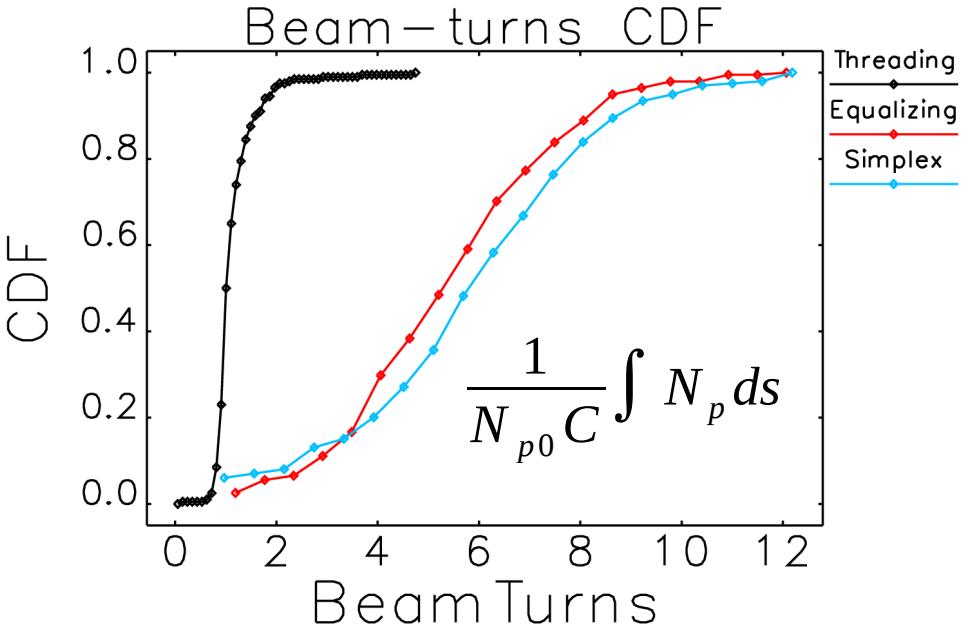
BPM verification

- 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

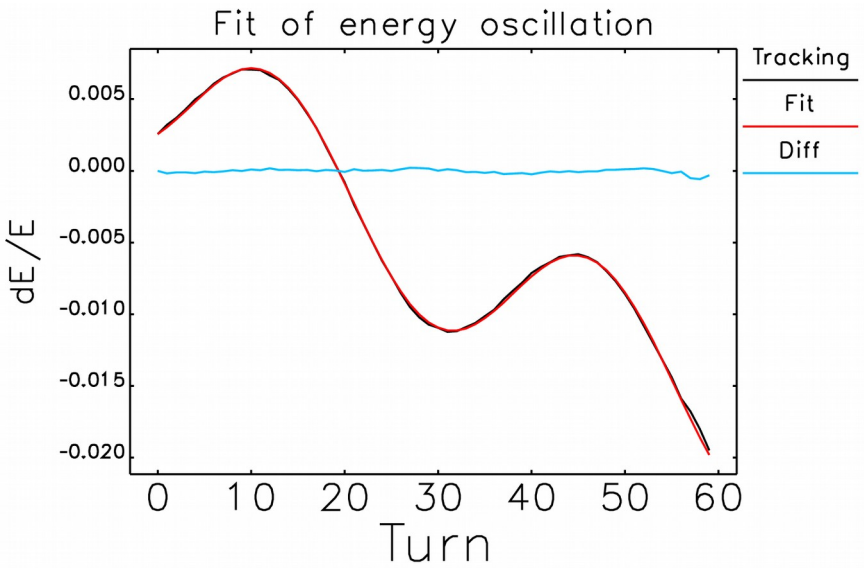


RF setup

- 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*:

$$\frac{\Delta E_n}{E} = -\frac{eV}{E \cdot \Delta\omega T_0}\left(\cos(\Delta\omega T_0 n + \phi_0 + \Delta\phi) - \cos(\phi_0 + \Delta\phi)\right) - n\frac{U_0}{E}.$$

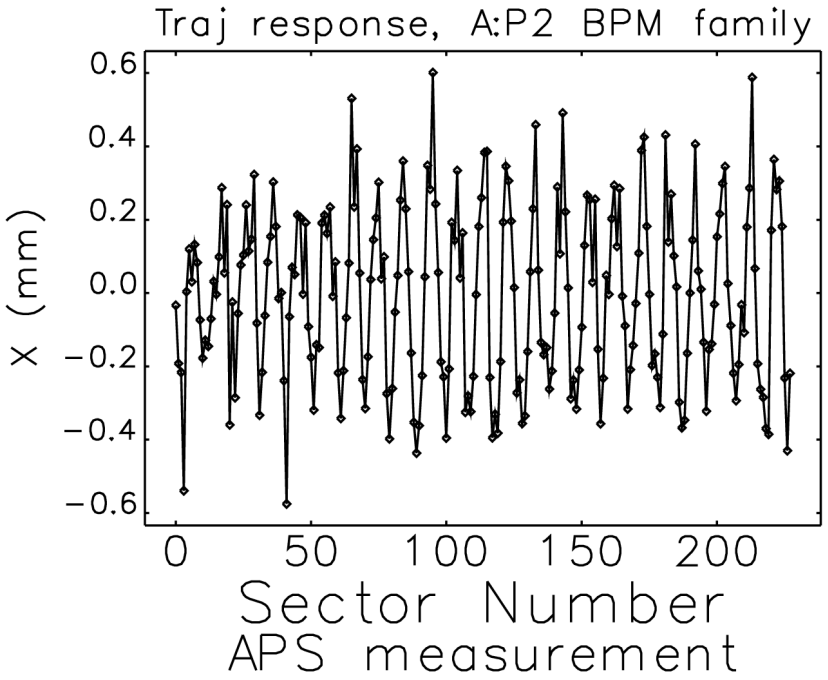
- This expression is used to determine phase and frequency error of RF
  - Relative phase of cavities is ignored presently
- RF setup is run after every iteration of trajectory correction since it does not require additional measurements



Example of RF error determination
Δf_{RF}=8 kHz, $\Delta\varphi$=35°

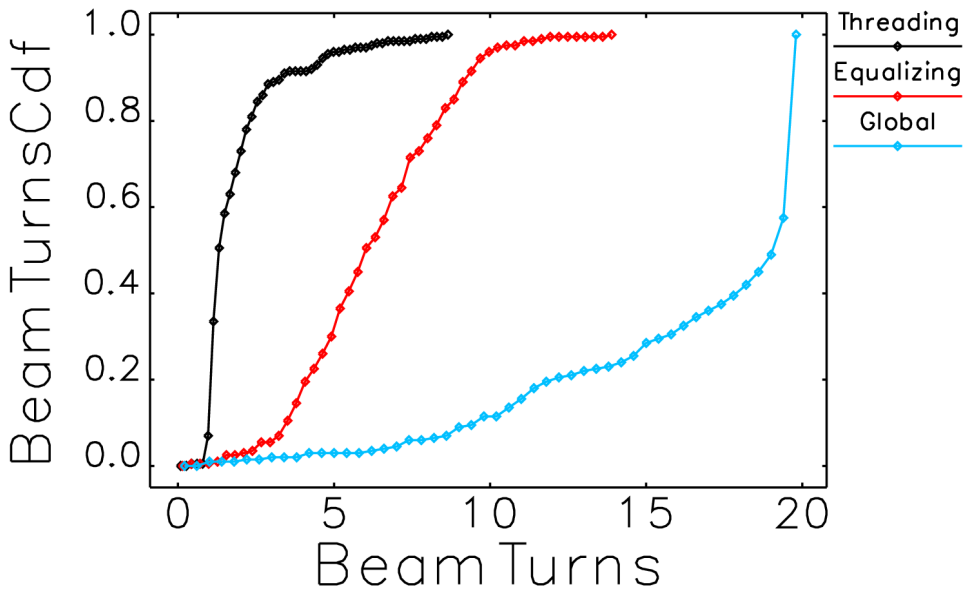
Tune correction

- 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



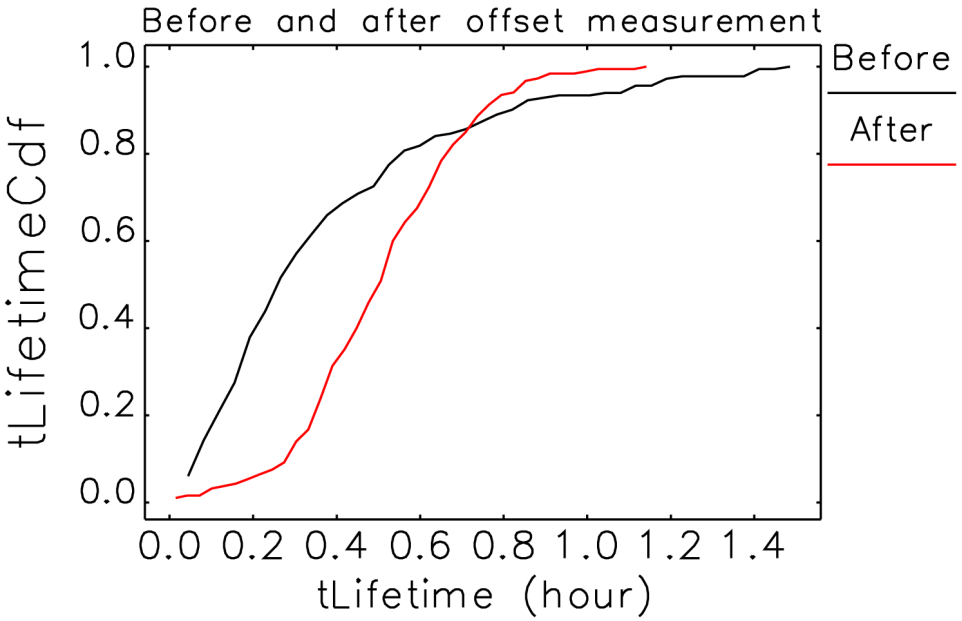
Global trajectory correction

- 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



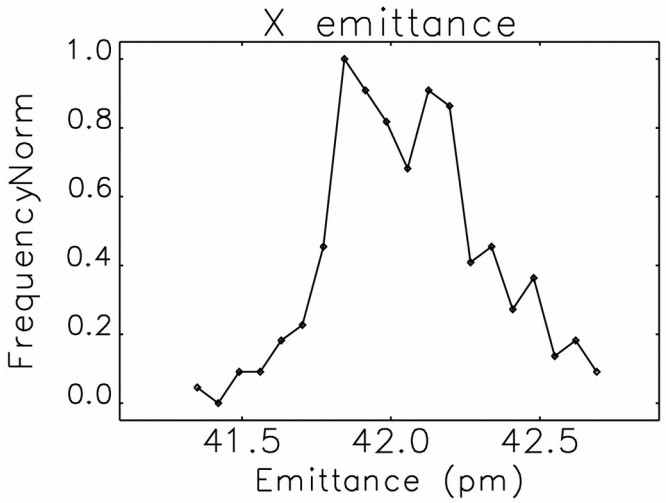
Orbit correction

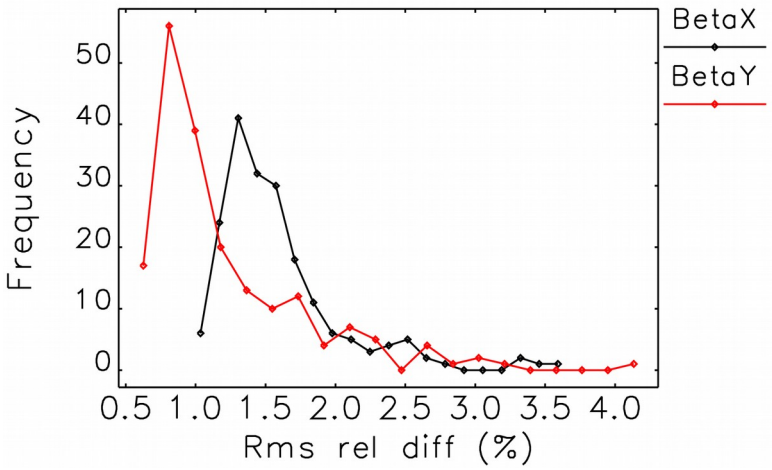
- Orbit correction is run using the same 3 loops only with orbit response matrix
- In addition to RF setup and tune correction, sextupole ramp is run every few iterations
  - Keeping tunes away from integer and half-integer is crucial
- After sextupole ramp is completed, the expected median lifetime 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

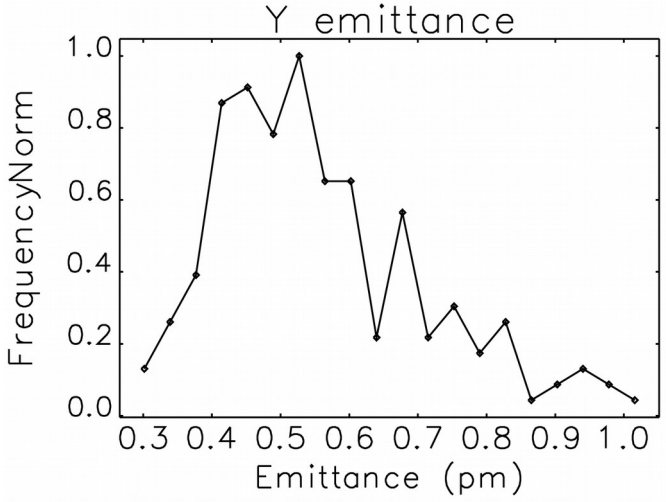


Lattice correction

- 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