β^* Measurements and Adjustments

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(Optics Measurements, Corrections & Modeling for High Performance Storage Rings)
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Optics Measurements Tested in Tevatron

- The following optics measurements were used in Tevatron
  - Orbit response
    - Manual data analysis was used before LOCO was available
    - LOCO
  - Turn-by-turn
    - Based on continuous Fourier Transform
      - Yuri Alexahin & Eliana Gianfelice-Wendt
    - On-line coupling correction
      - Yuri Alexahin & Eliana Gianfelice-Wendt
    - Independent component Analysis – aimed to replace LOCO
      - PhD students: Xiaobiao Huang, Alexey Petrenko, Kseniya Astrelina
    - AC-dipole (adiabatically excited forced oscillations)
      - PhD student - Ryoichi Miyamoto
  - Tune shifts due to small change of quad current (limited application)
- Only LOCO delivered accuracy sufficient for building a good model of the machine optics
  - The turn-by-turn is promising but did not achieve yet the same level of accuracy and sophistication

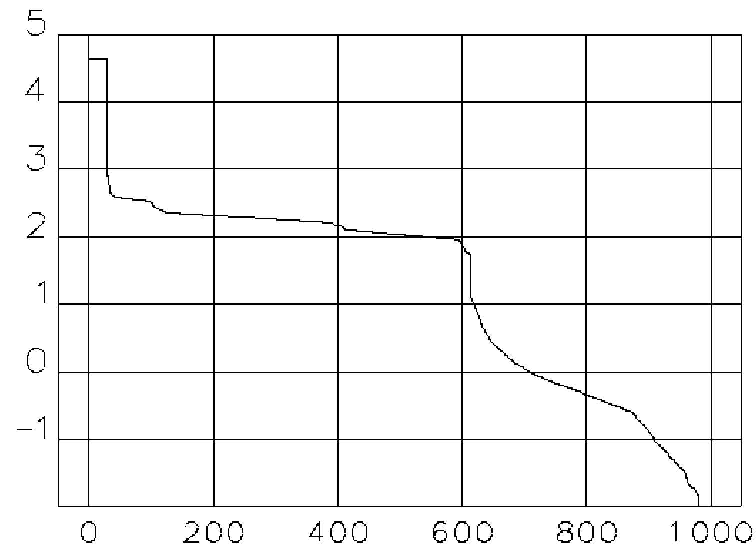
Orbit Response - LOCO (Linear Optics from Closed Orbit)

Data Acquisition

- Data acquisition is completely automated
  - Large number of differential orbits ([20 – 100] + energy)
  - Each orbit has all BPMs (both planes)
  - Dif. orbit is difference between positive and negative excitations
    - Smaller excitation – less sensitivity to non-linearities
  - Settings and readbacks for all magnets are recorded and then these files are directly included to optics files
- Data acquisition time
  - usually ~20 orbits are acquired for each polarity & then averaged (~40 data acquisitions, "+" & "-")
  - 50 correctors, 2 s per acquisition, 40 acquisitions per orbit
    $\Rightarrow$ 2000 acquisitions & 4000 s total time
  - Depending on time available and required accuracy the measurement takes 1 to 2 hours

Data Analysis for Orbit Response

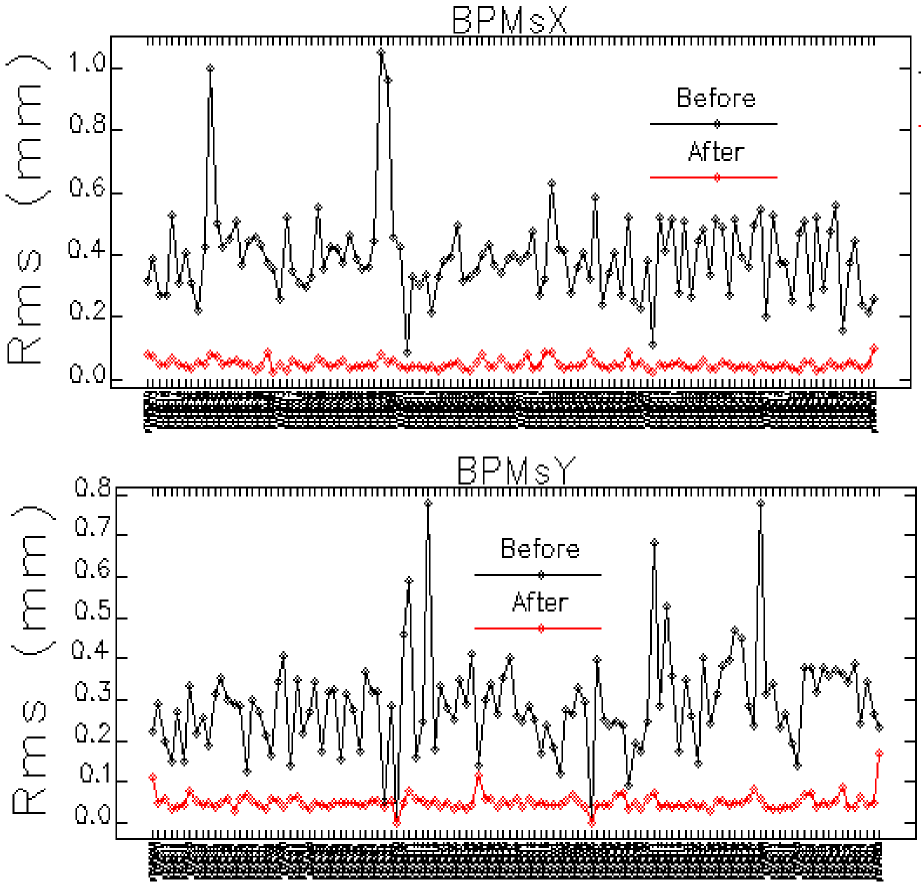
- Data analysis is based on SVD inversion of response matrix
  - We extended the algorithm developed by V. Sajaev of ANL
  - The extension included
    - Fully coupled x-y treatment of betatron motion
    - Addition of dispersion measurements to the fit
  - Software also includes a correction to dif. orbit due to energy change related to the orbit length change
  - Good initial approximation (made manually) was important for convergence
    - Design model did not converge
  - Data analysis is not completely auto-matic – a good physicist is required
    - SVD cut-off, choice & number of quads & skew-quads for correction, etc.
  - What removes degeneracy???
    - Number of unknowns is larger than the SVD cut-off



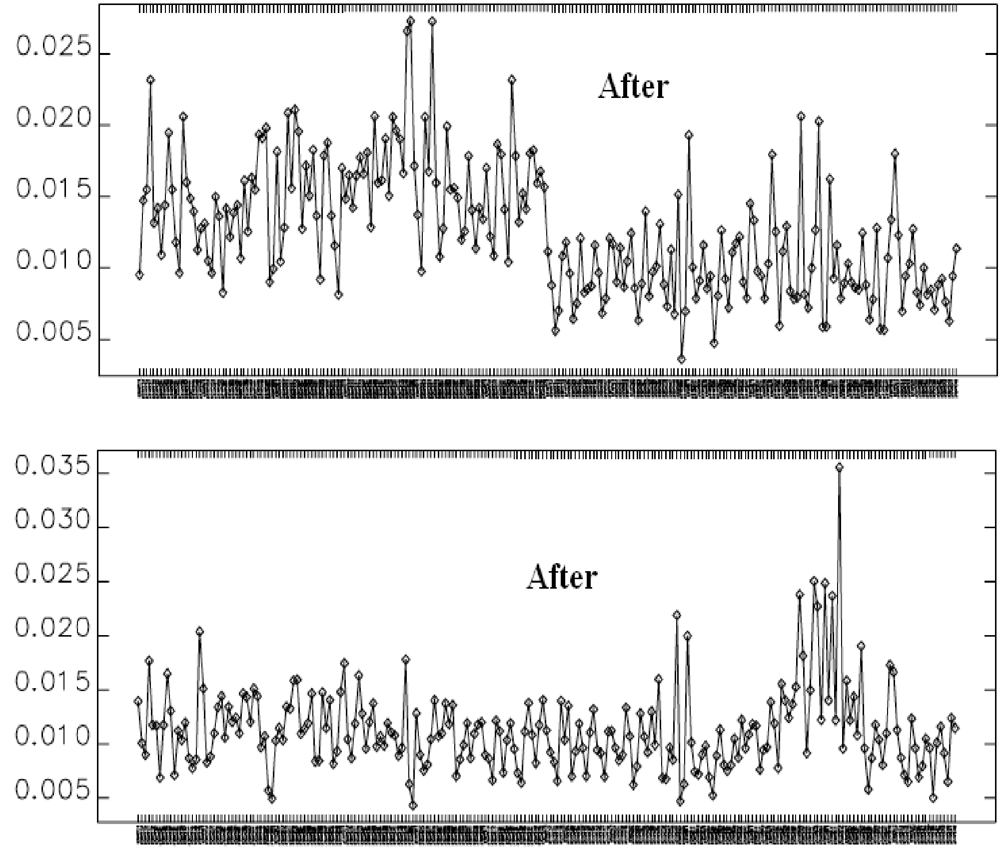
The spectrum for Tevatron
SVD cut-off was typically chosen at 1, which corresponds to 600-650 singular values.

Orbit Response Measurements in Tevatron

- New Tevatron BPMs significantly improved accuracy (50→15 μm)



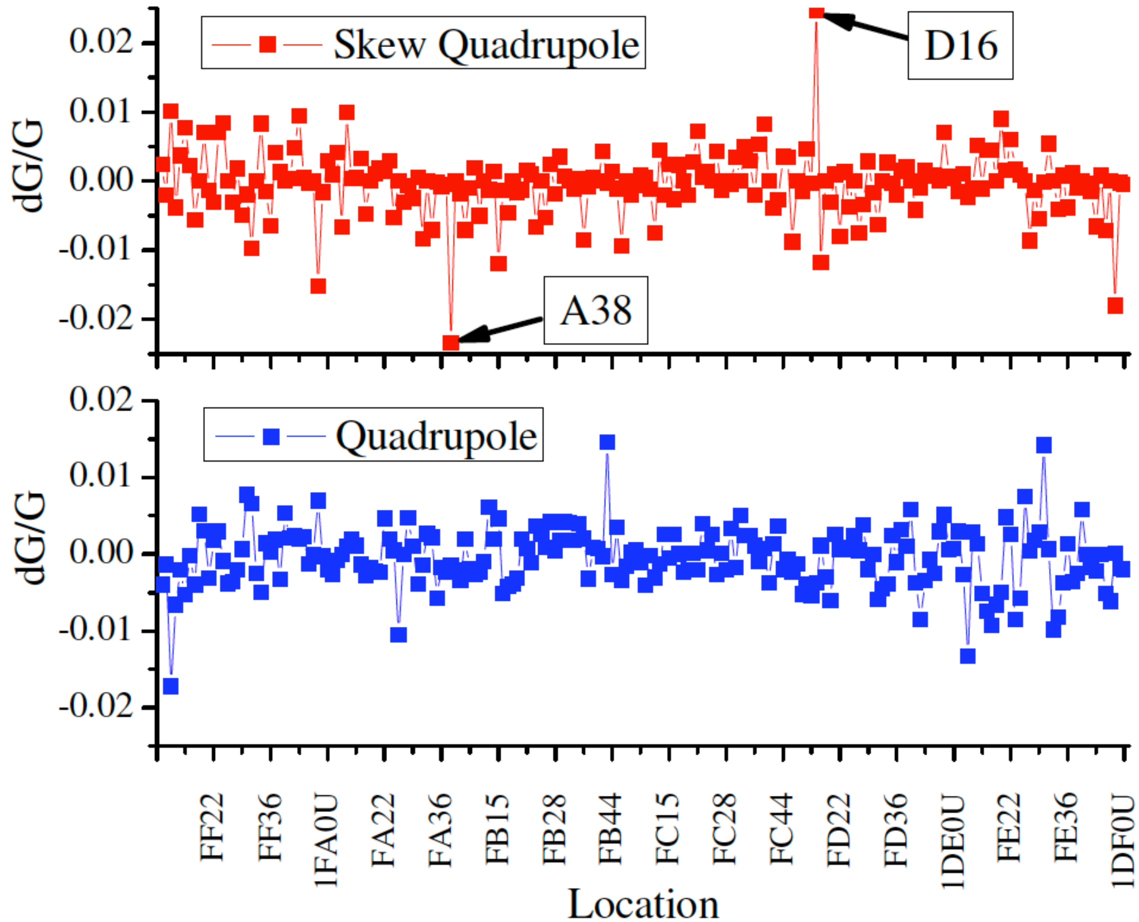
Old Tevatron BPMs



New Tevatron BPMs

RMS difference (mm) between the measured and modeled orbit vs. BPM name. Top – horizontal orbit, bottom - vertical orbit.

Orbit response measurements in Tevatron (continue)



Measured relative quadrupole and skew-quadrupole errors for Tevatron (D16 was rolled in wrong direction at the shutdown previous to the measurements: it is fixed now)

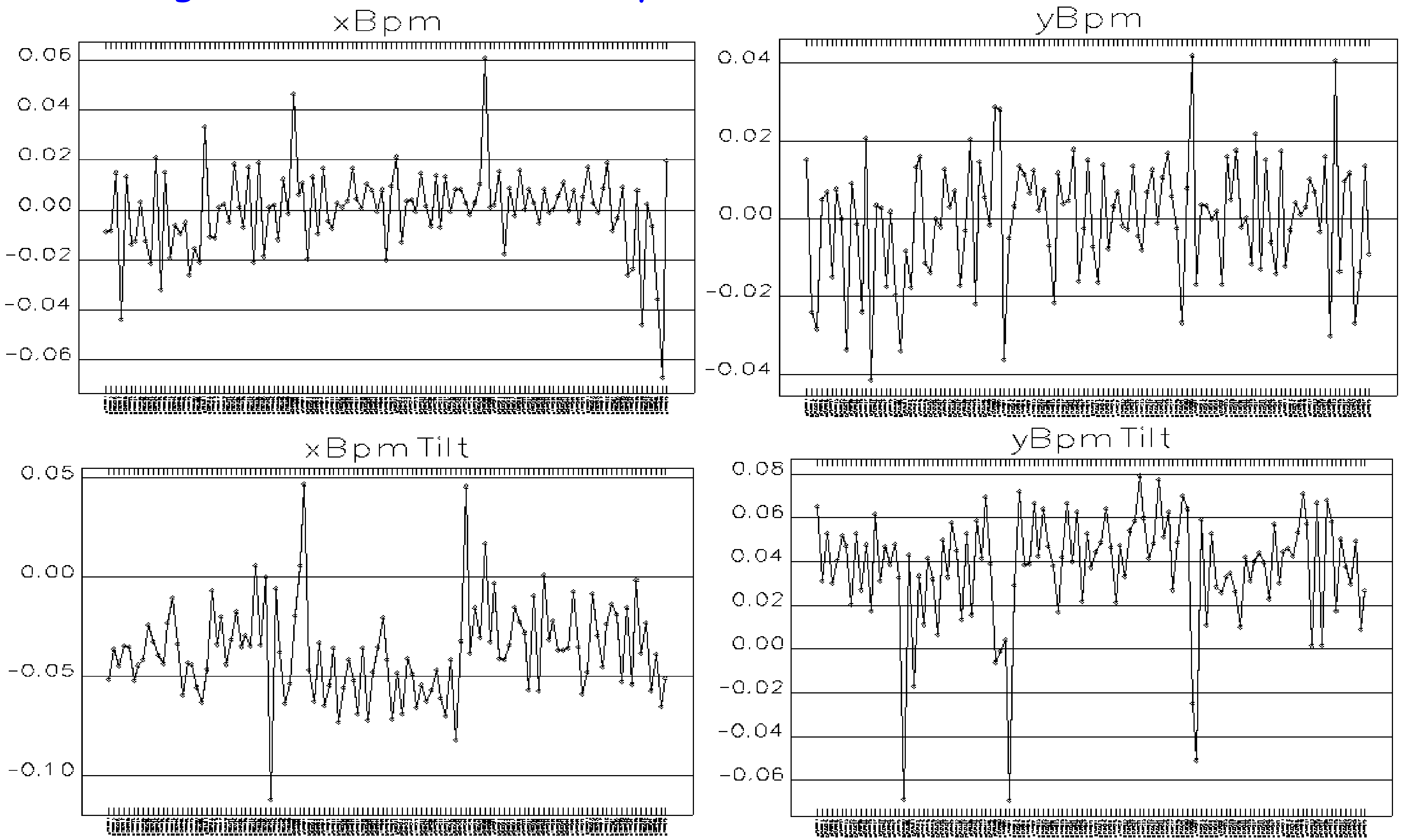
Relative quadrupole errors in the Tevatron final focus

Name	Gradient Error 0.1%
B0Q3	-1.118
B0Q2	-0.187
B0Q3D	-0.009
B0Q3F	-0.047
D0Q3	-0.949
D0Q2	-0.083
D0Q3F	0.024
D0Q3F	-0.184

- There is a systematic difference between main bus SC dipoles and quads
  - Comparing to magnetic meas. (~30 years old) quads are ~0.15% stronger at injection and ~0.18% at the top energy

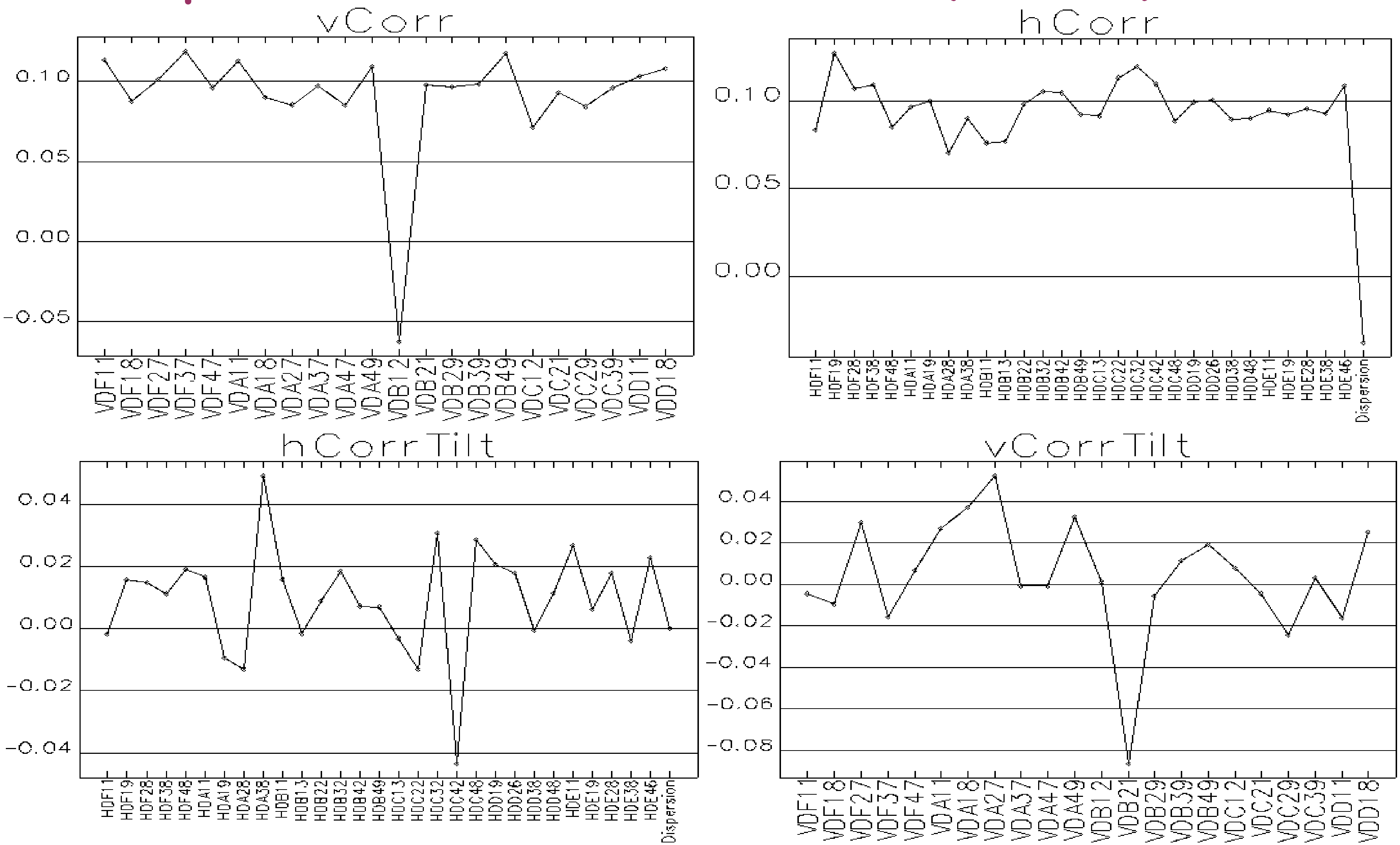
Orbit response measurements in Tevatron (continue)

- Unaccounted gain errors would result in up to 10% errors for $\Delta\beta/\beta$
- ~4 deg. rolls are related to asymmetric locations of BPMs connections



Relative gain errors (top) and rolls (bottom, 1 unit=90 deg.) for Tevatron BPMs.

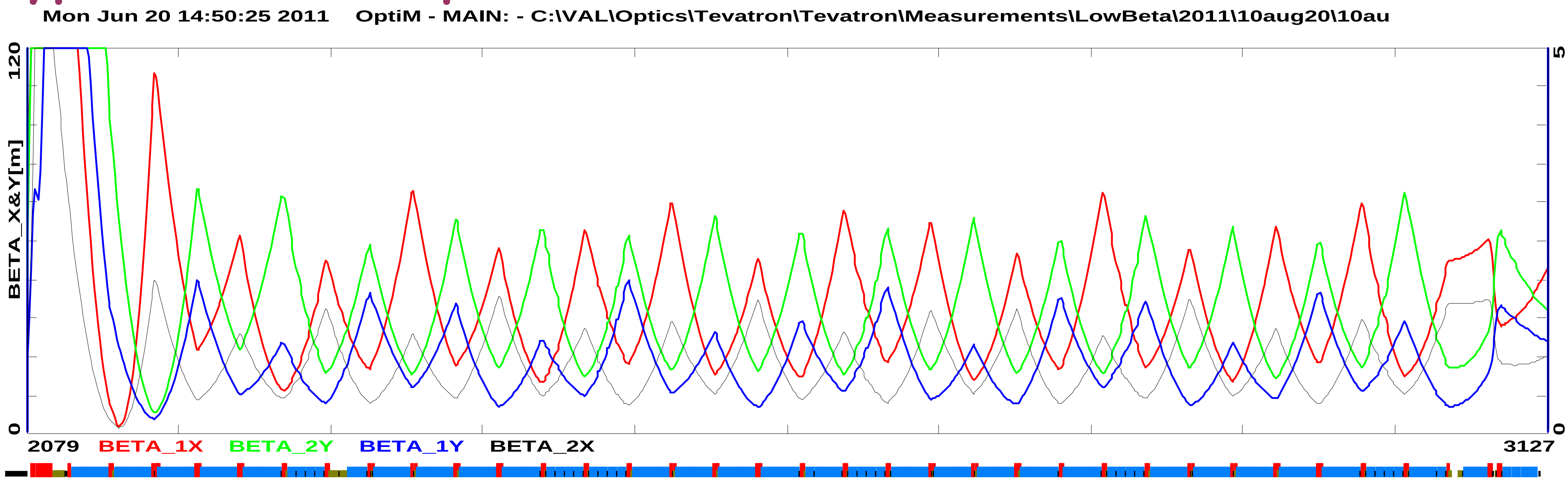
Orbit response measurements in Tevatron (continue)



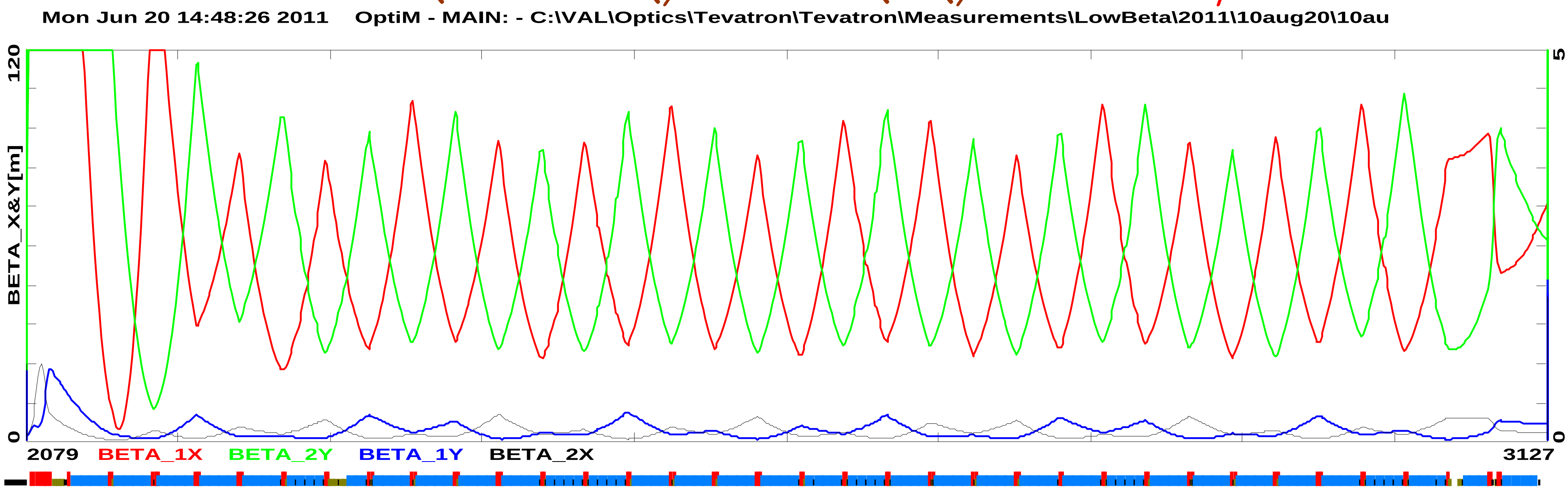
Relative corrector errors (top) and Corrector rolls (bottom, 1 unit=90 deg.)

- In average the corrector calibration error is not distinguishable from BPM calibration error

Typical Collision Optics at the Central orbit



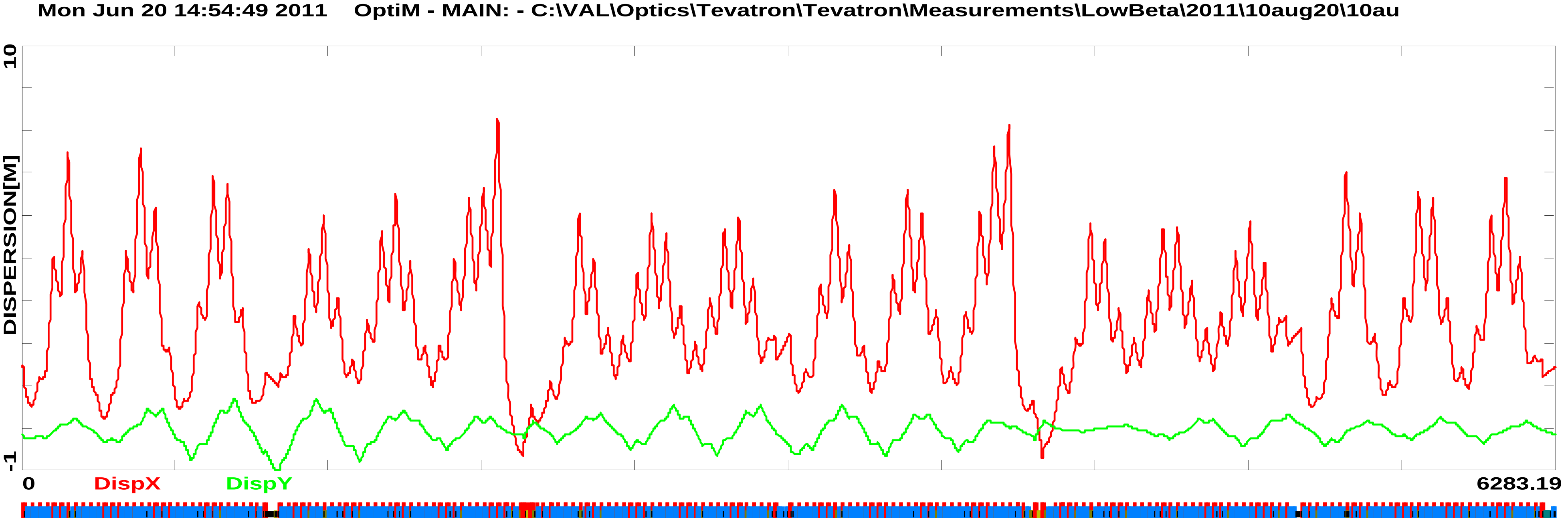
Nominal tunes: Qx=0.5891 Qy=0.5866 Qx-Qy=0.0024 Tune split=0.0020



Tunes are separated: Qx=0.5884 Qy=0.5782 Qx-Qy=0.0102 Tune split=0.0014

Coupled β-functions for Tevatron sector B

Typical Collision Optics at the Central orbit (continue)

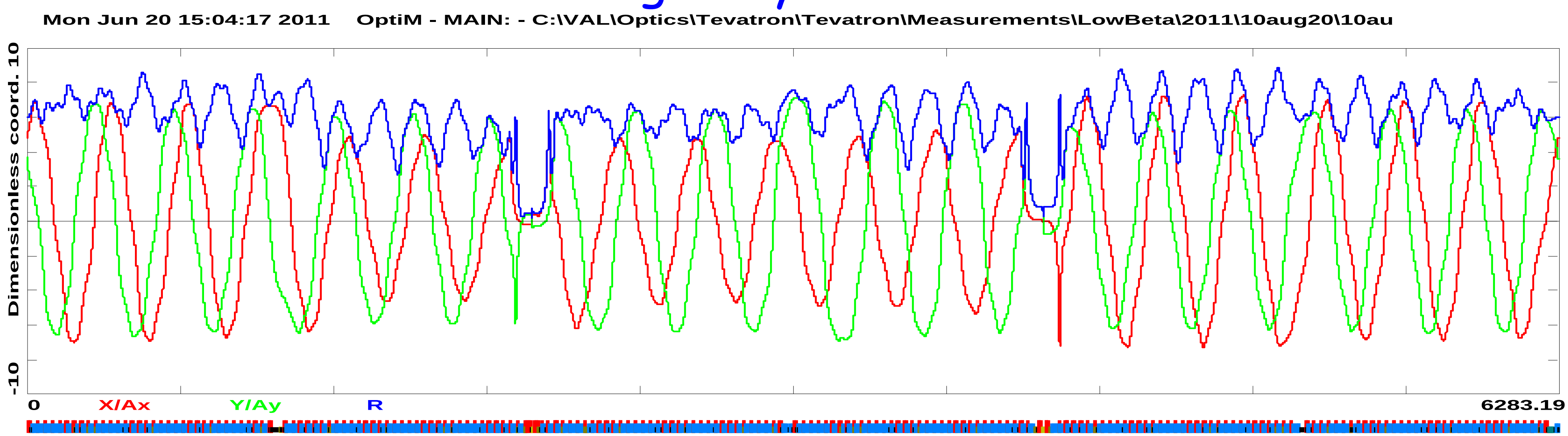


Dispersions through the Tevatron

- Optics design strategy for the latest Tevatron tune
  - Make both dispersions zero in IPs
  - Make β^* equal to 28 cm

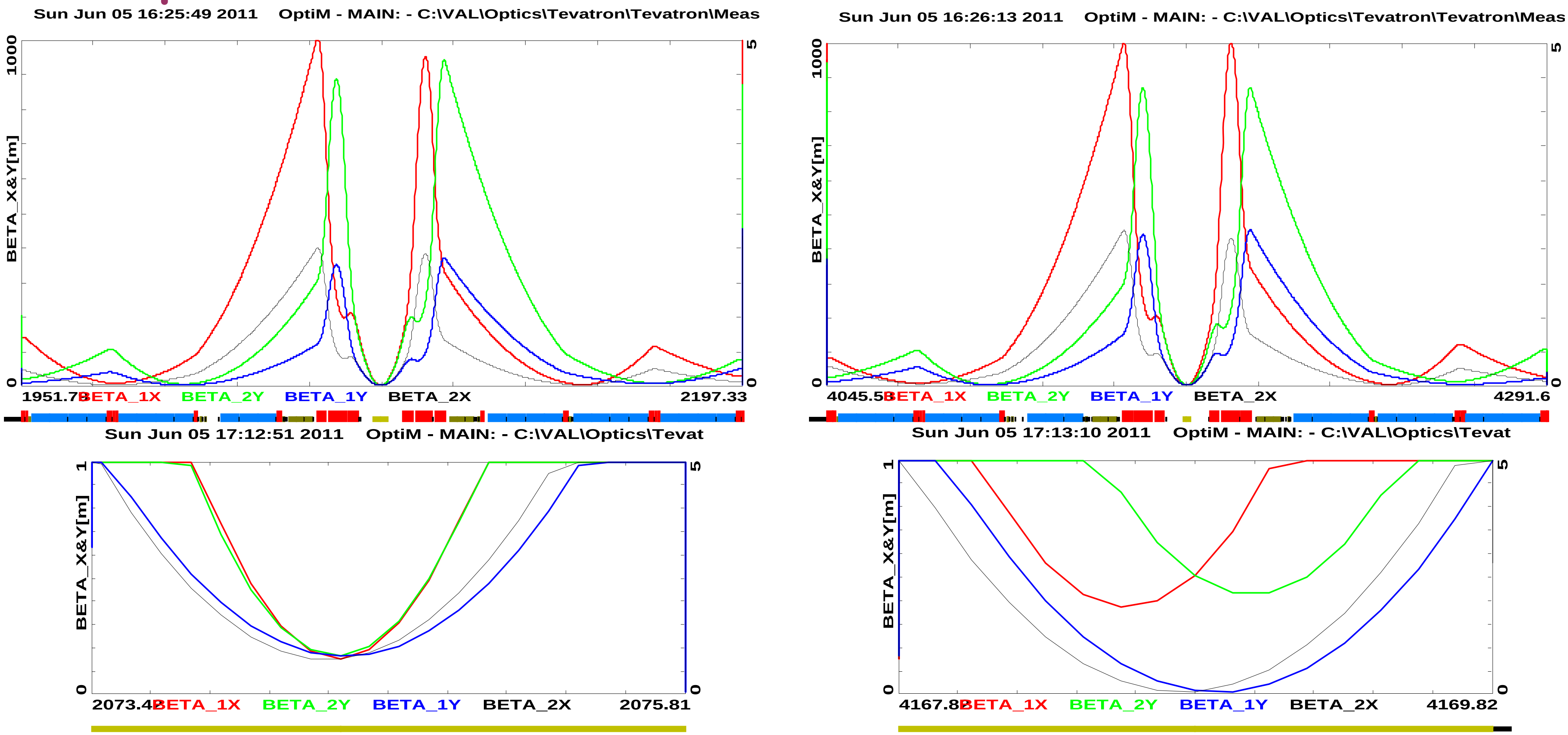
Beam Separation and Two Beam Optics Handling

- Beams are separated at helical orbits with el.-static separators
- The beam separation is limited by
  - the aperture at injection
  - and by available voltage at the top energy
- It was a considerable effort to optimize the separation at collisions and transition from the injection- to collision-helix
- Parasitic near-IP collisions make a larger contribution to the beam-beam effects than all other parasitic collisions together
- Beta-functions are changed by ~15% when beams are at helix



Helical beam separation in Tevatron in beam sigmas

Twiss parameters in IPs



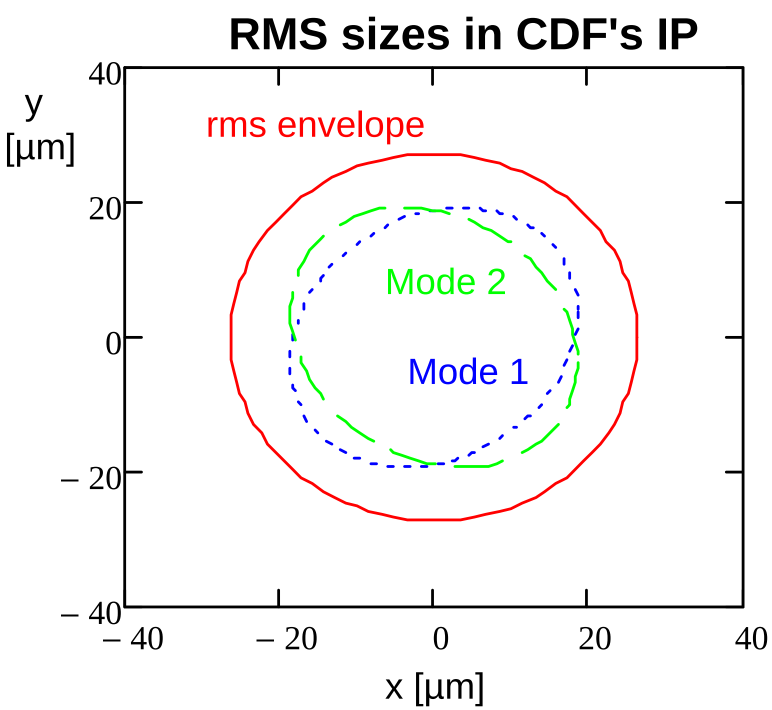
Coupled beta-functions for CDF (left) and D0 (right); Q_x=20.5891, Q_y=20.5866, Q_x-Q_y=0.0025, Tune split=0.0020

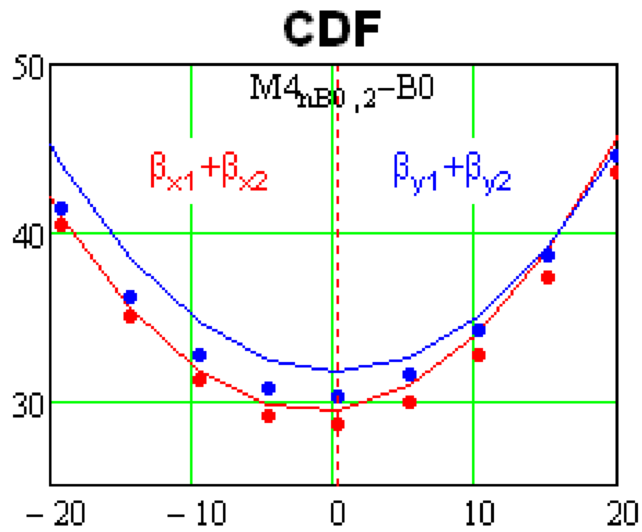
Name	β_{X1}	α_{X1}	β_{Y1}	α_{Y1}	$\nu_1/2\pi$	β_{X2}	α_{X2}	β_{Y2}	α_{Y2}	$\nu_2/2\pi$	u
IMB0	14.8	-0.0084	15.7	0.0186	0.2194	14.6	-0.0503	15.9	-0.029	0.2814	0.3835
IMD0	50.4	-0.5968	0.78	0.0920	0.4658	0.23	-0.0516	50.0	0.4316	0.0563	0.0275

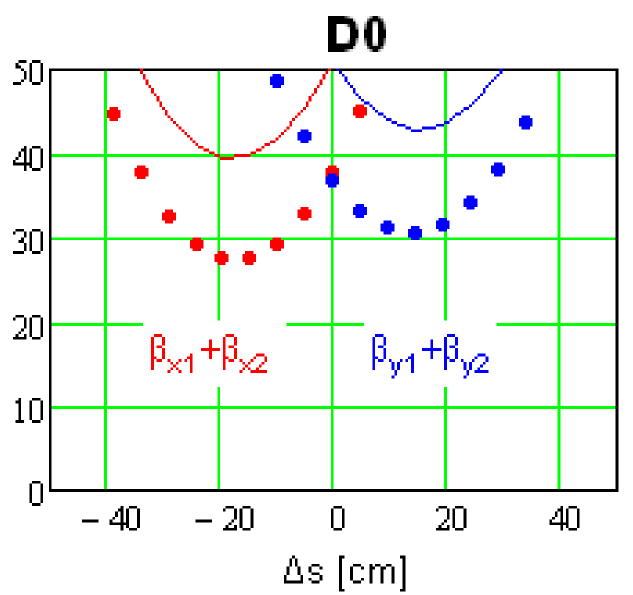
- LOCO cannot accurately predict IP waists if BPMs are outside IP region

Twiss parameters in IPs (continue)

- Nearest to the IPs BPMs are located 7.4 m from them ($\beta \approx 200$ m)
- 1% error in one BPM differential sensitivity moves IP position by 3.7 cm
  ($\delta z \approx \Delta_{err} L/2$, $\Delta_{err}=0.01$, $L=7.4$ m)
- In normal operations the Machine is completely coupled

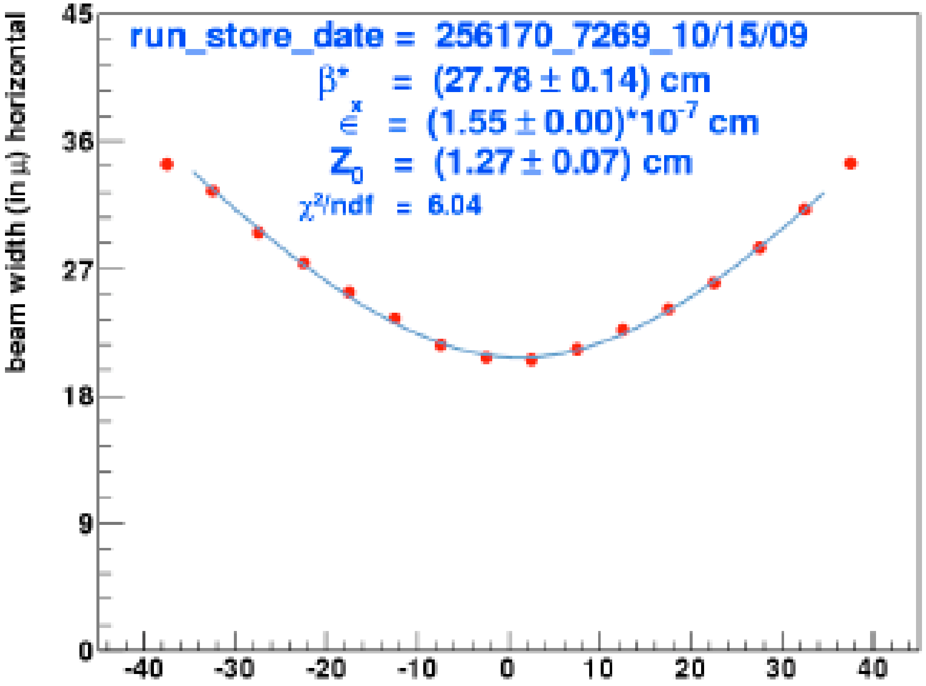


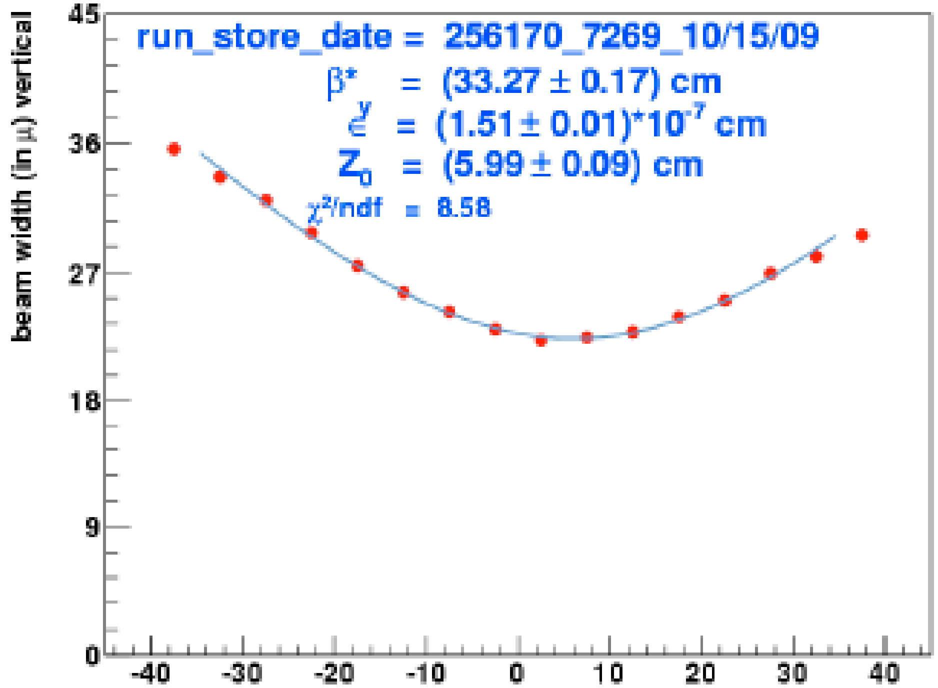




Dots show b-functions computed without coupling

Optics Measurements by Detector Collaborations





D0 reconstruction of β^* values (made by Avdhesh Chandra)

- Detector collaborations measure the positions and rate of events
  - $\sigma_s > \beta^*$ => one can compute β^*, z_0 and ε_{eff}

$$\sigma^2 = \varepsilon_{eff}\left[\beta^* + \frac{(z-z_0)^2}{\beta^*}\right]$$

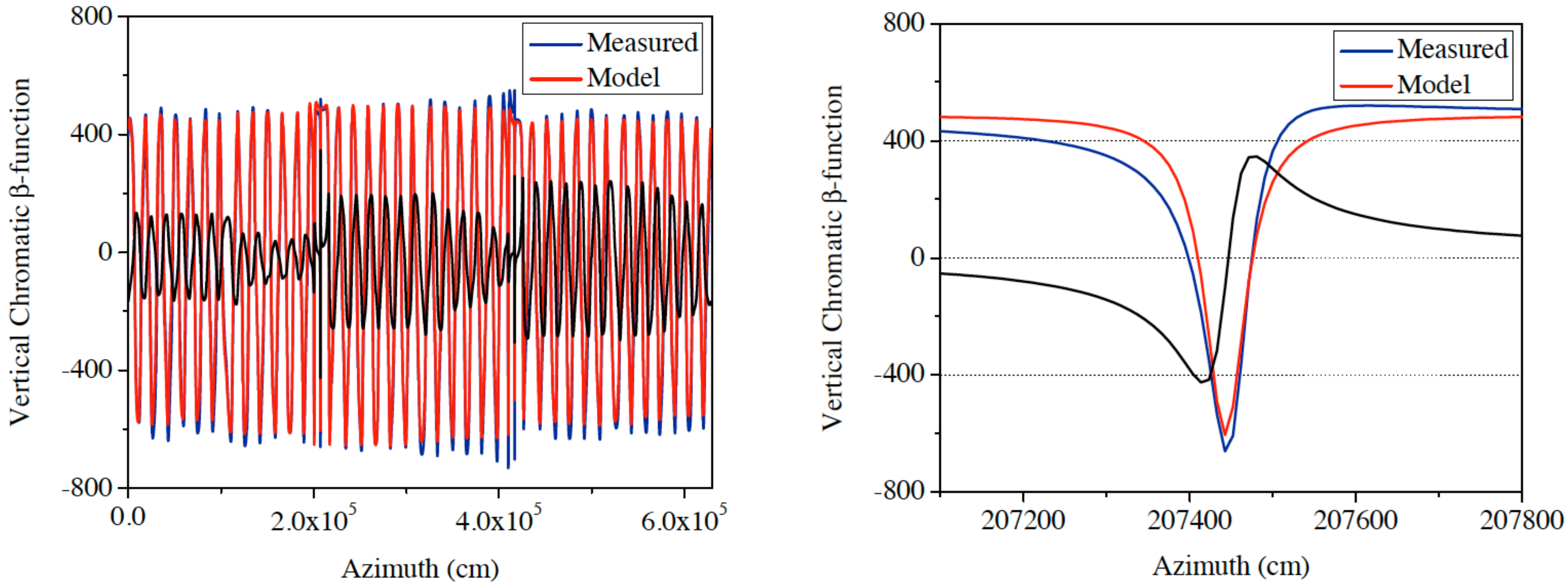
Second order chromaticity correction

- Horizontal beta-beating excited by a single quadrupole for an off-momentum particle can be described by the formula

$$\frac{\delta\beta}{\beta}(s) = -\frac{(\delta p/p)}{2\sin(2\pi Q)}\frac{(QL)}{(B\rho)}\beta_0 \cos\left(2\left|\psi_0 - \psi(s)\right| - 2\pi Q\right).$$

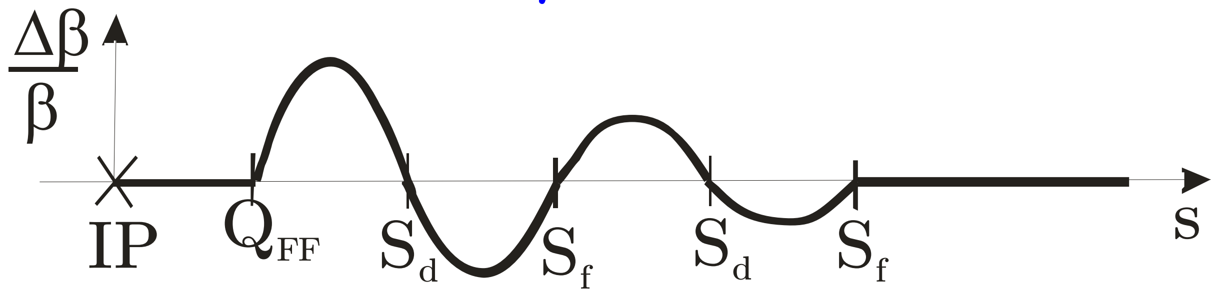
- The contribution to second-order chromaticity of the horizontal tune derived from the perturbation theory is given by the following expression

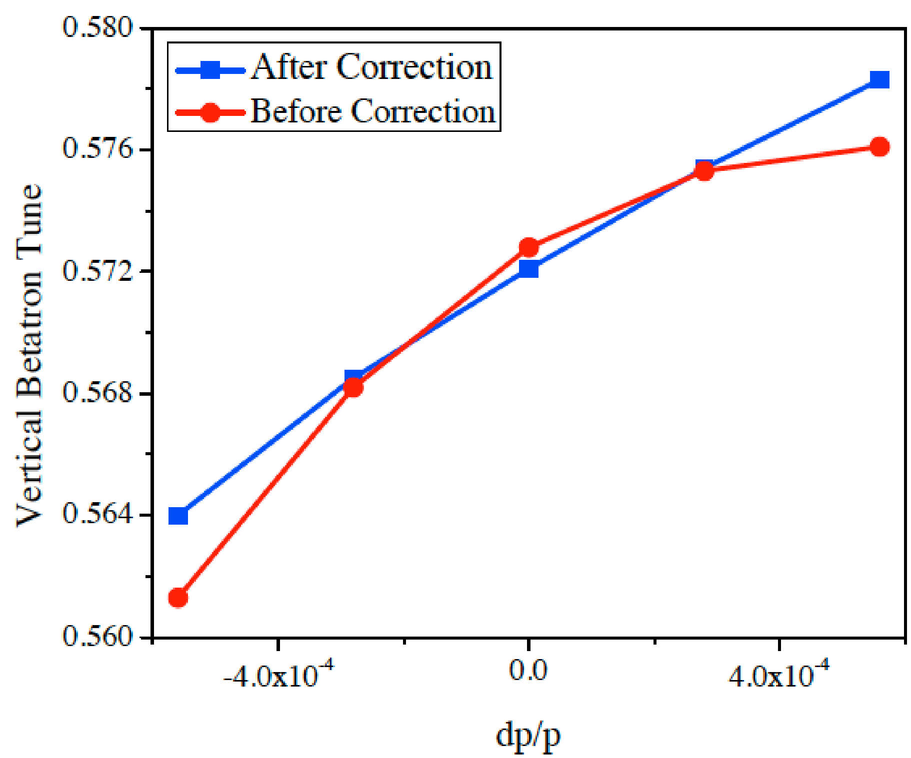
$$\frac{d^2Q}{d\delta^2} = \left(\frac{1}{4\pi}K\tilde{\beta}\right)\left(\frac{\delta\beta}{\beta}\frac{p}{\delta p}\right).$$



Chromatic beta-function vs. azimuth: left – entire machine starting at F0, right – in vicinity of CDF. Blue line - measured, red - model, black - proposed correction.

- Splitting chromaticity quads into families resulted in a suppression of beta-function chromaticity and, consequently, the second order chromaticity

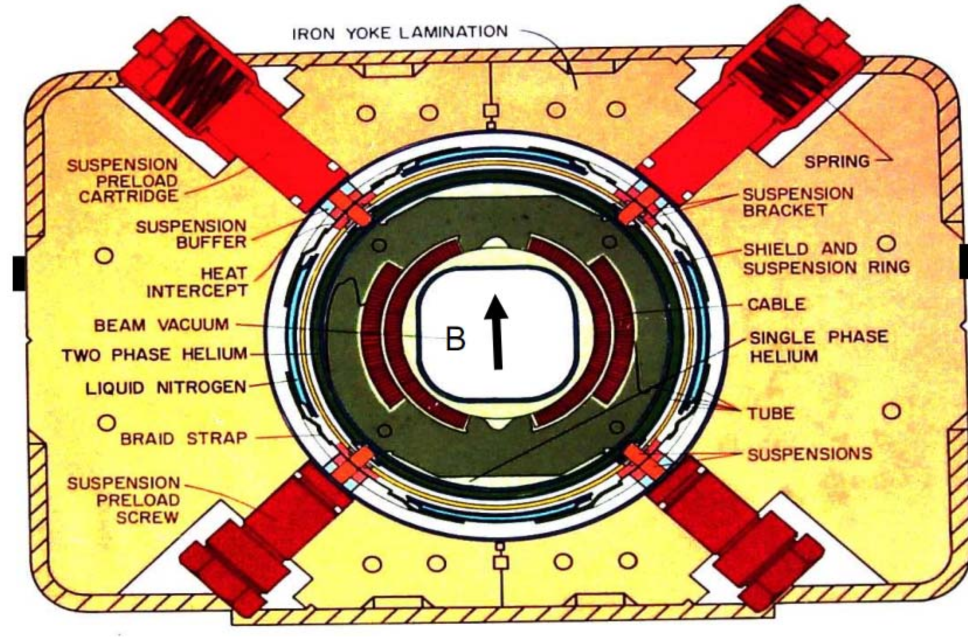




Dependence of the vertical betatron tune on particle momentum in the collider mode

X-Y coupling in Tevatron

- At the Run II beginning Tevatron had very large coupling
  - tune split ~0.4
- The reason was a displacement of SC coils in dipoles relative to the steel core due to compression of thermo-isolating coil support by ~150 μm
  - It makes skew-quad field in dipoles of $G_s A/B_0 \sim 1.4 \cdot 10^{-4}$ for $A=2.54$ cm
- The problem was exacerbated by a partial removal of main family skew-quads in vicinity of the IPs which made long pieces without coupling (112 dipoles without nearby skew-quad)
  - It looks like that the coupling was not making negative impact on the machine optics with one exception the emittance growth at transfers from the MI of ~15%



Tevatron dipole cross section

X-Y coupling in Tevatron (continue)

- The coupling was corrected by shimming dipoles which did not have nearby skew-quads in the summer 2003 shutdown
  - As it was expected it reduced the emittance growth at transfers
  - Later all dipoles were shimmed.
    - It reduced current of main skew-quad bus but did not reduce coupling coming from scatter of skew-quad components in dipoles
- Before and after coupling correction we operated Tevatron at small tune split ($\Delta Q < 5 \cdot 10^{-3}$)
  - Simulations show that for equal emittances ΔQ has comparatively small effect on the emittance growth at transfers
- The coupling correction reduced the cross-plane β-functions (still depending on ΔQ) and yielded a reduction of the emittance growth

$$\varepsilon_1' = \varepsilon_1 A_{11} + \varepsilon_2 A_{12}$$

$$\varepsilon_2' = \varepsilon_1 A_{21} + \varepsilon_2 A_{22}$$

$$A_{11} = \frac{1}{2}\left(\frac{\beta_x}{\beta_{1x}}\left[(1-u)^2 + \alpha_{1x}{}^2\right] + \frac{\beta_{1x}}{\beta_x}\left[1 + \alpha_x{}^2\right] - 2\alpha_{1x}\alpha_x\right), \quad A_{12} = \frac{1}{2}\left(\frac{\beta_y}{\beta_{1y}}\left[u^2 + \alpha_{1y}{}^2\right] + \frac{\beta_{1y}}{\beta_y}\left[1 + \alpha_y{}^2\right] - 2\alpha_{1y}\alpha_y\right),$$

$$A_{21} = \frac{1}{2}\left(\frac{\beta_x}{\beta_{2x}}\left[u^2 + \alpha_{2x}{}^2\right] + \frac{\beta_{2x}}{\beta_x}\left[1 + \alpha_x{}^2\right] - 2\alpha_{2x}\alpha_x\right), \quad A_{22} = \frac{1}{2}\left(\frac{\beta_y}{\beta_{2y}}\left[(1-u)^2 + \alpha_{2y}{}^2\right] + \frac{\beta_{2y}}{\beta_y}\left[1 + \alpha_y{}^2\right] - 2\alpha_{2y}\alpha_y\right)$$

Optics Measurements with Turn-By-Turn BPMs

- A replacement of LOCO with turn-by-turn measurements has been highly desirable
  - Much faster measurements
  - Possibility to use it in the Booster
- Its implementation was exacerbated by the following problems
  - Strong coupling
    - ⇒ both betatron modes are present at each BPM
  - Operation near coupling resonance
    - ⇒ Synchro-betatron modes are overlapped making difficult to find mode amplitudes
  - Normally the longitudinal mode is weakly presented
    - ⇒ Dispersion measurements from transverse kicks have bad accuracy and are not helpful in building the model
  - Damping time depends on the beam emittances
    - Each measurement is unique – no reproducibility
- See details in A. Petrenko presentation

Optics Measurements with AC Dipole

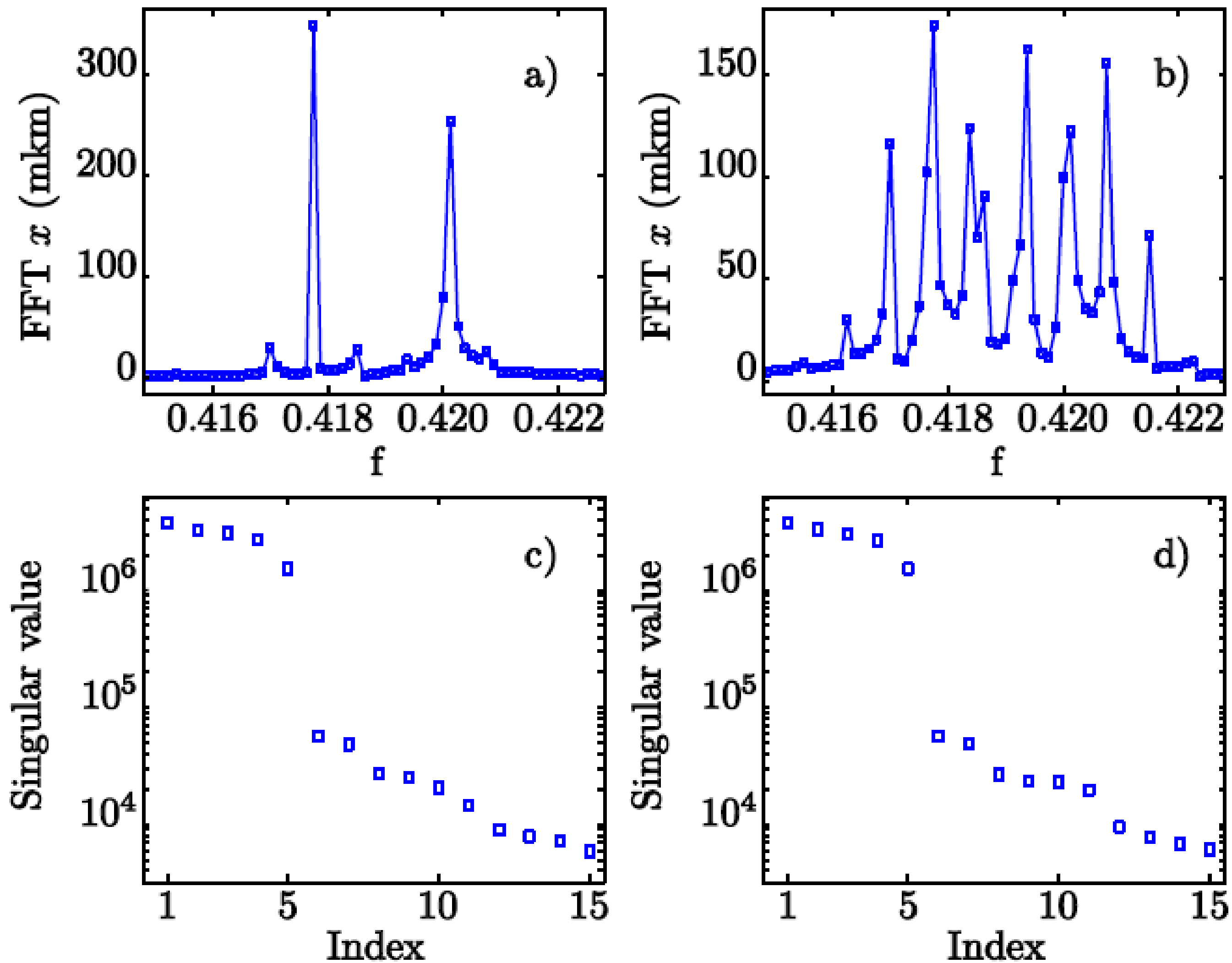
- Non-trivial effect of coupling and synchro-betatron motion on the amplitudes observed on BPMs when tunes are close (real machine tunes)
- Cannot be used in Booster ("too fast" cycling synchrotron, 20000 turns altogether) and in the course of acceleration in Tevatron
- Never was considered as a replacement for LOCO

Conclusions

- LOCO delivered accuracy required for the Tevatron Run II commissioning and upgrades
  - But it requires long time for data acquisition
- Tevatron proved to be quite reproducible machine (once in half year measurements are sufficient to keep it at optimal tune)
- Turn-by-turn is still did not delivered the same accuracy
  - Never has had the same priority because LOCO already satisfied our needs
  - Booster improvement plan (next few years) requires turn-by-turn measurements
    - It will be a priority in the near future

Backup Slides

Simulations with small and large chromaticity



$$\mathbf{M} \equiv [x_{nm}] = [\mathbf{x}_1, ..., \mathbf{x}_M]$$

$$\mathbf{x}_m = x_m(t_n)$$

$$m = 1, ..., M$$

$$n = 1, ..., N$$

$$\mathrm{M} = \mathbf{U\Sigma V}^T$$

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & & 0 \\ 0 & \sigma_2 & & 0 \\ & & ... & \\ 0 & 0 & & \sigma_M \end{bmatrix}$$

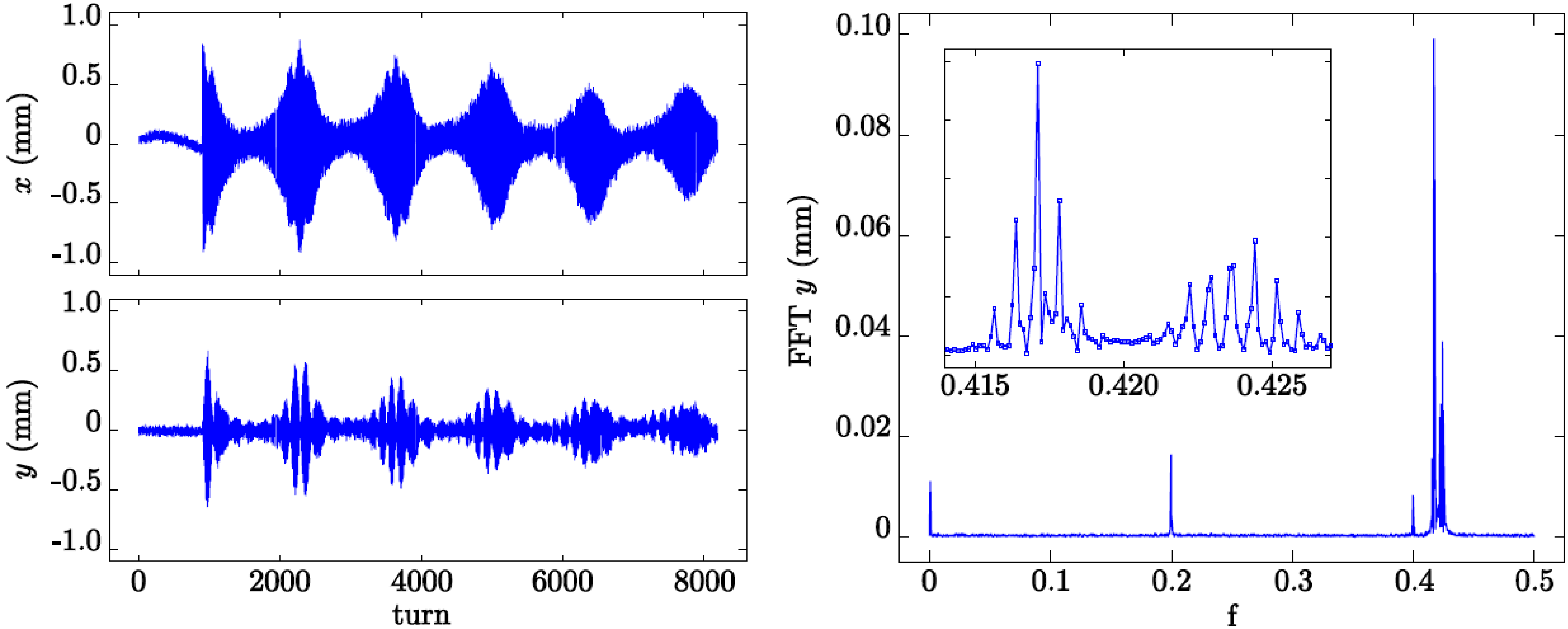
$$\begin{bmatrix} x_1 \\ x_2 \\ ... \\ x_N \end{bmatrix}_m = \sum_{j=1}^{5} \sigma_j \mathrm{V}_{mj} \begin{bmatrix} u_1 \\ . \\ ... \\ u_N \end{bmatrix}_i + ...$$

Fourier amplitudes and singular values for single particle experiencing betatron and synchrotron oscillations in the Tevatron.

Beam tracking was performed with Elegant for two sextupole settings corresponding to small and large chromaticities: left - $\xi_x = -3$, $\xi_y = 3$; right - $\xi_x = 19$, $\xi_y = 26$.

- 5 modes: s & c for 2 betatron modes + energy offset ($M / f_0 < \tau_{decoh}$)

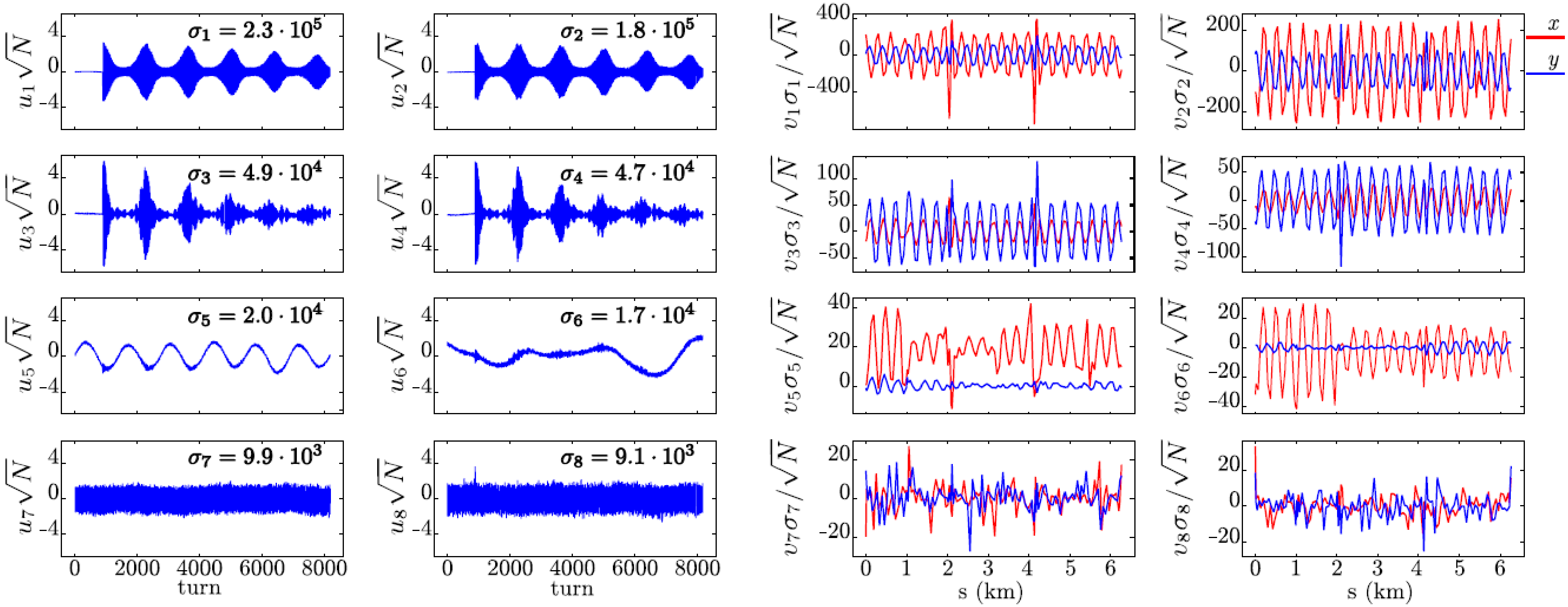
Measured turn-by turn data and its spectra



Coherent transverse oscillations of proton beam in the Tevatron recorded by horizontal and vertical BPMs (left). At about 900th turn beam was kicked in the horizontal plane. FFT amplitude of the vertical BPM signal is shown on the right. Timing errors of BPM electronics with the periodicity of five turns produce coherent lines at tunes of 0.2 and 0.4. Oscillation amplitude damping is due to nonlinear decoherence of betatron oscillations.

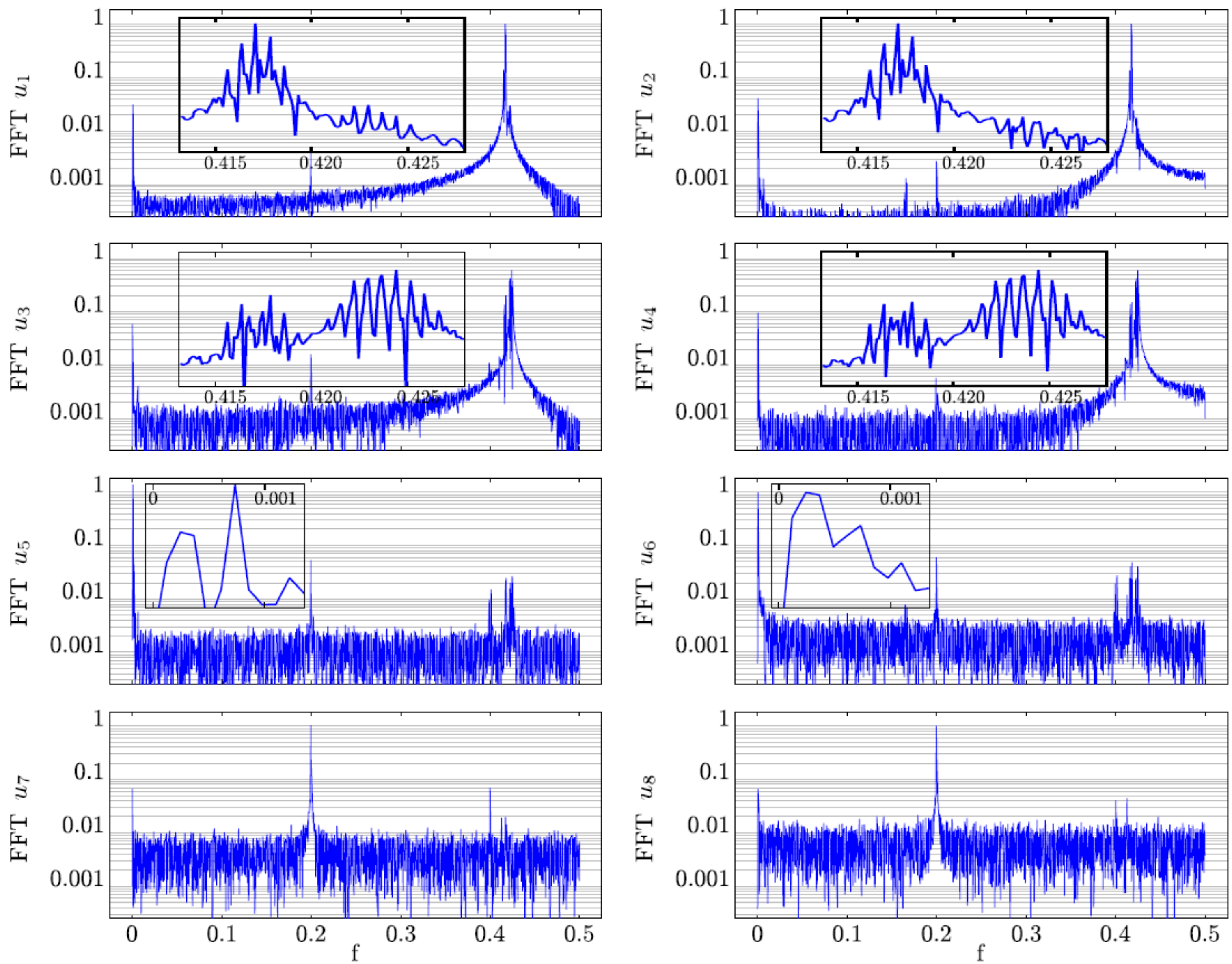
- Synchro-betatron lines are overlapped for nominal Tevatron settings

Singular Value Decomposition for Tevatron turn-by-turn data



Temporal (left) and spatial (right) modes of MIA corresponding to the largest 8 singular values.

- 8 modes
  - 1-4: sin-like and cos-like for two betatron modes
    - The same envelopes but 90 deg. phase difference for each mode
  - 5: synchrotron motion
    - The same on all BPMs because of small frequency (spatial comp ∝ D)
  - 6: beam motion excited by motion of FF quads
  - 7-8: timing errors of BPM electronics



FFT amplitude spectra of temporal modes presented in previous slide

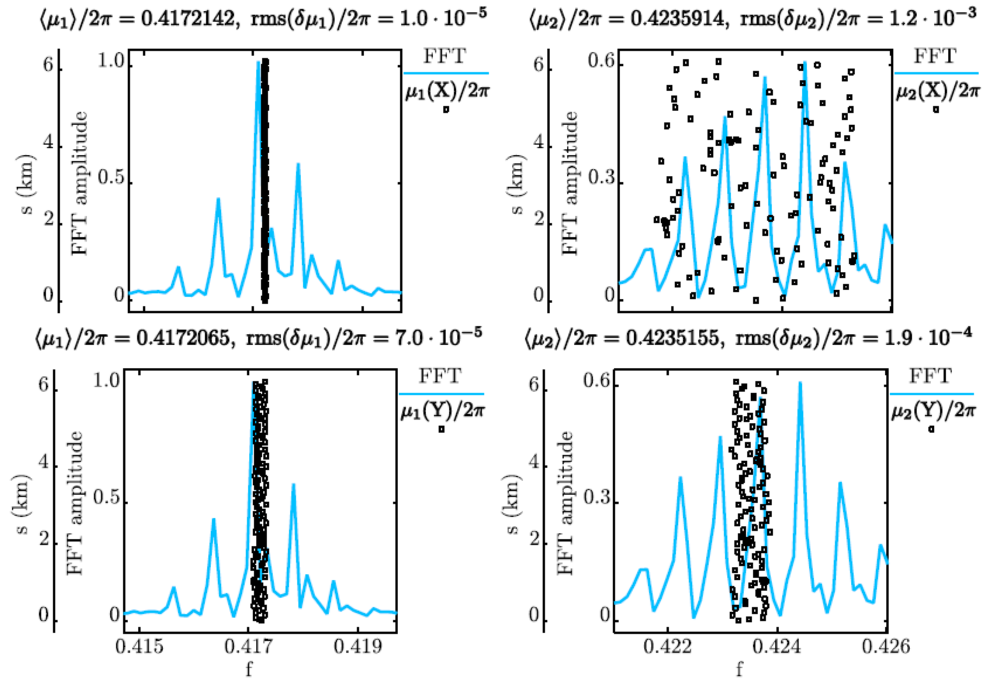
- Betatron modes are not completely separated
  - Errors are too large up to 10%

- Mode orthogonality
  - SVD makes the betatron (temporal) modes globally orthogonal

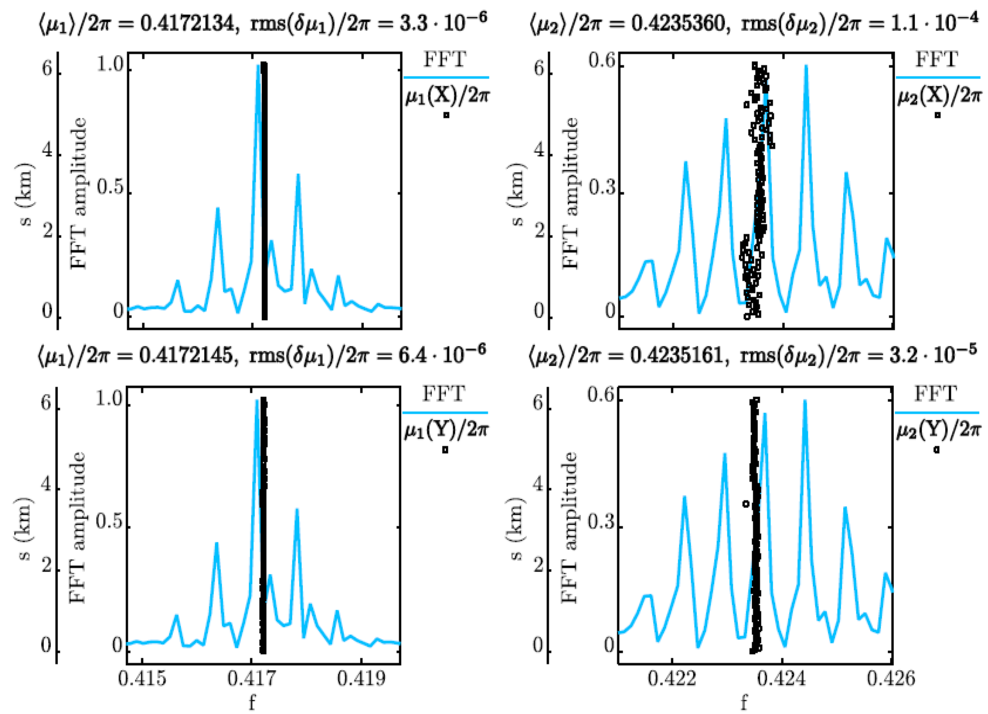
$$\sum_k u_{ki} u_{kj} = \delta_{ij}$$

  - However being sin and cos parts of betatron motion each 2 modes must be locally orthogonal (90°phase shift)
    - It is not delivered by SVD
- Mode separation/decoupling
  - Linear combination of four betatron modes should address the problem
  - Other mode suppression in spectrum does not work for overlapped modes
  - A. Petrenko suggested a method for improvement of mode orthogonality
    - Each BPM is treated as two BPMs separated by 1 revolution
    - Algorithm minimizes the spread of phase advances between each pair of virtual BPMs
  - I.e. it restores local orthogonality

Before rotation



After rotation



Building the model from turn-by-turn data

- The same as LOCO without dispersion data the turn-by-turn measurements do not deliver satisfactory accuracy for the optics model built on the base of measurements
- More work and new ideas are required

Optics Model versus Model Independent Analysis

- Building an optics model on the base of optics measurements delivers a better accuracy for beta-functions and dispersion measurements
  - It allows to correct errors of the measurements !!!
- MIA can be a good first step but cannot deliver good accuracy if its results are not "digested" through the optics model