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Determination of precise model of a storage ring using response matrix fit: Application to Advanced Photon Source and Tevatron

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Tevatron related work is together with V. Lebedev, V. Nagaslaev, and A. Valishev, FNAL

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Sources of optics errors in accelerators

- Large accelerators like APS have hundreds of focusing elements designed to keep stored particles on orbit. Some of these elements may have unintended errors, some of them are designed to be nonlinear such that the focusing depends on the particle orbit inside the element
- Hundreds of small focusing errors result in accelerator optics that may differ significantly from the designed optics. As a result, the accelerator performance gets worse and accelerator control gets more complicated
- About 8 years ago, smaller light source storage rings developed a response matrix fit method to calibrate their optics. Around 2001 we have started such work at the APS storage ring

Orbit response matrix

- The orbit response matrix is the change in the orbit as measured by Beam Position Monitors (BPM) as a function of changes in steering magnets.

$$\begin{pmatrix} x \\ y \end{pmatrix} = M_{\substack{measured \\ model}} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}$$

- The response matrix is defined by the linear lattice of the machine; therefore it can be used to calibrate the linear optics in a storage ring
- Modern large accelerators usually have a few hundreds of BPMs and several dozens of steering magnets, so the measurements of the response matrix generates a very large amount of precisely measured data

Orbit response matrix fit method

- The main idea of the analysis is to adjust all the variables that the response matrix depends on, in order to make the model response matrix best fit the measured response matrix
- To do this, we solve the following equation:

$$M_{measured} - M_{model}(z) = 0\,,$$

$$\Delta z = \left(\frac{\partial M_{model}}{\partial z}\right)^{-1} \cdot \left(M_{measured} - M_{model}(z_0)\right)$$

Here *z* is a vector of all variables that the response matrix depends on

The method was first suggested by Corbett, Lee, and Ziemann at SLAC and refined by Safranek at BNL. A very careful analysis of the response matrix was done at the NSLS X-ray ring, ALS, and later at APS. A similar method was used at ESRF for characterization and correction of the linear coupling and to calibrate quadrupoles by families.

Orbit response matrix fit

- The response matrix depends on the following parameters:
  - Focusing errors
  - Steering magnet calibrations
  - BPM gain errors
  - Energy shift associated with steering magnet changes
  - BPM nonlinearity
  - Longitudinal position of BPMs and correctors
  - Quadrupole tilts
  - Corrector tilts
  - BPM tilts

Main parameters (Focusing errors, Steering magnet calibrations, BPM gain errors)

Main coupling parameters (Quadrupole tilts, Corrector tilts, BPM tilts)

- For many accelerators coupling is not significant, therefore response matrix fit can be performed separately for direct and coupled responses
- For APS, we use all the parameters above except longitudinal positions

Orbit response matrix fit

- APS has 400 quadrupoles and 320 steering magnets and 400 BPMs per plane
- For our measurements we use 27 steering magnets in each plane and all BPMs. The resulting coupled response matrix has about 44,000 elements, and the number of variables is 2400.
- Finally we solve the following equation (by iterations):

$$X = M^{-1} \cdot V$$

$$\begin{pmatrix} 1 \\ \times \\ 2400 \end{pmatrix} = \begin{pmatrix} 2400 \\ \times \\ 44000 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \times \\ 44000 \end{pmatrix}$$

800 Mb

Program organization chart

GUI: tcl/tk - unix, linux

↓

Fitting program
tcl/tk

↓

Response matrix derivative calculation

- optim or elegant calculate RM for different variables (can run in parallel)
- sddstoolkit is used to postprocess and build RM derivative
- Inverse RM derivative is computed with matlab of sddstoolkit

↓

Iterations

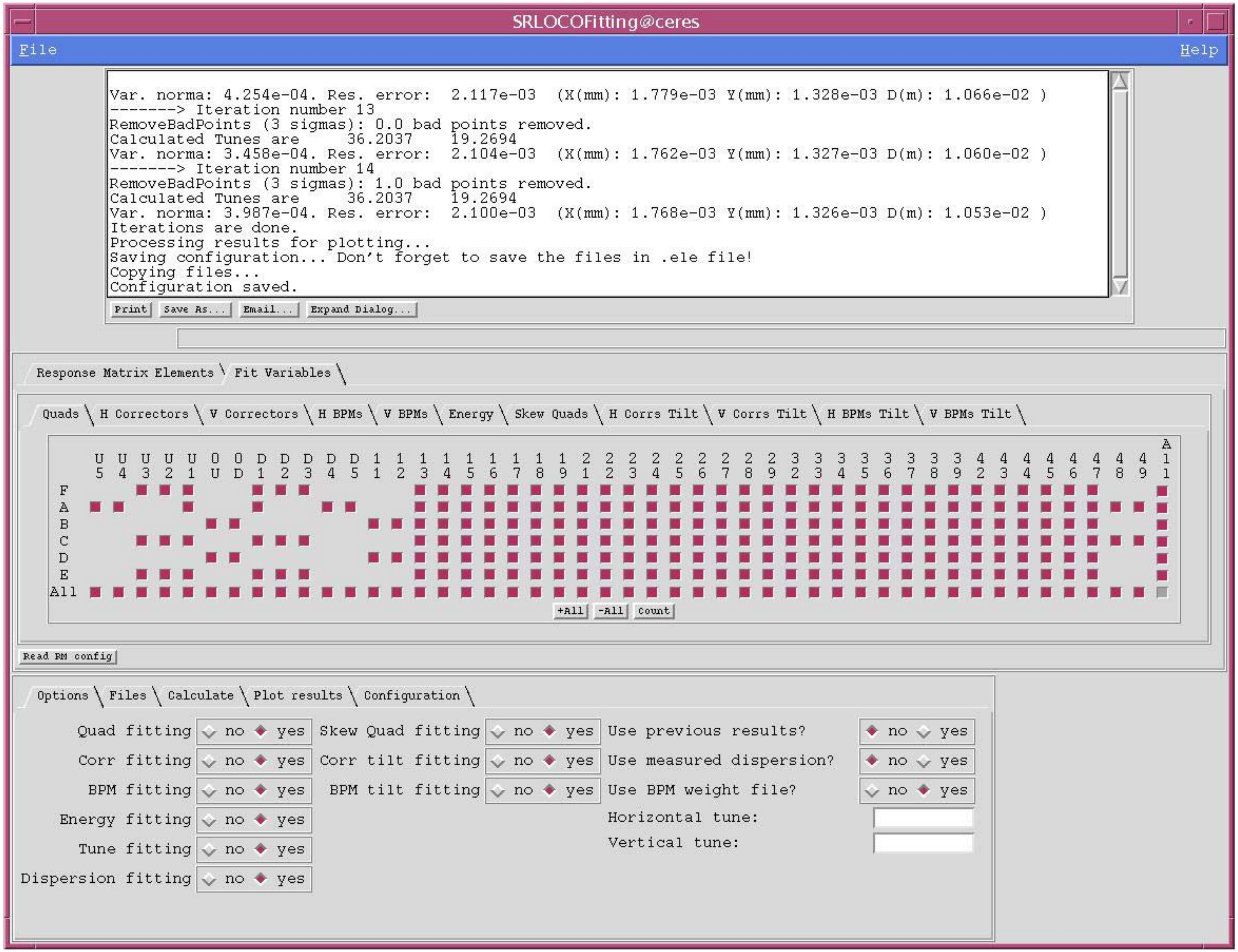
- RM calculations – elegant or optim
- preprocessing, postprocessing - sddstoolkit

↓

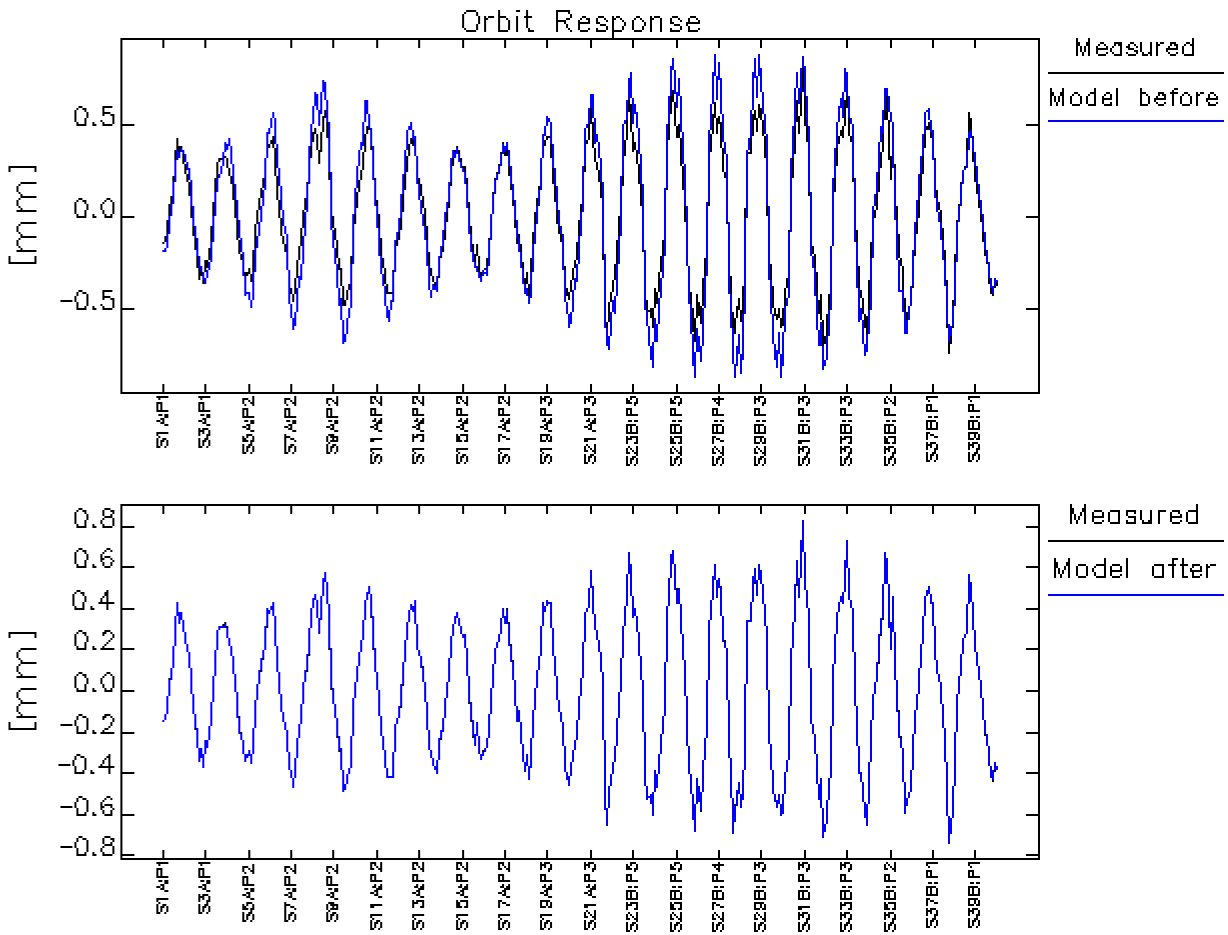
Output

- all results are stored in sdds files
- `sddsplot` can be used for graphic output

Program interface



Measurement and fitting



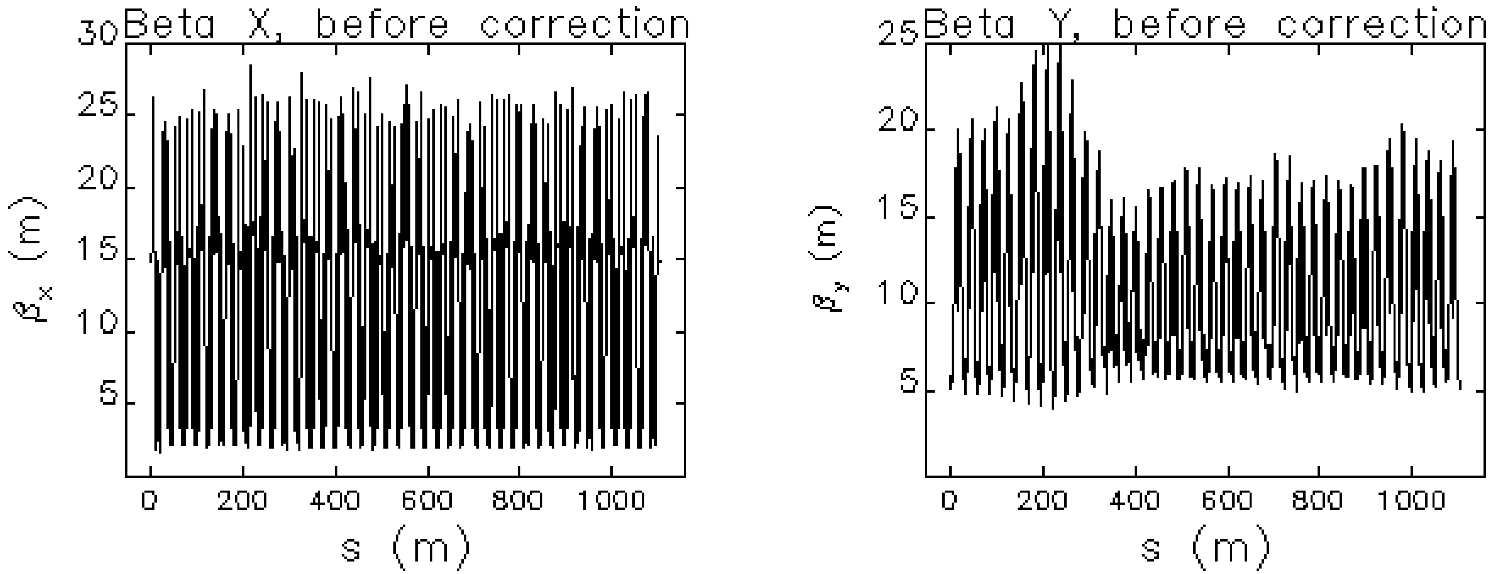
Typical rms error before the fit: 40 μm

Typical rms error after the fit: < 1.5 μm

After the fit is done…

- The result of the fit is the “parameter” file for `elegant` containing quadrupole errors, BPM gains, corrector calibrations, and tilts. This file represents the real model of the machine and can be used for all kinds of calculations in `elegant`.

First measured beta functions
(they are actually calculated based on calibrated model)



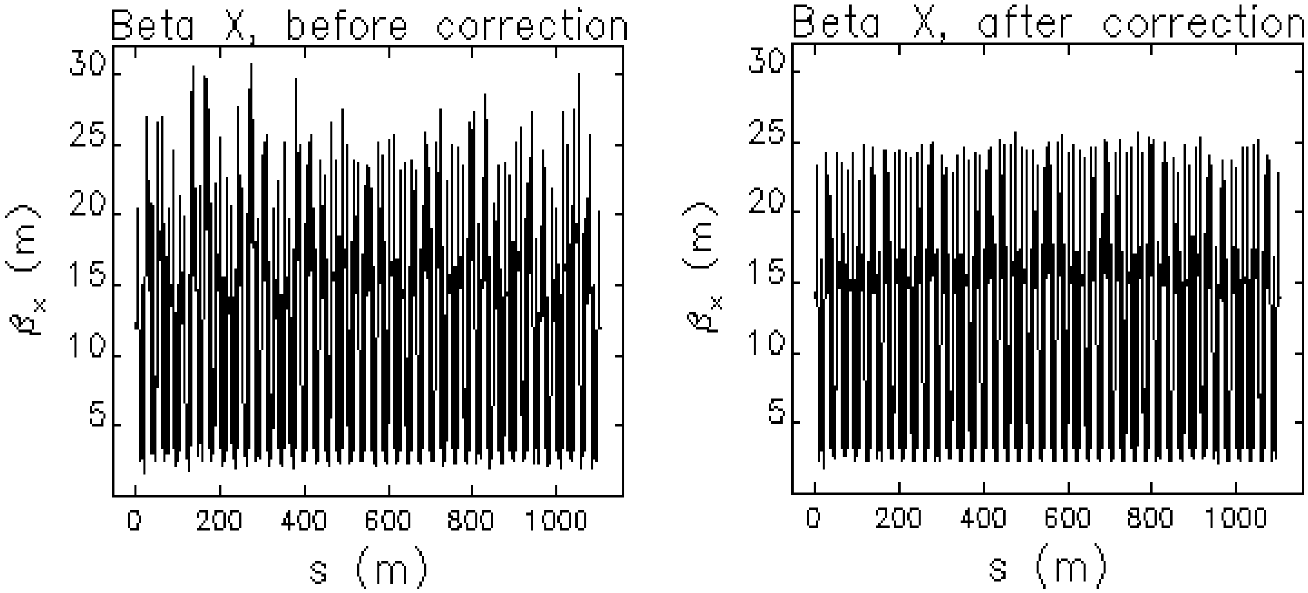
Exploitation of the model

- Improving the performance of the existing machine
  - Beta function correction - to improve lifetime, injection efficiency and to provide users with the radiation exactly as specified
  - BPM gain calibration
- Creation of new lattices
  - Increasing brightness of x-rays by decreasing the beam emittance
  - Exotic lattices:
    - *Longer ID straight section*
    - *Decreased horizontal beam size for some users*
- Learning new things about the machine
  - Local impedance distribution

Beta function correction

- All quadrupoles at APS have separate power supplies. SVD was used to calculate quadrupole corrections
- Beta functions and dispersion are corrected simultaneously

Example of beta function correction for low-emittance lattice



- As a result of this correction, the lifetime increased from 6 hours to 9 hours (measured momentum acceptance increased from 1.8% to 2.5%). The lifetime increase was crucial for top-up operation
- Beta function correction is performed regularly

Toward brighter beam

- Brightness is the main single parameter characterizing a synchrotron light source. It is inversely proportional to the electron beam emittance.
- Over the last one and a half years, APS has made two big steps toward increasing the brightness:

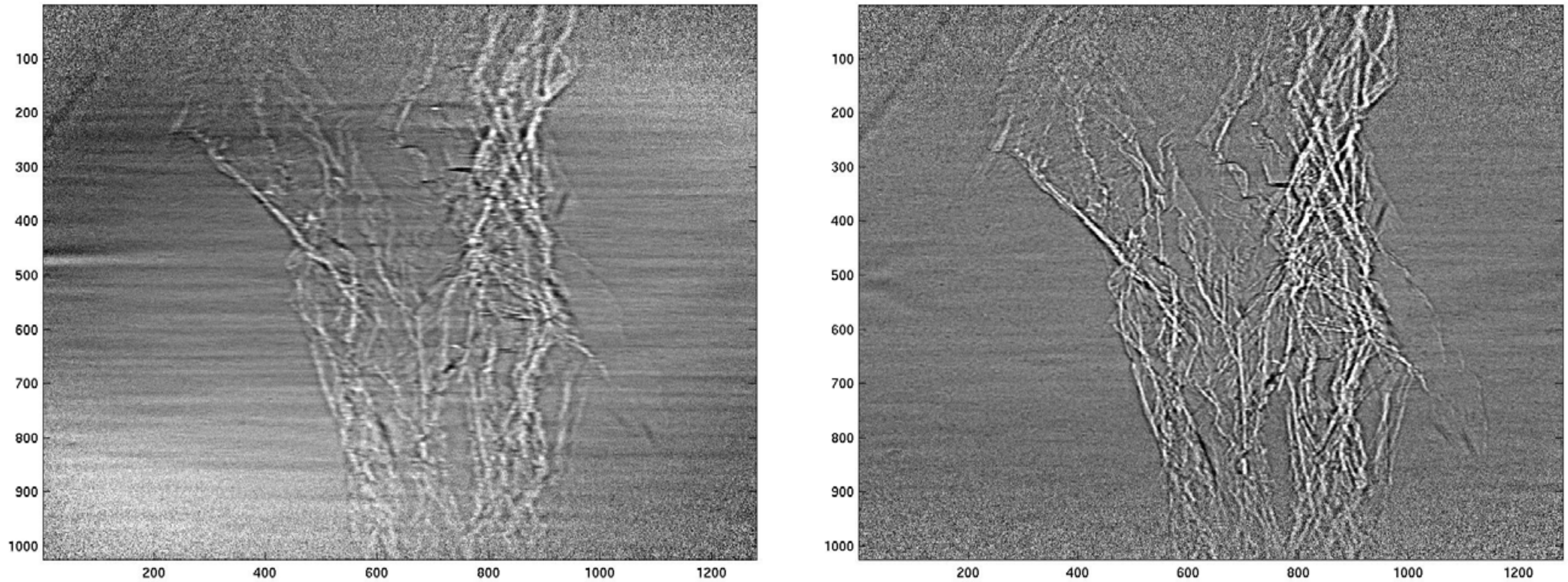
Lattice: "High emittance" 8 nm×rad	→	Lattice: "Low emittance" 3.3 nm×rad	→	Lattice: "Lower emittance" 2.4 nm×rad

- Response matrix fit allowed us to perform these changes quickly and ensured that the delivered beam parameters corresponded to the designed ones

Low horizontal beam size lattice

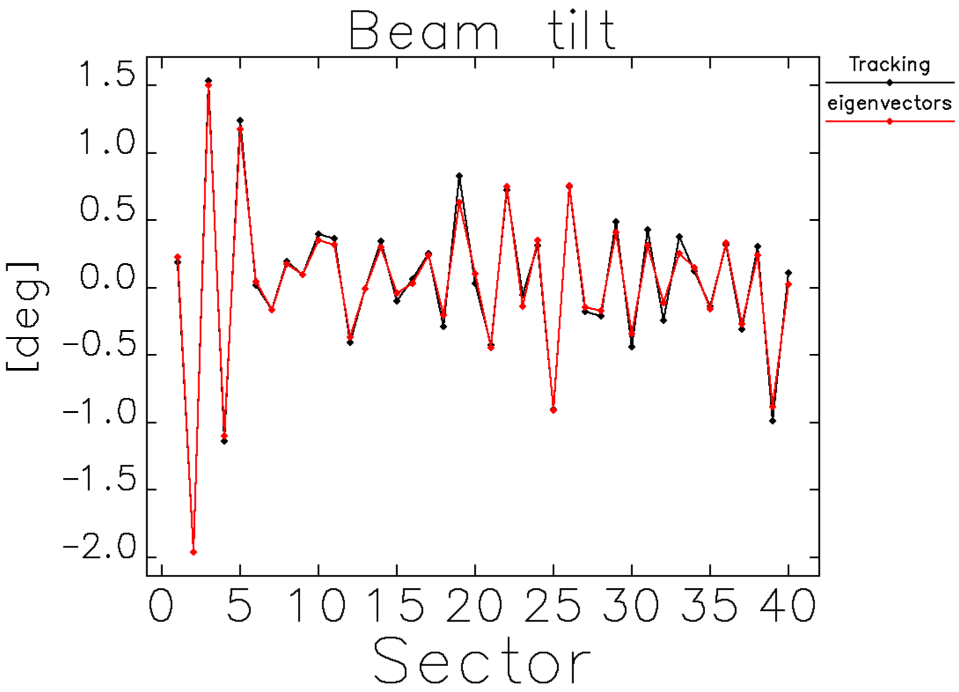
- Horizontal beam size reduced from 270 μm rms to 120 μm for 2 users by locally adjusting beta functions
- Tests were performed during machine studies, the lattice will go into operation this October

Aluminum stress crack sample: in-line phase contrast imaging:
left – 270 μm, right – 120 μm



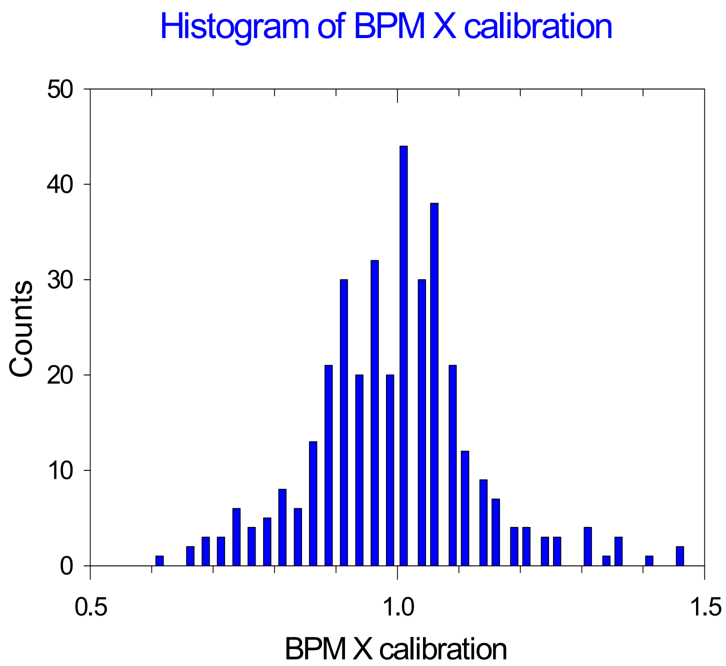
Coupling

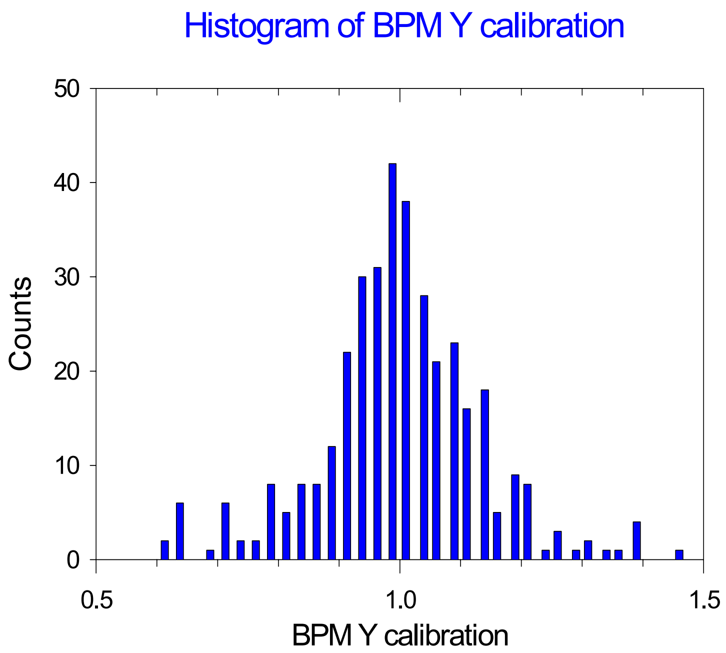
- Coupling is measured using synchrotron radiation at one location
- Coupling can be corrected to about 0.3%. To have lifetime suitable for 2-minute top-up injection interval, we have to maintain coupling at 1% using skew quadrupoles. This leads to unwanted beam tilts around the ring that are impossible to measure directly.
- Response matrix fit provides for skew quad gradients around the ring that can be used to calculate beam tilts



BPM gains

- As a side product, response matrix fit provides us with gains of all BPMs
- BPM gains were included into the BPM signal processing
- BPM calibration is performed regularly





Accuracy of BPM gain determination

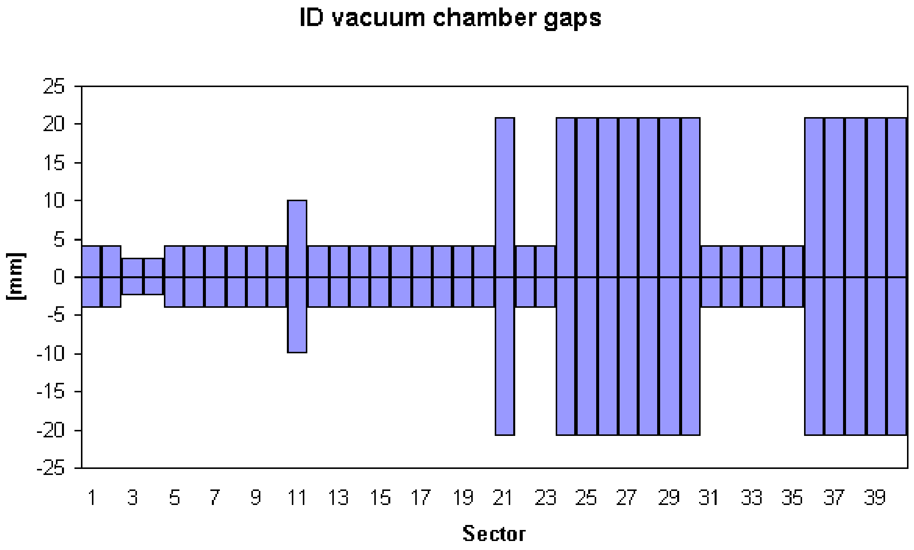
- Due to complexity of the calculations, it is impossible to tell BPM gain accuracy directly. The only way is by comparing the results of several different measurements
- Recently, several new lattices were being developed and we happened to have 7 measurements performed for different lattices over less than a month time period. Based on these measurements, the following accuracy was determined:

	Average X	RMS X	Average Y	RMS Y
P0	1.040	1.93×10^{-3}	0.989	2.95×10^{-3}
P1	0.965	1.88×10^{-3}	1.030	2.33×10^{-3}
P2	1.062	2.26×10^{-3}	0.981	2.36×10^{-3}
P3	1.069	3.22×10^{-3}	0.975	2.45×10^{-3}
P4	1.097	3.13×10^{-3}	0.982	2.29×10^{-3}
P5	1.075	1.94×10^{-3}	0.968	1.92×10^{-3}

Local impedance

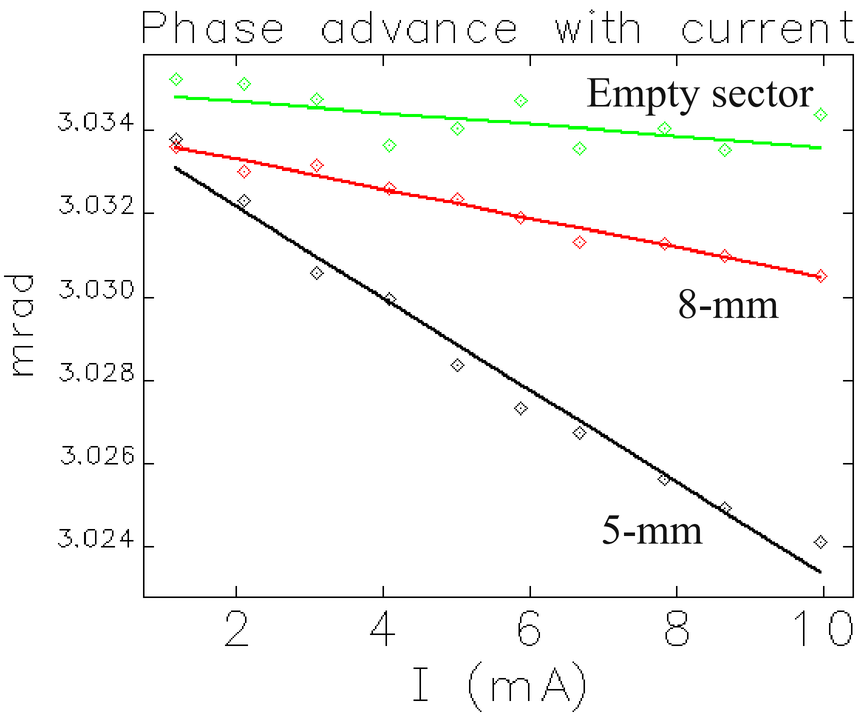
- The beam sees the transverse impedance as defocusing quadrupole whose strength depends on the beam current
- We use response matrix fit method to measure beta functions for different beam currents, then we calculate local phase advance changes with beam current, then we determine the transverse impedance
- Main source of impedance is ID vacuum chambers and transitions

Locations of the small-gap ID vacuum chambers; each ID chamber is 5-m long aluminum extrusion

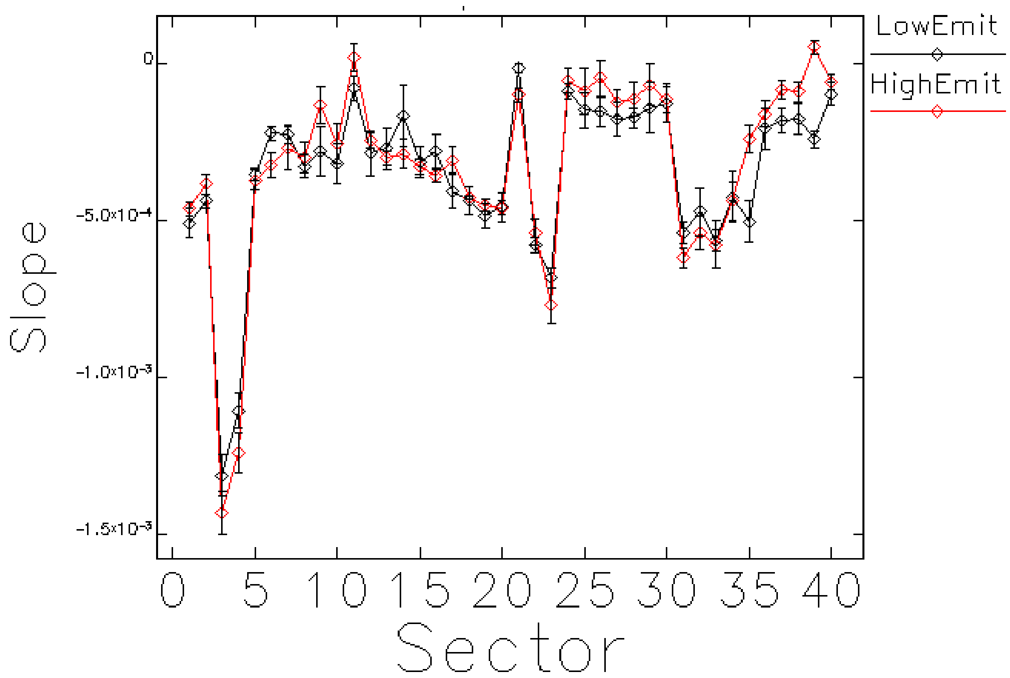


Local impedance

- To get the local distribution of the impedance, we analyze the phase-advance changes sector by sector



Vertical betatron phase slope distribution



Local impedance

For a particular component, the effective impedance can be found from measured slopes of the phase advance:

$$Z_{eff}^{i} = \frac{E/e\,\sigma_s}{R\beta_i}\frac{d\mu}{dI}$$

	Units	High emittance	Low emittance
$d\mu/dI_{no\ ID}$	A^{-1}	-0.09	-0.14
$d\mu/dI_{8mm}$	A^{-1}	-0.39	-0.40
$d\mu/dI_{5mm}$	A^{-1}	-1.33	-1.21
Z_{noID}^{eff}	kΩ/m	3.5	4.1
Z_{8mm}^{eff}	kΩ/m	31	34
Z_{5mm}^{eff}	kΩ/m	126	138
Z_{total}^{eff}	MΩ/m	1.1	1.2

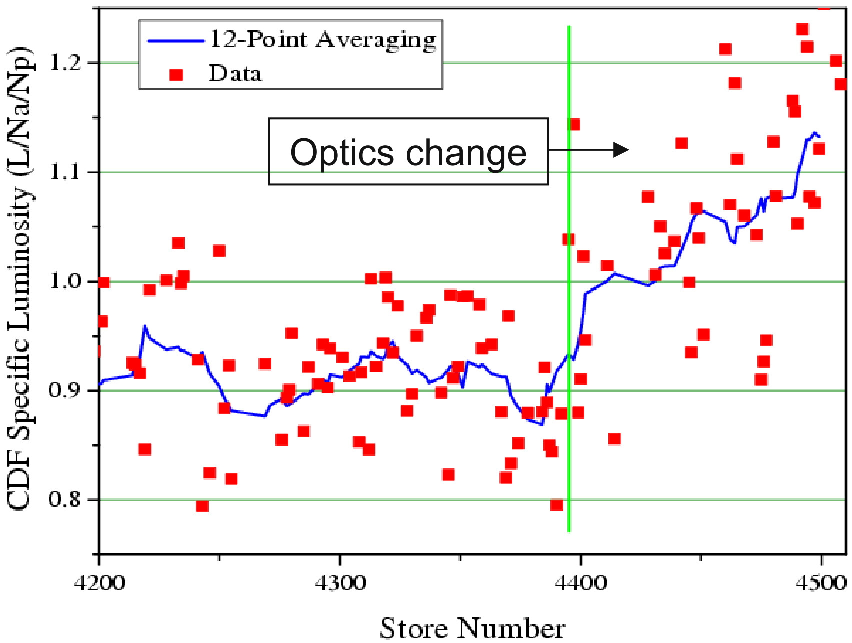
Application to Tevatron at FNAL

- This work was a joint effort by V. Sajaev, ANL and V. Lebedev, V. Nagaslaev, A. Valishev, FNAL

- As part of this effort, the fitting software was modified to be compatible with FNAL measurements and simulations
- Coupling analysis (shown above) was actually a part of this effort too
- Optics models for Tevatron, Debuncher, and Recycler (all are parts of the Tevatron accelerator complex) were obtained using response matrix fit

Tevatron improvements[1]

- Detailed optics model revealed significant (up to 1%) errors in FF quadrupoles, several coupling sources, and beta function beating
- Based on the model, new optics has been designed that
  - Eliminates beta function beating in the arcs
  - Corrects the discrepancy in the value of β^* between two IP
  - Decreases β^* from 35 to 28 cm
- New optics has been implemented and measurements confirmed β^* changes
- Luminosity was increased by 10%



1. A. Valishev, et. al., Proceedings of EPAC 2006

Debuncher[1]

- Debuncher is a part of Antiproton Source, it is used for stacking and cooling of antiprotons. Acceptance increase in Debuncher was one of important steps to increase antiproton production rate
- Model derived by the RM fit was used to redesign Debuncher optics to reduce the beam size at locations of the stochastic cooling tanks
- Measured acceptance was increased from $30\pi/25\pi$ mm·mrad to $35\pi/35\pi$ mm·mrad
- The implementation of new optics allowed to avoid building new cooling tanks with larger aperture
- Ability to perform fast and precise optics measurements strongly supported this work

1. V. Nagaslaev, et. al., Proceedings of EPAC 2006

Conclusions

- Response matrix fit proved to be a very valuable tool for optics measurements
  - Routine optics measurements and correction at APS
  - New lattice development at APS
  - Routine BPM calibration at APS
  - Collision optics improvement at Tevatron
  - Acceptance increase at Debuncher
    - *And the list goes on…*