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Beam optics tuning with 6dsim framework

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Optics Tuning and Corrections for Future colliders workshop

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Motivation for 6dsim

Started in 2005 as a student project

- Education
- Full 6D formalism necessary for the proposed VEPP-2000 layout with fully coupled "mobius" lattice for round colliding beams

Became major personal research tool, later adopted by several groups. It was used for the following machines:

- Budker
  - VEPP2000, BEP, VEPP-4M, VEPP-5 accumulator ring
- GSI
  - Collector Ring
- Fermilab
  - IOTA, FAST, Gm2 beamlines, DR

Sixdsimulation (6dsim)

- Computational core is based on the linear lattice solver in 6D phase space
  - 6x6 matrixes
- GUI for on-line analysis of lattices and data
- Compatibility with other codes
  - OptiM
  - MADX (via “sequence” files)
  - ELEGANT (limited)

Problems addressed with 6dsim

- Linear lattice simulations and optimizations
- Statistical analysis of trajectory and lattice corrections precision
- Injection bump optimizer
- **On-line trajectory measurement and correction**
  - Quad-centering
- **On-line lattice correction using LOCO with extended data sets**
- On-line trims balancing
- Linear lattice matching for the circular machines in presence of the linear space charge forces

For more details about 6dsim correction algorithms see: https://arxiv.org/abs/1703.09757

Sixdsimulation: lattice correction

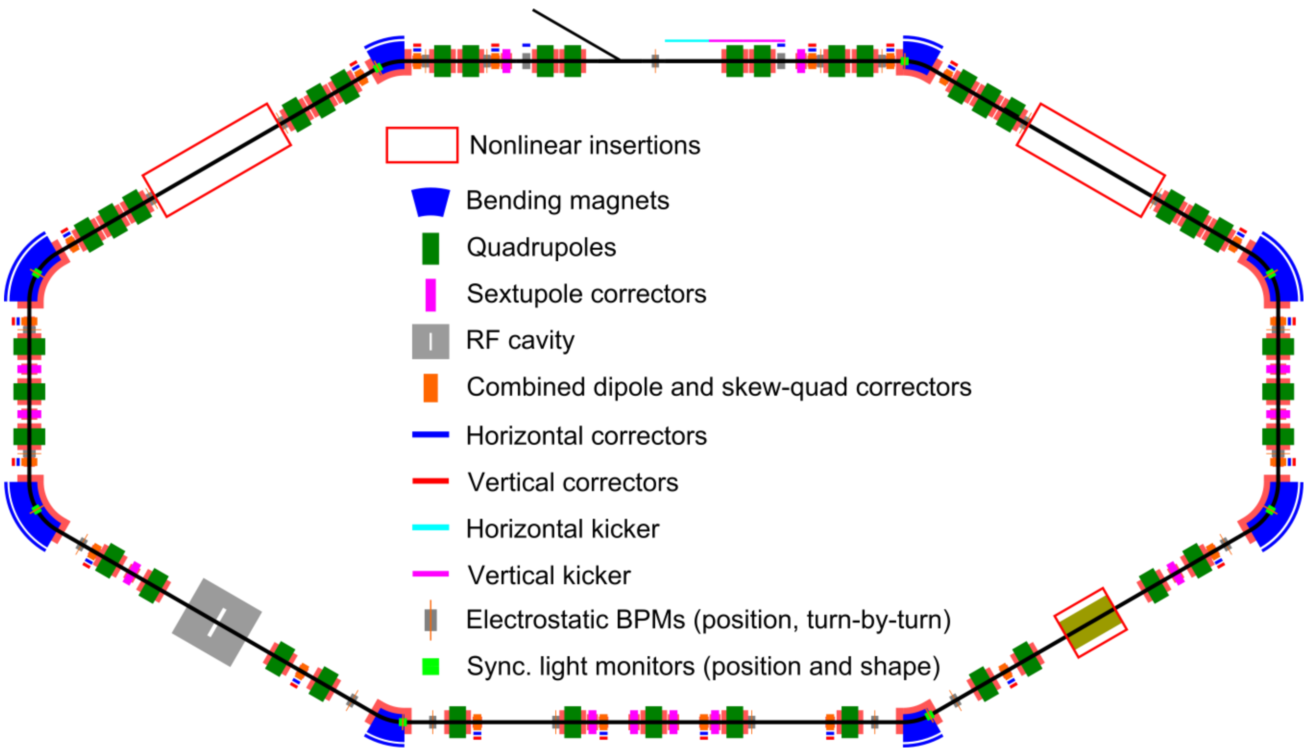
- LOCO based on the extended data sets:
  - Trajectory responses to trims variations
  - Dispersions
  - Betatron tunes
  - BPM-to-BPM phase advances
  - Beta- and alpha-functions
  - Responses of betatron tunes to quads variations
  - Responses of trajectory bumps to quads variations
- Model lattice can be fitted to experimental data using any combination of parameters that were used to define elements
  - Field parameters
  - Positions and tilts
  - Calibrations
  - Restrictions for variable parameters

Sixdsimulation: trajectory correction

- Correction is done towards specific values in the selected BPMs
  - Zeros by default
  - Specific bump can be selected
  - Trims settings solver
    - SVD inversion with user selectable cutoff for singular values
    - Best of N trims
- Quads and multipoles centering
  - An individually powered quad or multipole (6- and 8-poles) can be used as a BPM
  - Differential orbits measurements for various magnet's settings allow to reconstruct relative position of the orbit and element's magnetic axis

IOTA ring

- 39 individually powered quads
- 21 electrostatic pickups and 8 sync.-light cameras
- 20 combined correctors (H&V dipoles and skew-quads)

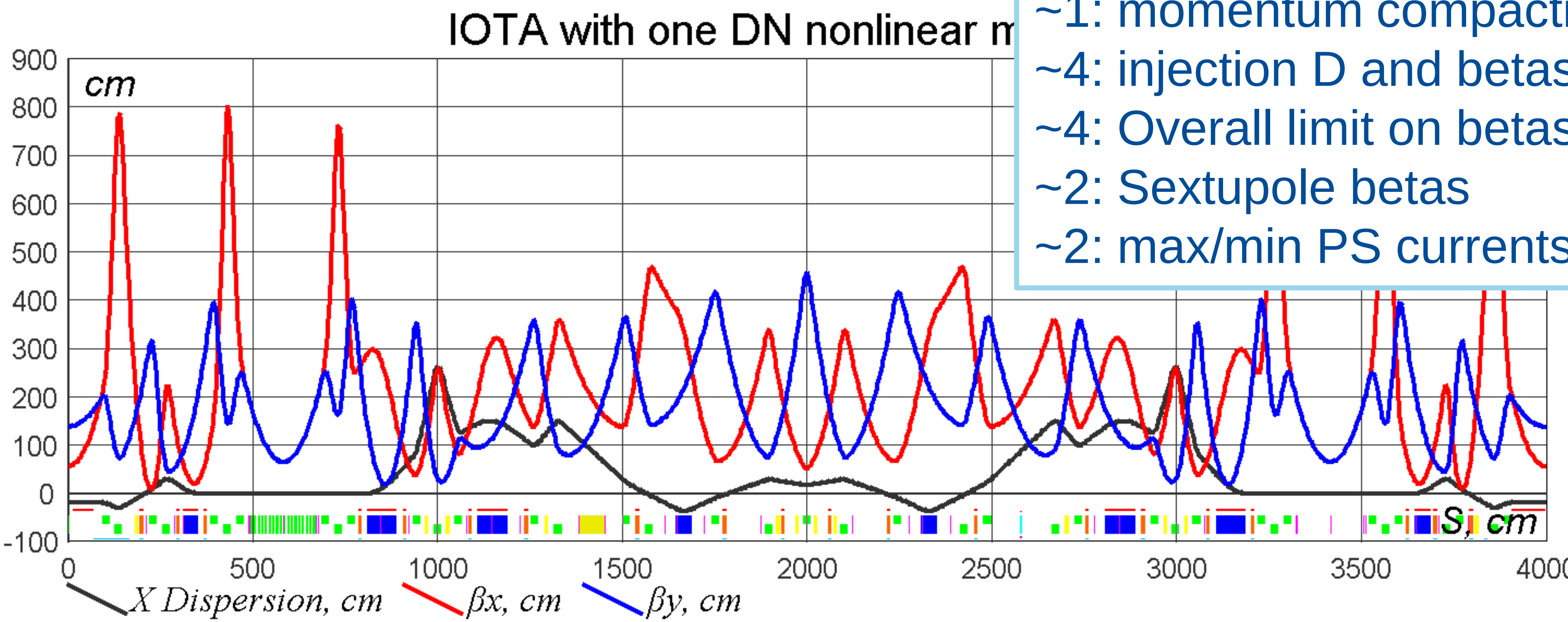


Momentum	< 200 MeV
Perimeter	40 m
RF voltage	<1 kV
RF frequency	30 MHz & 2.18 MHz
3 Experimental straights	2x180 cm, 1x150 cm
Main vacuum chamber aperture (R)	25 mm
Lambertson and kickers aperture (R)	20 mm
Electrons	10^9 e, 1.2 mA
Protons	10^{11} p, 9 mA
Vacuum	6×10^{-10} torr

IOTA lattice (1NL experiment)

- Lattice was optimized with 6dsim

4: 2 betas & alphas
2: tunes
2: D, D'
~1: momentum compaction
~4: injection D and betas
~4: Overall limit on betas
~2: Sextupole betas
~2: max/min PS currents



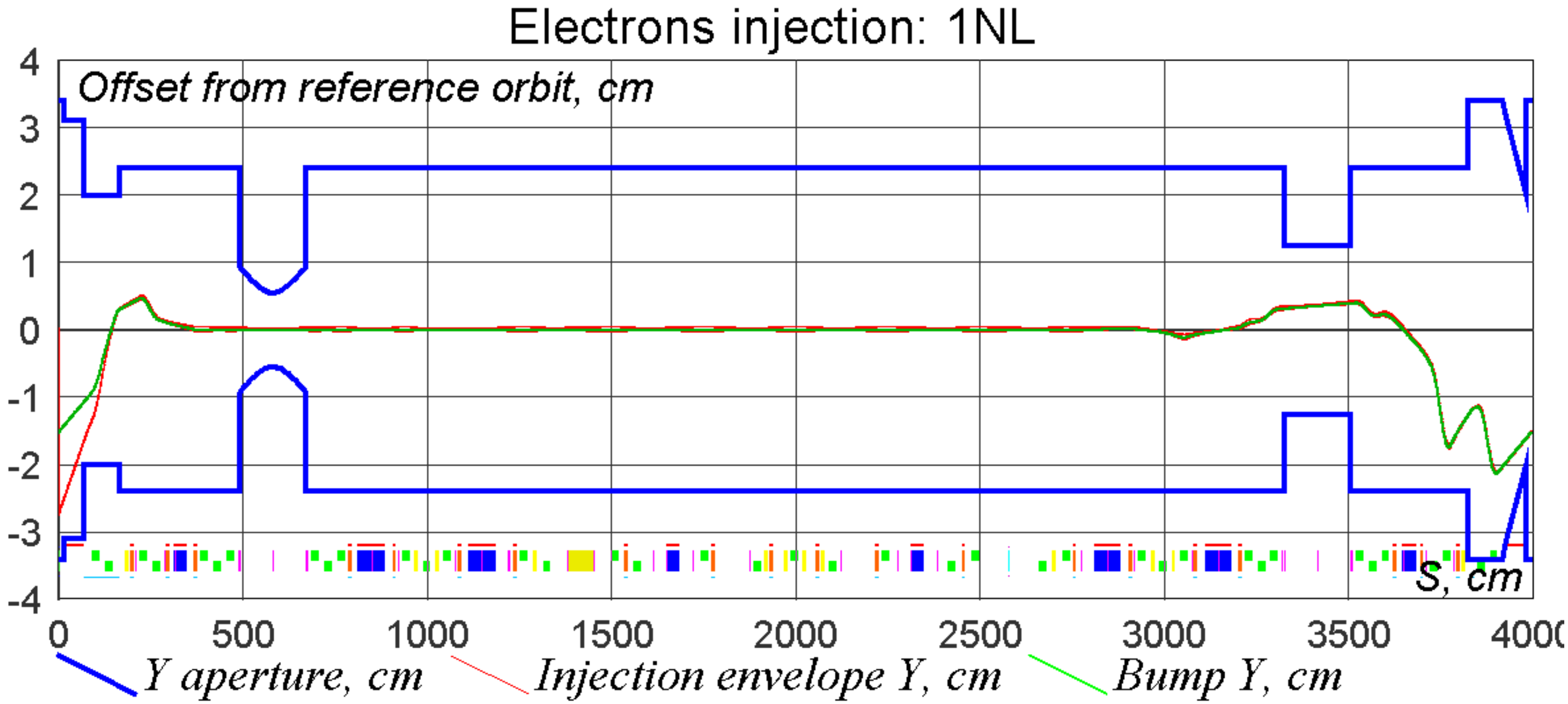
Momentum	150 MeV
Tunes, x,y	5.3, 5.3
Mom. comp.	0.072
Emittances, x,y	3.4 E-6 cm

Bunch length @1kV	11 cm
Energy spread	1.34 E-4
Sync. Tune @1kV	5.5 E-4
Damp. times (x,y,s)	(0.92,0.92,0.23) s

Injection trajectory

- Injection bump was designed with 6dsim

Clearance (Y):	**3.8 mm**	**18 sigmas**



Analysis of requirements for a lattice to be tunable

- Modeling of corrections for a big number of random seed errors was used to find required BPMs precision for LOCO
  - Closed orbit responses to the dipole correctors measured with 1 µm precision at 1mm amplitude of responses.
  - Betatron tunes with errors of 10^{-5}.
  - Dispersion measured with precision of 0.5cm.
  - Responses of closed orbit bumps to the quadrupoles' variations

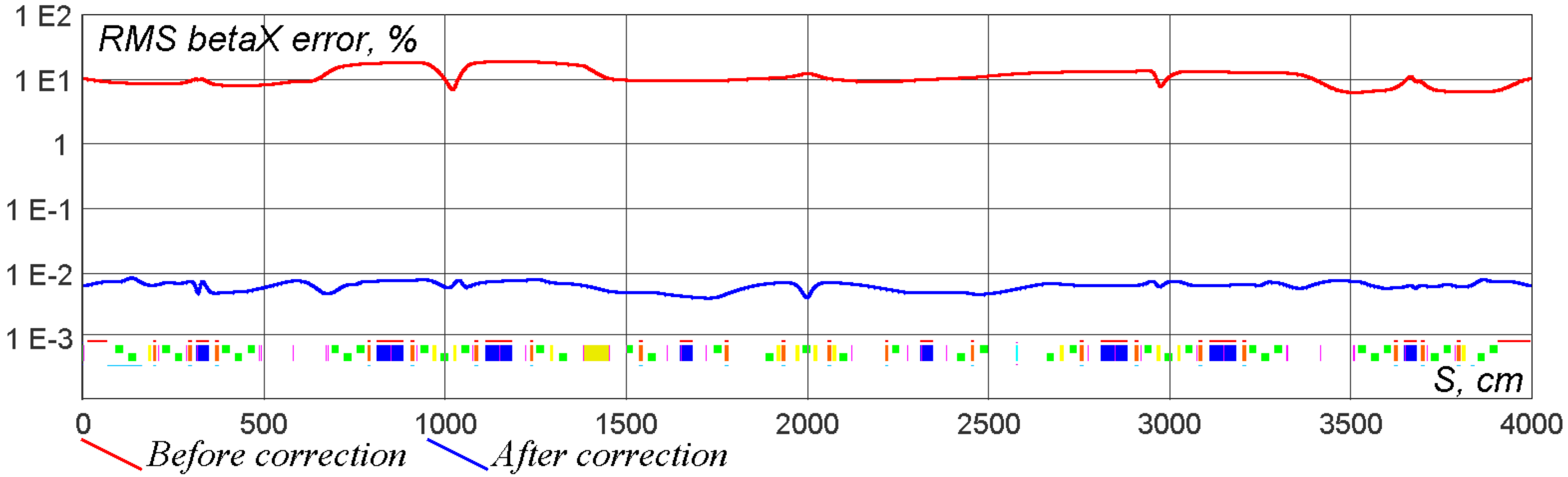
Standard deviations of errors for linear lattice correction modeling

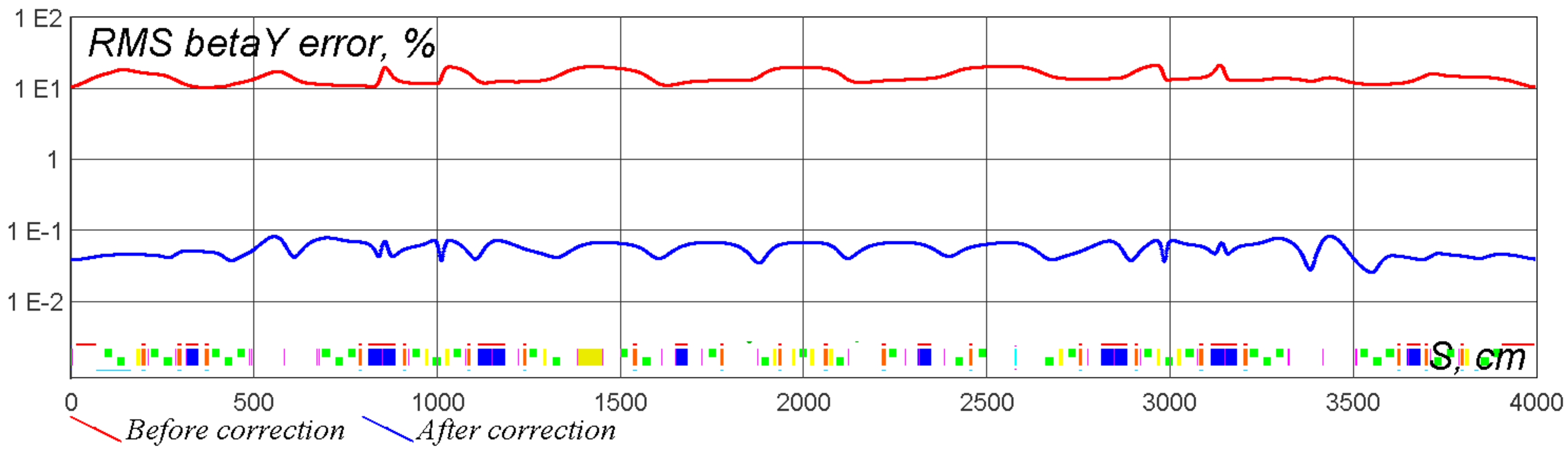
Quads		BPMs		Corr. calibr.
G	Rot.	Calibr.	Rot.	X&Y
1G/cm	1°	1 %	1°	2 %

Maximal errors of the IOTA lattice for the NL experiment

Betas at the insertion	1 %
Beta beating	3 %
Dispersion	1 cm
Arc phase advance	0.001

Beta functions correction quality





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Dispersions correction quality

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Analysis of requirements for an orbit to be tunable

- Statistical analysis was used to analyze closed orbit corrections:
  - Closed orbit distortions for the expected alignment errors and
  - Closed orbit distortions after corrections
  - Required correction fields

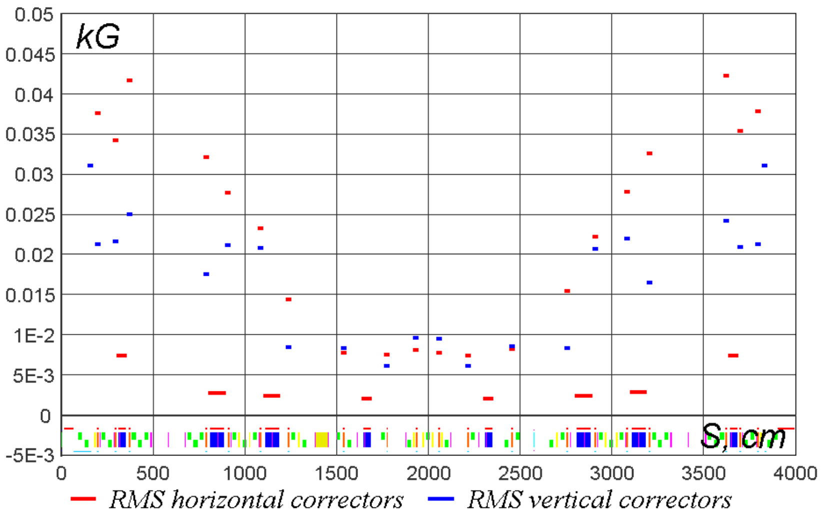
Standard deviations of errors for closed orbit correction modeling

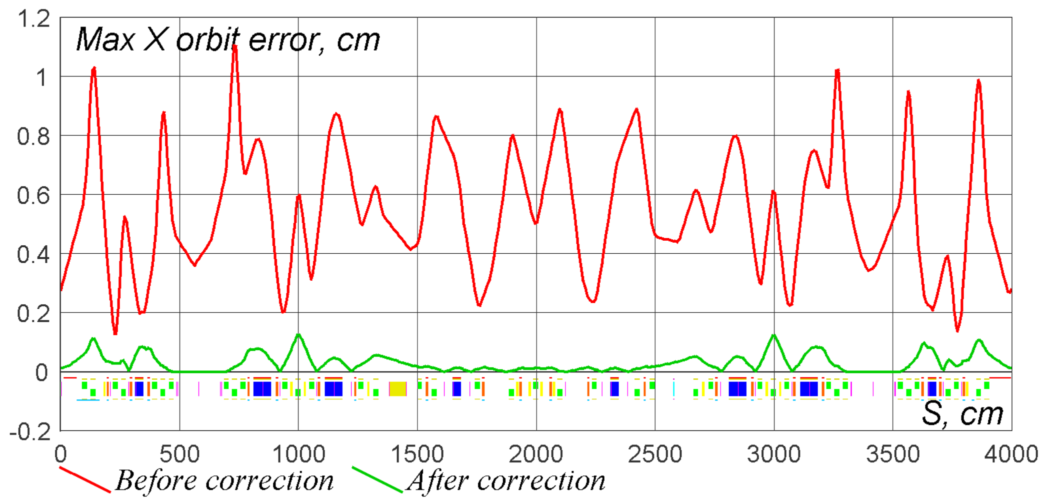
Quads	Bends	
X, Y shifts	X,Y Shifts.	X,Y tilts
0.1 mm	0.1 mm	0.06°

Maximal errors of the IOTA lattice for the NL experiment

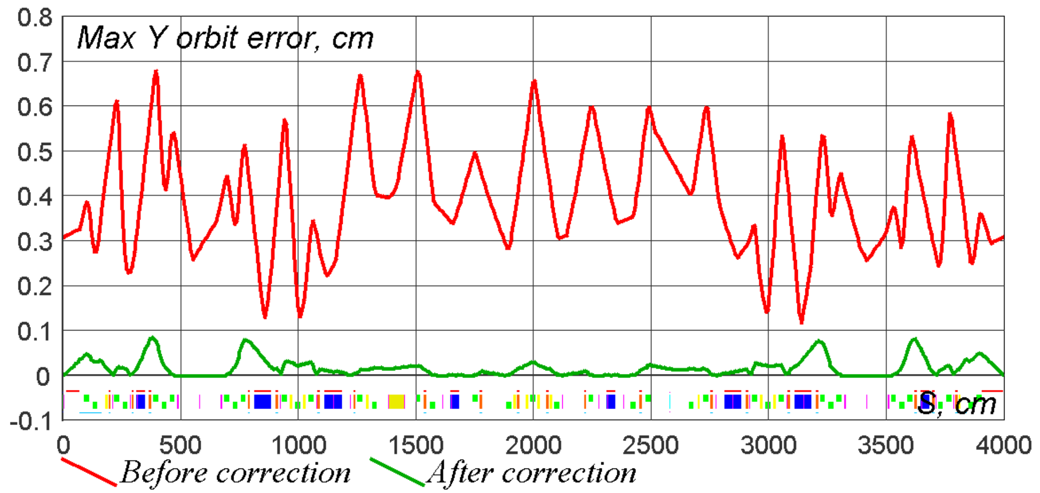
Closed orbit at insertion	0.05 mm

Closed orbit correction quality

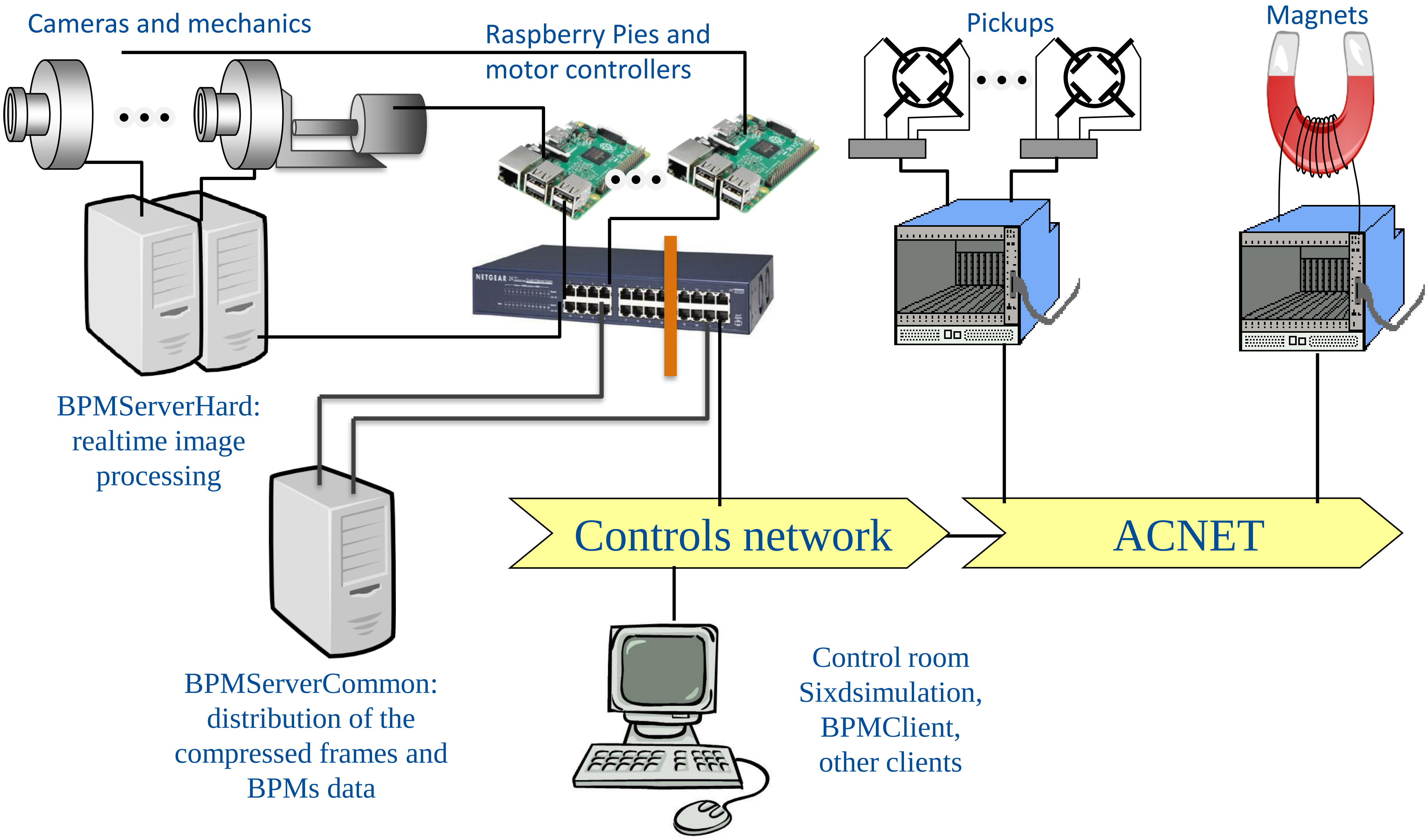




Orbit correction precision is limited by precision of BPMs



6dsim framework layout



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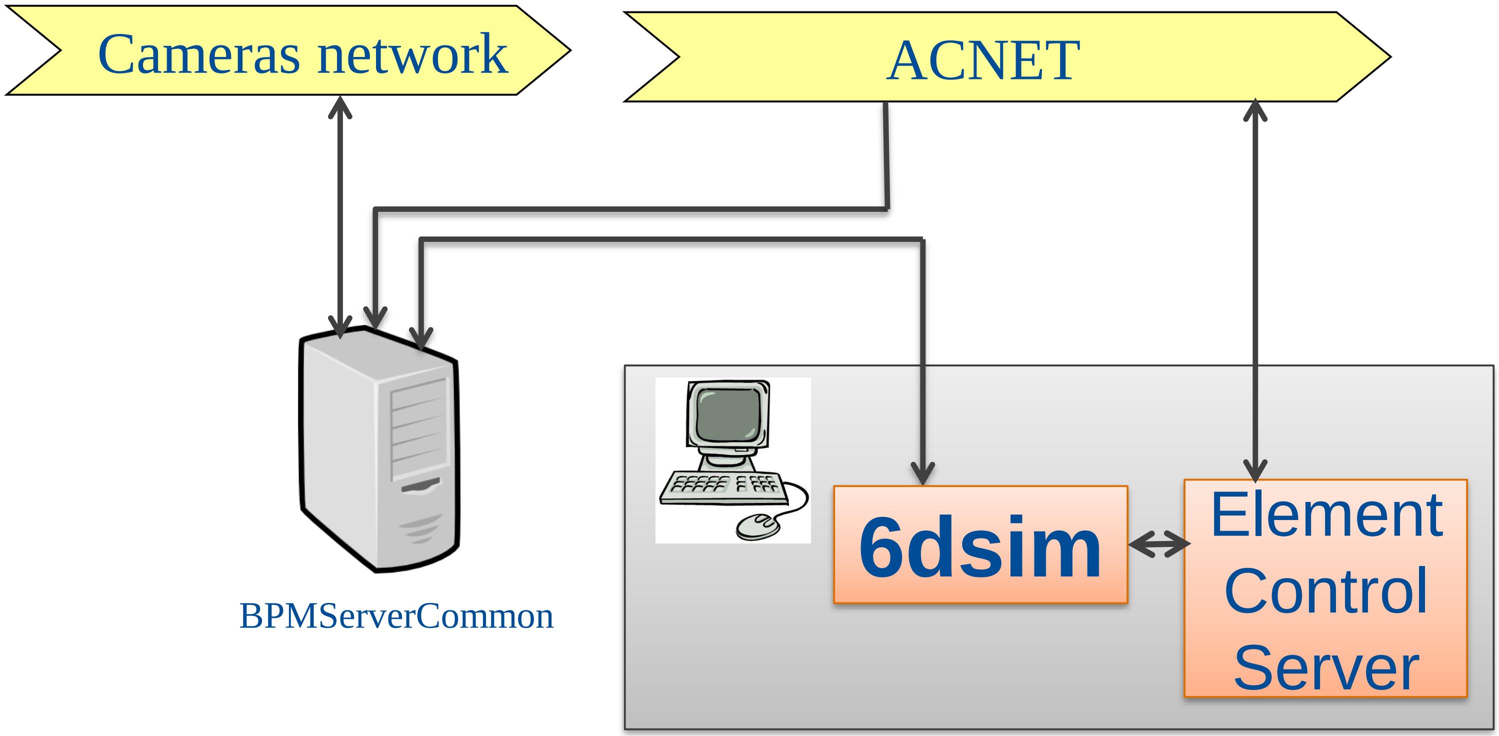
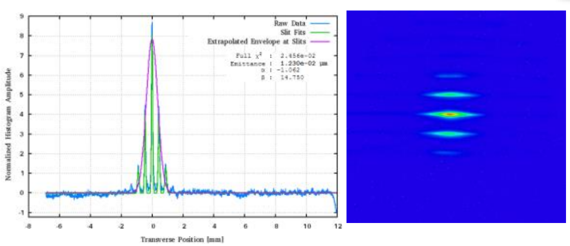
6dsim framework layout

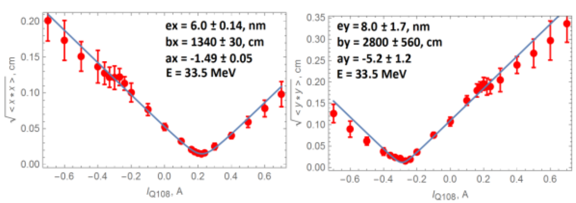


FAST tuning

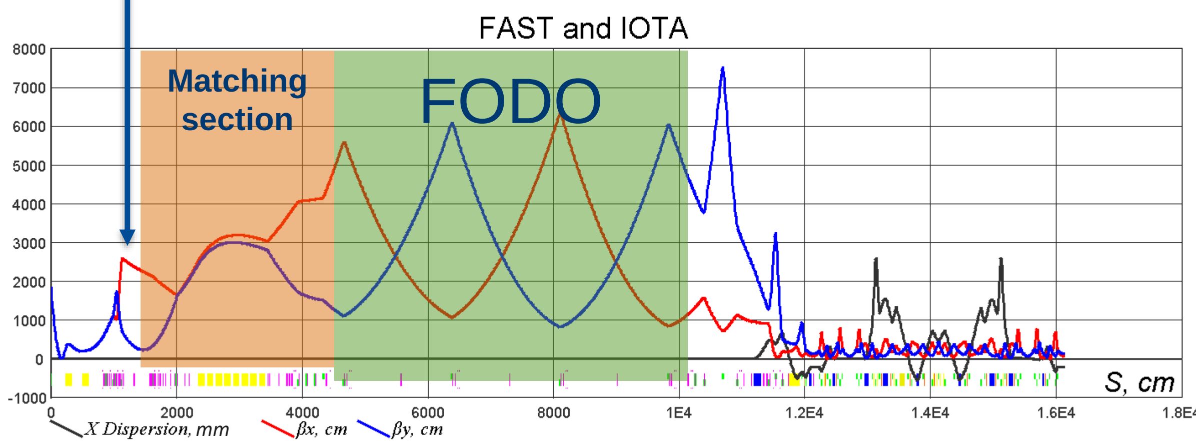
- Measure beam parameters before FODO
- Adjust FAST model to account for the as-found beam parameters
- Use LOCO to tune real lattice to match the model



Data from the horizontal multi-slits emittance measurements



Quadrupole scan data and fits for horizontal (left) and vertical sizes (right) for the same beam conditions as during the multi-slit measurement presented above



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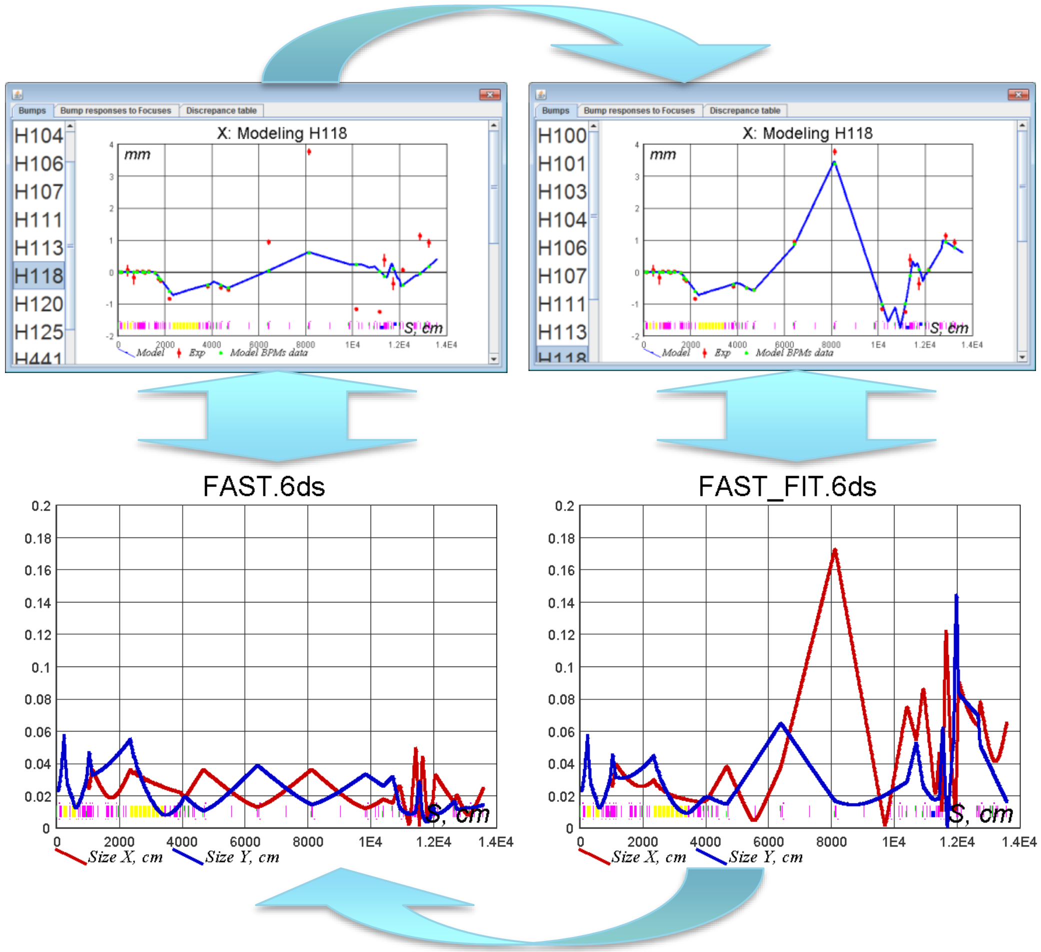
Lattice correction method based on LOCO

Fit model to measurements



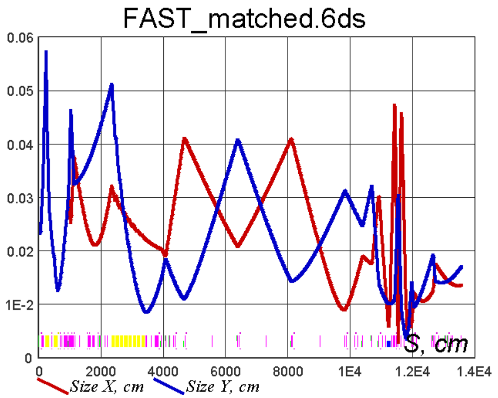
Implement correction

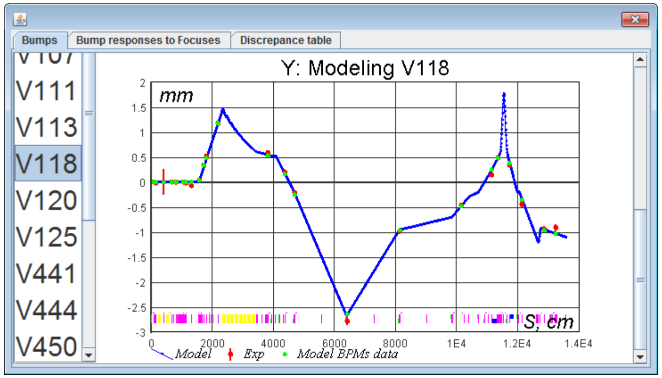
Pictures shows FAST data from 2017 run

Lattice correction method based on LOCO

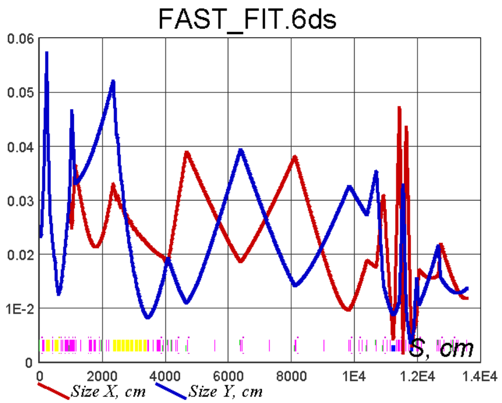
- 5 iterations gave a good lattice configuration for main sections of the FAST
  - Residual discrepancy at the end of line can be corrected locally if needed

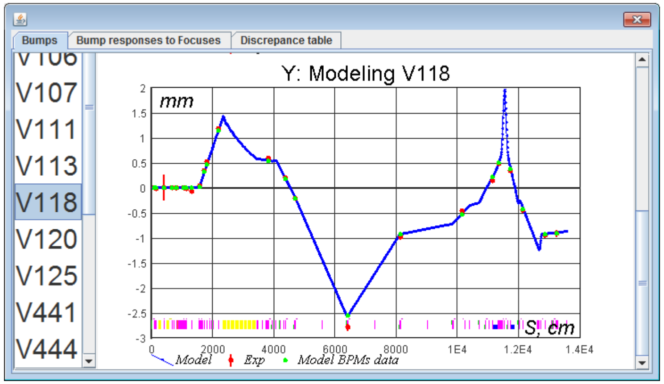
Model lattice





Fitted lattice



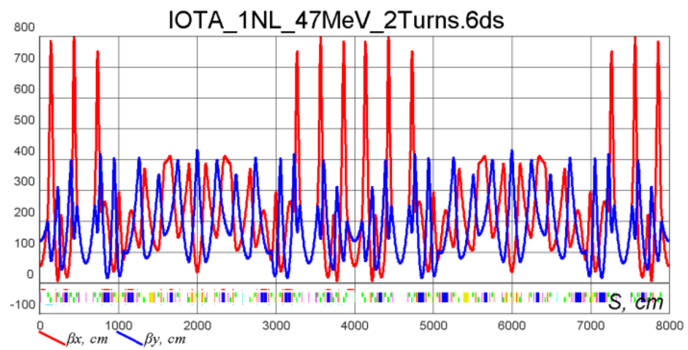


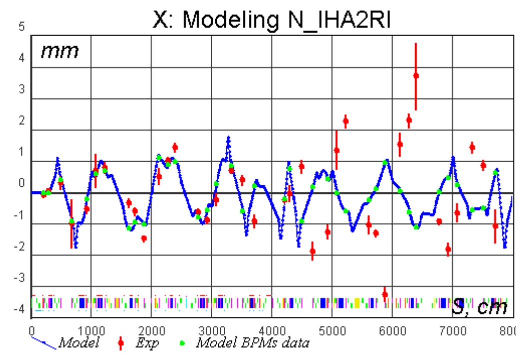
IOTA commissioning process

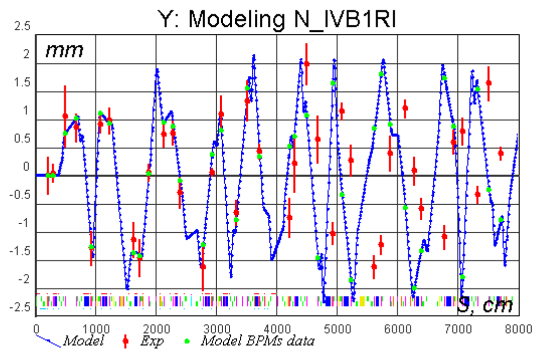
- Extensive preparations were made to have automated on-line diagnostics and corrections tools for quick IOTA commissioning
- Staged approach was used to capture beam into IOTA
  - Manual beam steering to get reliable beam through reasonable portion of the lattice
  - LOCO lattice tuning of the beam-accessible section with 6dsim
  - Rebalancing of the trims with 6dsim

Automated lattice control at IOTA

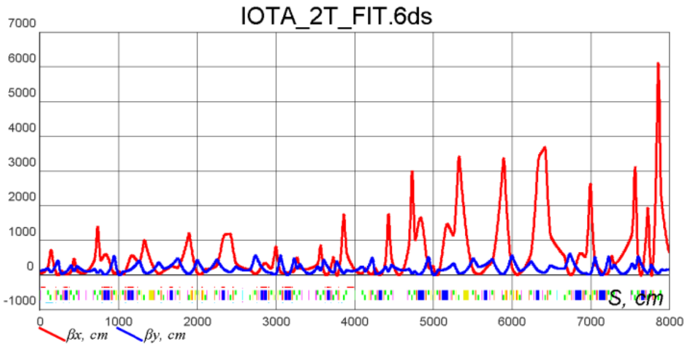
- After 2 consecutive turns with no losses were established a LOCO based correction was applied treating IOTA as a channel with correlated trims
  - **First correction iteration made stable betatron lattice**

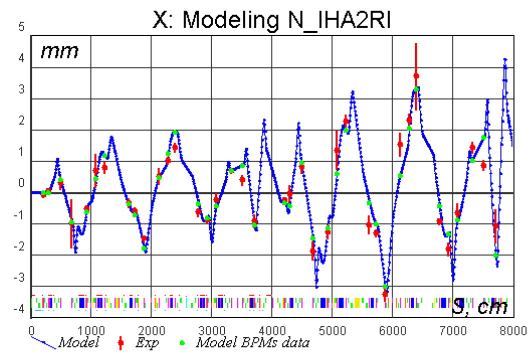


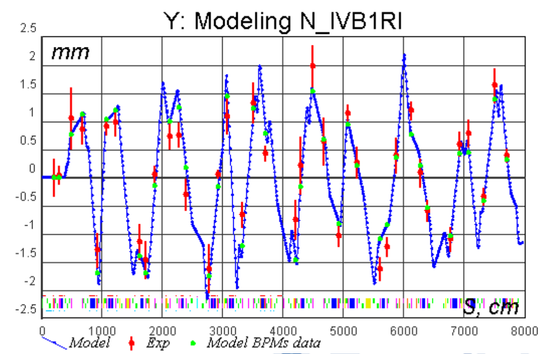




Fitted model has clear instability in X plane





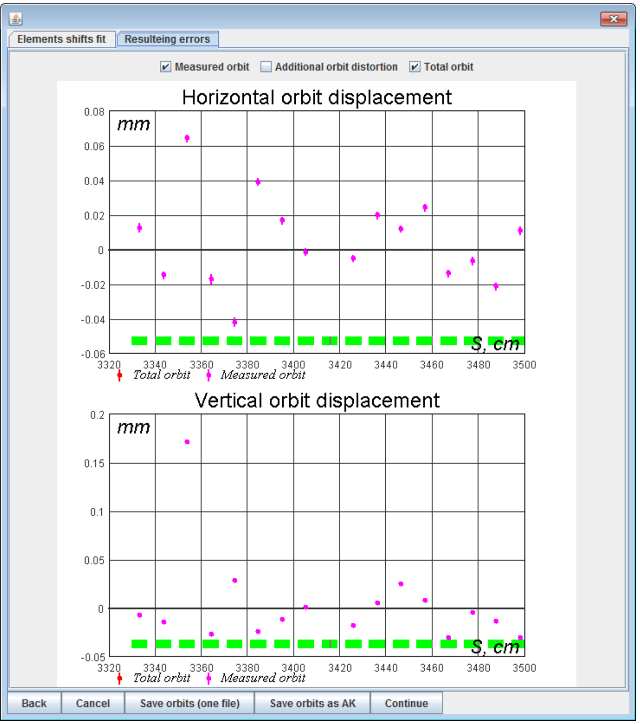


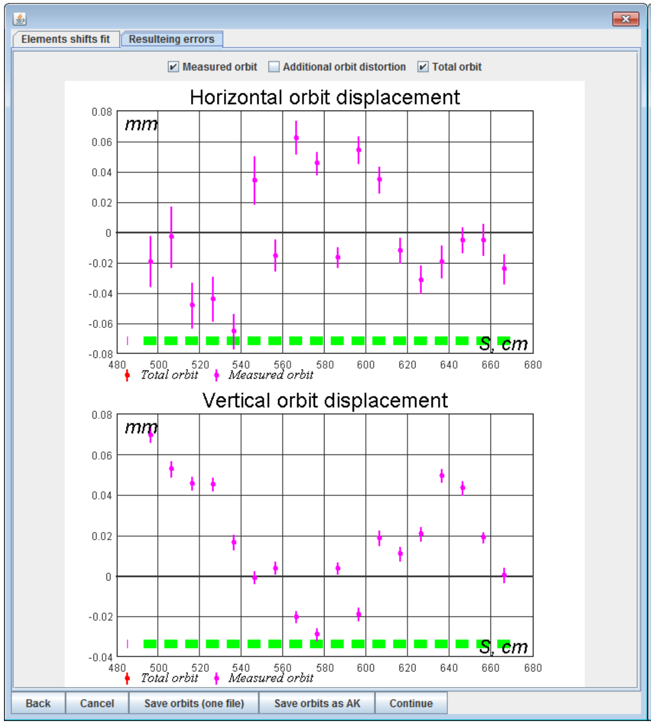
Orbit centering

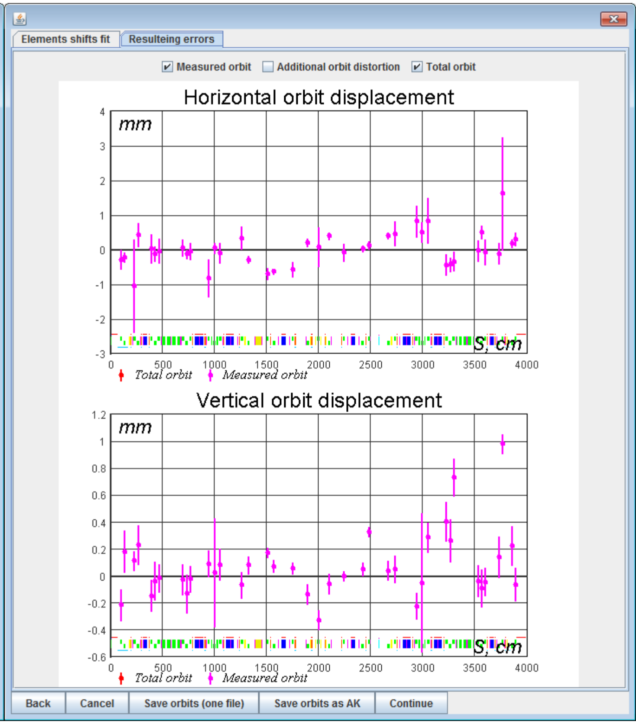
Octupoles

NL magnets

IOTA's quads





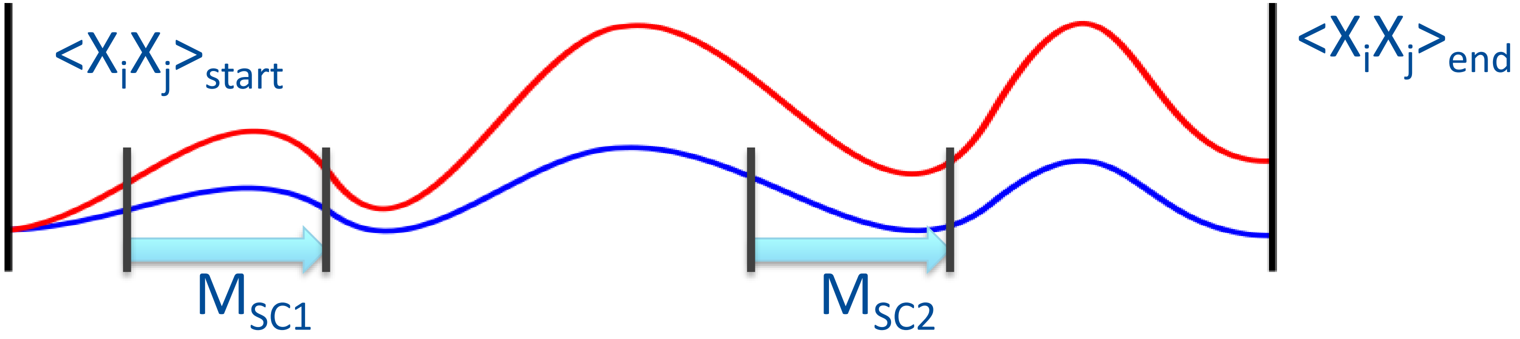


IOTA with intense beams

- Algorithm was developed to find self-consistent solutions in presence of linear space charge forces and at the same time preserving necessary form of T-insert transport matrix.
- Ring lattice is treated as a single path channel to avoid instabilities at the intermediate fit steps.
- In addition to standard requirements to the lattice, second moments at the beginning and the end of the lattice should be the same.

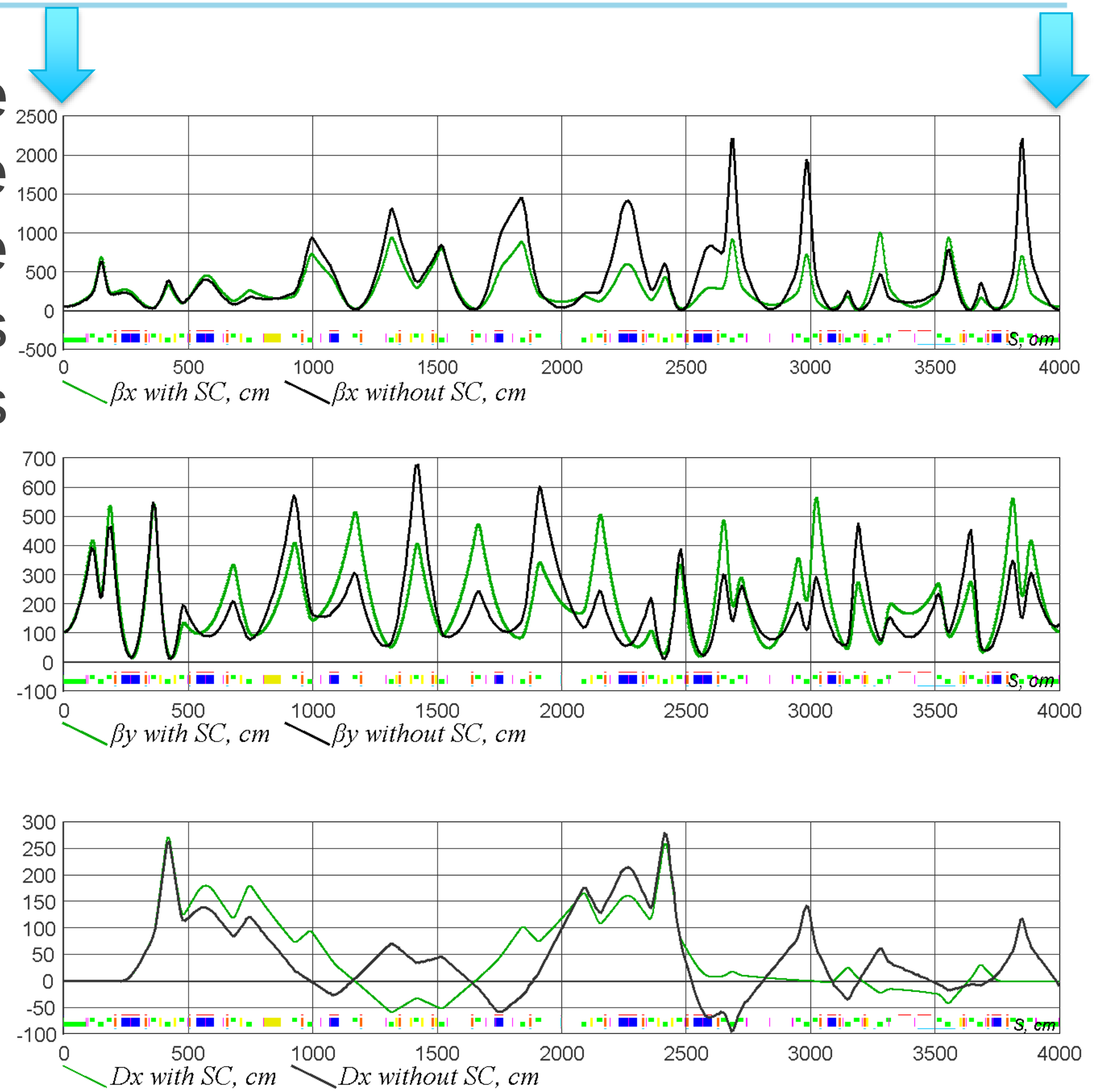
$$\langle X_i X_j \rangle_{start} == \langle X_i X_j \rangle_{end},\ M_{SC1} == M_{goal1},\ M_{SC2} == M_{goal2},\ \ldots$$

- Variable parameters include standard set extended with Twiss parameters, or second moments in general case.



Example of linear space charge compensation for 1NL

- Plots illustrate lattice functions across one path through IOTA for the same initial conditions but space charge forces being “on” and “off”
  - NL magnet at **t = 0.3**
  - SC tune depression: **-0.4**



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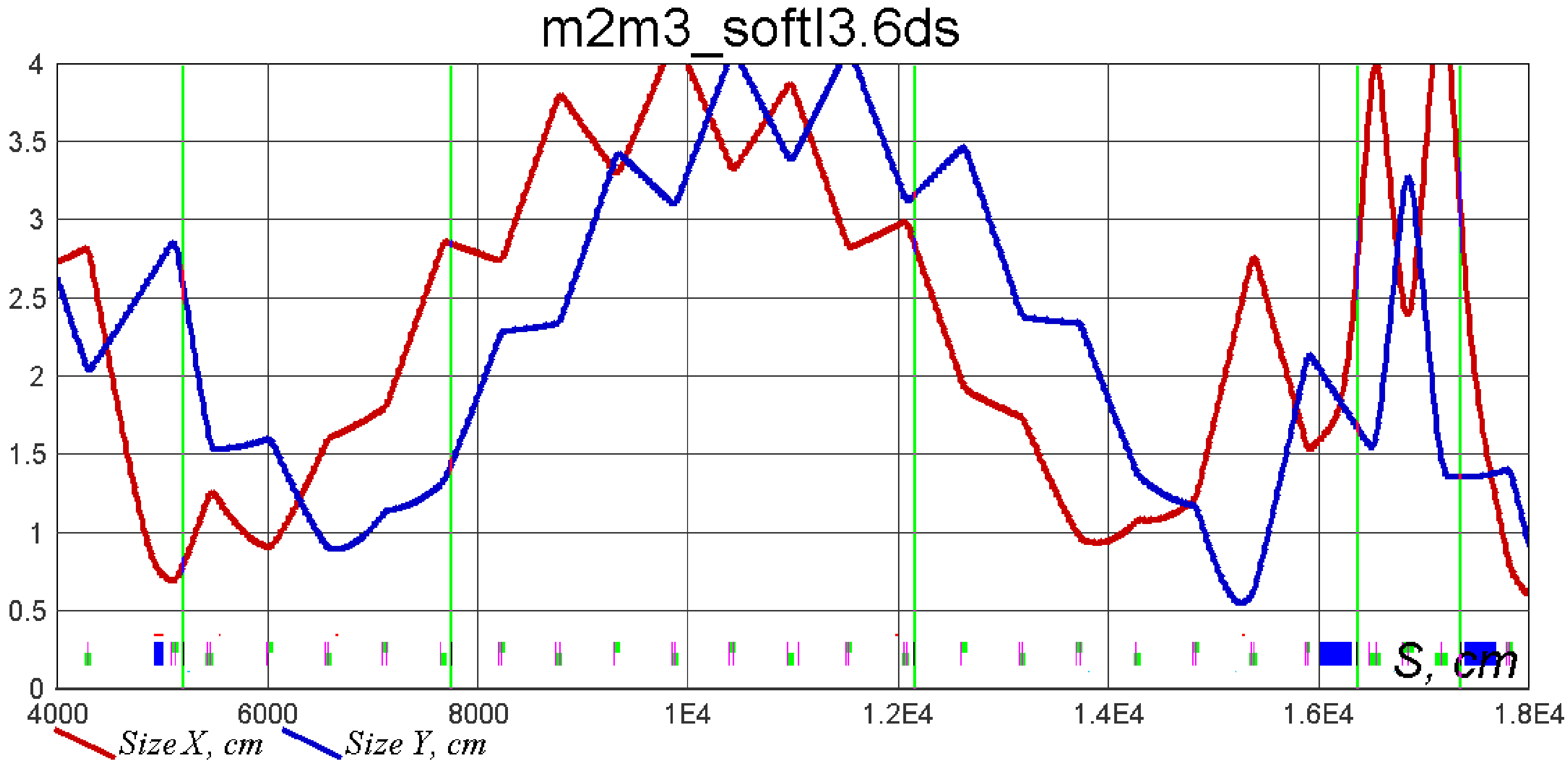
Quad scans

- "Multi-Quad scans" were used to understand lattice parameters
  - Initial conditions
  - Quad calibrations
- PS current were changed in a range where no significant aperture-induced shape artifacts were observed on selected TPMs
  - "Frame" contains averaged profiles + current settings in selected ACNET channels
  - Several quads are scanned with data from several TPMs

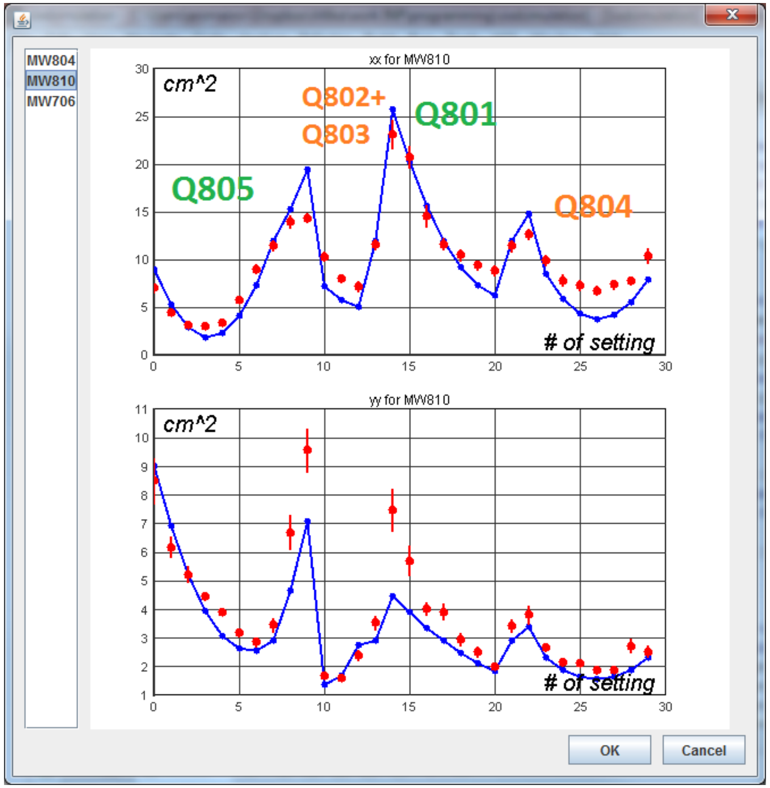
Quad scans: modeling

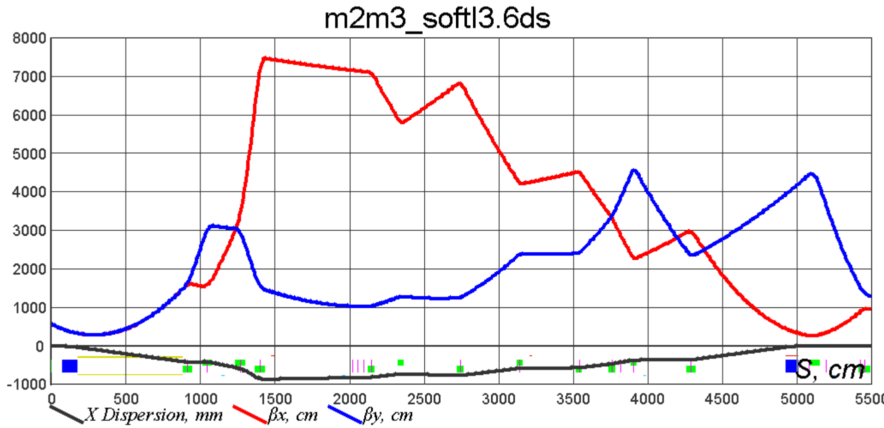
- Example of model scan for current in FODO string "Q709-Q723" from 27A to 117A

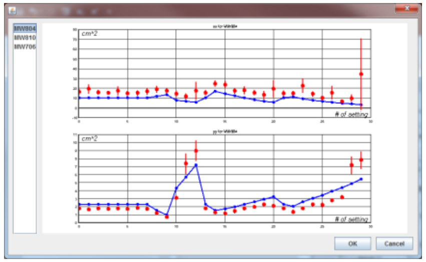


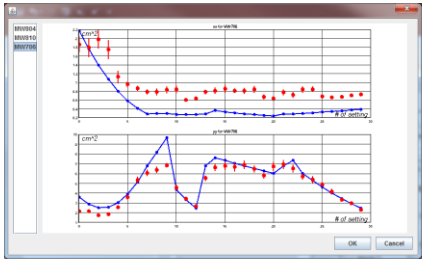
Quad scans: measurements

- To stabilize fitting process some assumptions made:
  – Equal X and Y betatron parameters (emittance, betas, alphas)
  – Energy spread of 2%









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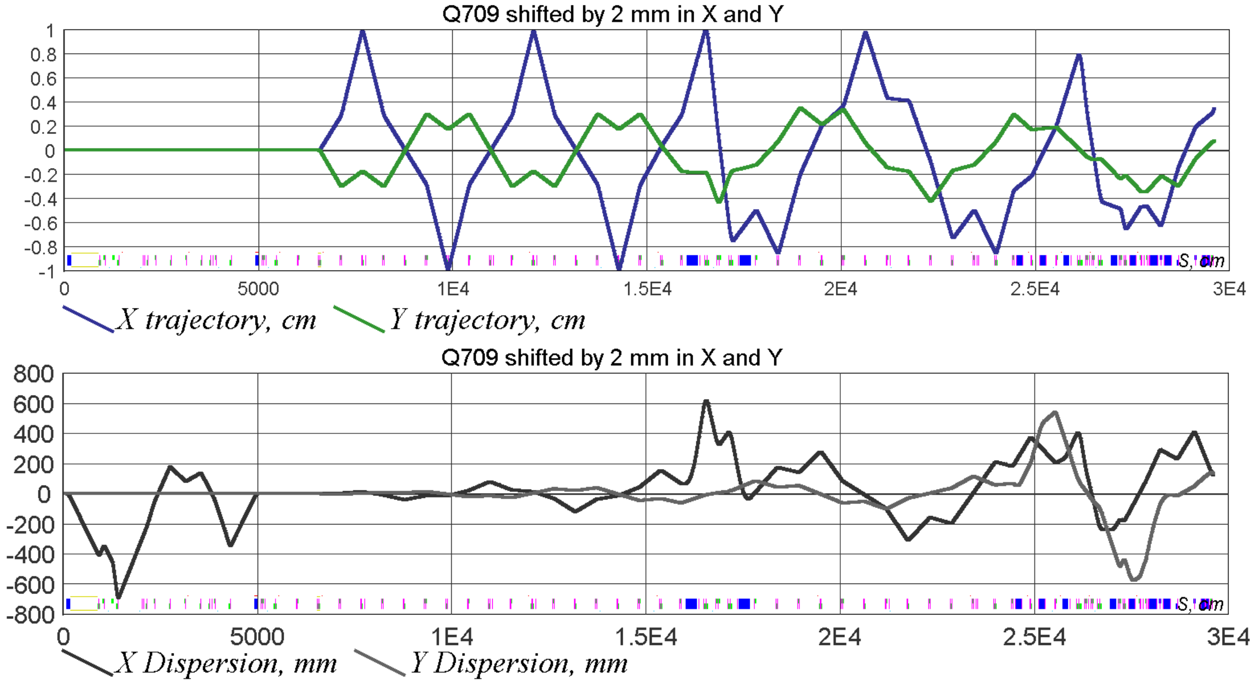
Second-order linear dispersion

- Trajectory wave goes forever after the excitation by single trim or misaligned focusing element
  - In each consequent focusing element second-order dispersion gets small addition, always in phase, because trajectory oscillates with the same phase advance as dispersion
  - In reality, particle with dp/p may stay bounded because of chromatic effects



Summary

- Functional lattice design and control
  - Extensively used for IOTA lattices for various experiments
- On-line lattice analysis and corrections capability
  - allowed to streamline IOTA commissioning
- Integration with ACNET allowed using the same framework to study and optimize other beamlines of the Fermilab complex
- Framework topology allows quick integration with other automation systems
  - Direct access to high-bandwidth data sources
  - EPICS
- Documentation is available for basic operations of 6dsim

Additional sliides

BPMServerCommon

- Serves as a proxy between Sixdsimulation and other clients and particular automation system
  - Read-only access to ACNET to grab pickups data for trajectory responses
  - Relays postprocessed data from cameras
  - Broadcasts settings to the cameras

- Configuration is defined in the properties file
  - Description of the data sources and corresponding BPMs
    - Cameras module
    - ACNET module
    - ACL through HTML module (no Kerberos required)
    - Several other modules

ElementControlServer

- Serves as a proxy between Sixdsimulation and particular automation system
  - Allows 6dsim to work in natural units
- Configuration is defined in the properties file
  - Only explicitly specified channels can be controlled
  - Each channel has specified range of acceptable settings
  - Non-trivial powering schemes are supported
    - One power supply for several elements
    - Several power supplies for one element
    - One power supply for a group of elements with individual trims
    - *Similar functionality can be achieved using variables in the 6dsim input file*

Tunes measurements (assistance program)

- Turn-by-turn coordinates from the electrostatic pickups are used to measure betatron tunes
  - Limited number of turns is typically available because of dipole mode decoherence (50-300 turns)
- FFT
  - Quick and reliable but not so precise with ~100 turns
- Primary Components Analysis
- Direct functional fit (on-line tool is available)