Determination and Correction of the Linear Lattice of the APS Storage Ring

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Motivation

- From the beginning of the APS storage ring operation there was a substantial difference between the model and the real storage ring.
- The APS storage ring is a complicated machine containing 400 quadrupoles, 280 sextupoles and 80 dipoles.
- Each focusing element can be a source of focusing errors. All together, small perturbations could significantly change the linear optics and seriously affect performance of the storage ring.
- The difference presents difficulties when tuning machine to new lattices such as low-emittance or converging β-function.
- We decided to develop a method for fast linear lattice calibration using orbit response matrices.

Orbit response matrix fit

- The orbit response matrix is the change in the orbit at the BPMs as a function of changes in steering magnets
- 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 storage rings have a large number of steering magnets and precise BPMs, so measurement of the response matrix provides a very large array of precisely measured data.
- The main idea of the analysis is to adjust the quadrupole gradients of a computer model of the storage ring until the model response matrix best fits the measured response matrix.

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

Challenges

Size of model.

NSLS X-ray ring:	626 parameters used to fit 8,640 elements
ALS:	500 parameters used to fit 15,744 elements
APS (the entire ring):	2,240 parameters and about 560,000 elements
APS (used):	1,200 parameters used to fit 28,800 elements

Degeneracy of model

- X-ray ring and ALS are able to store the beam without sextupoles
- average betatron phase advance per one quadrupole:

APS -	0.088
X-ray ring -	0.17
ALS -	0.28

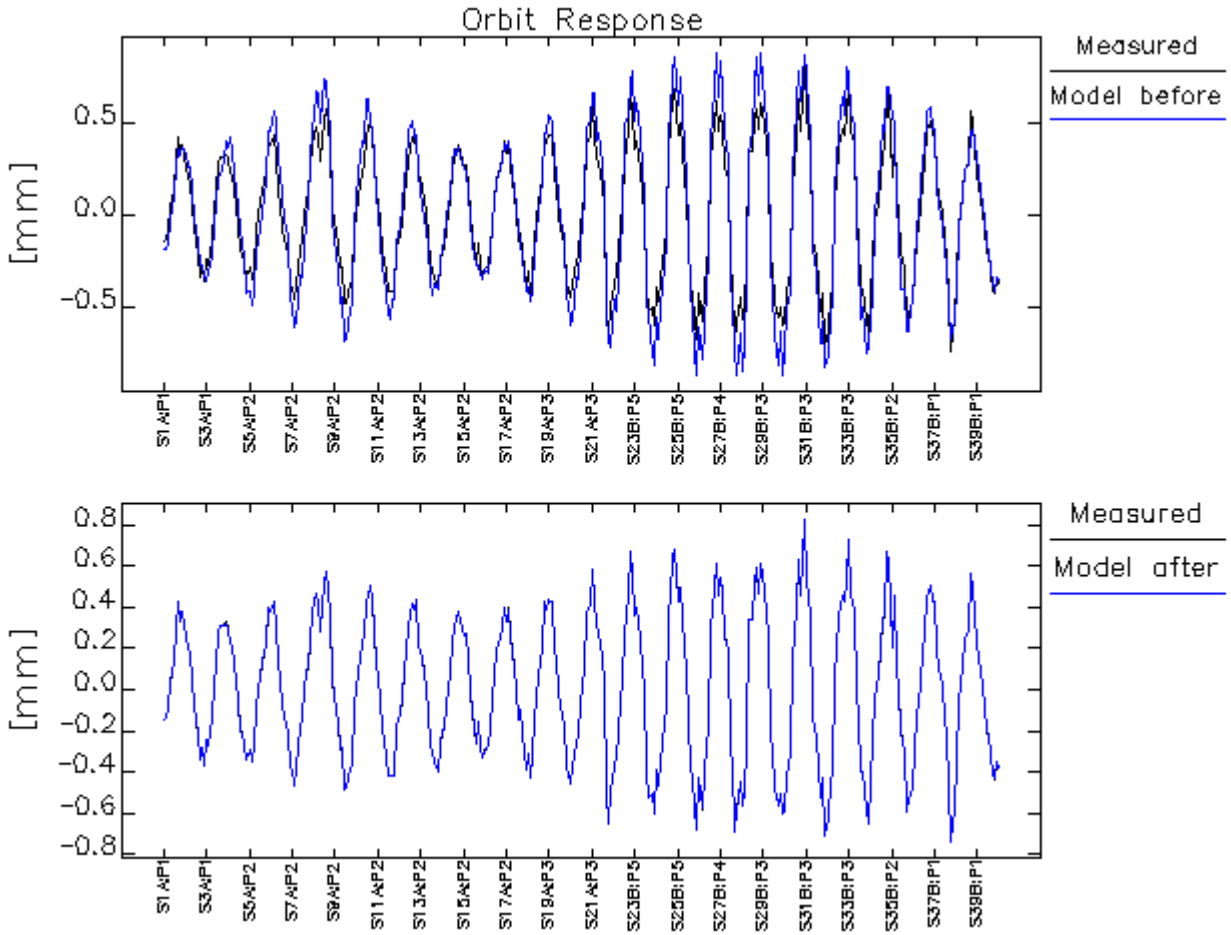
Measurements and fitting

- For our measurements we use 40 steering magnets in each plane. The resulting response matrix has 28800 elements
- This response matrix depends on quadrupole gradients, BPM gains and steering magnet calibrations. Total number of variables is 1200
- Finally we solve the following equation (by iterations):

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

$$\begin{pmatrix} 1 \\ \times \\ 1200 \end{pmatrix} = \begin{pmatrix} 1200 \\ \times \\ 28800 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \times \\ 28800 \end{pmatrix}$$

Measurements and fitting



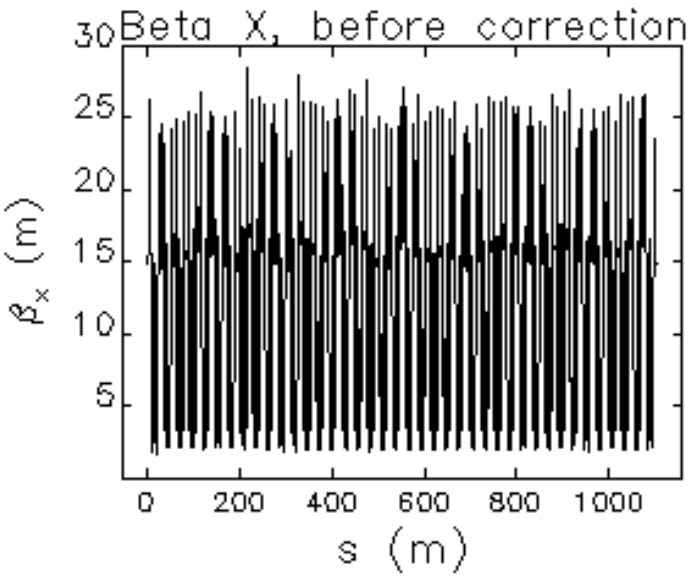
Typical rms error before the fit: 80 μm

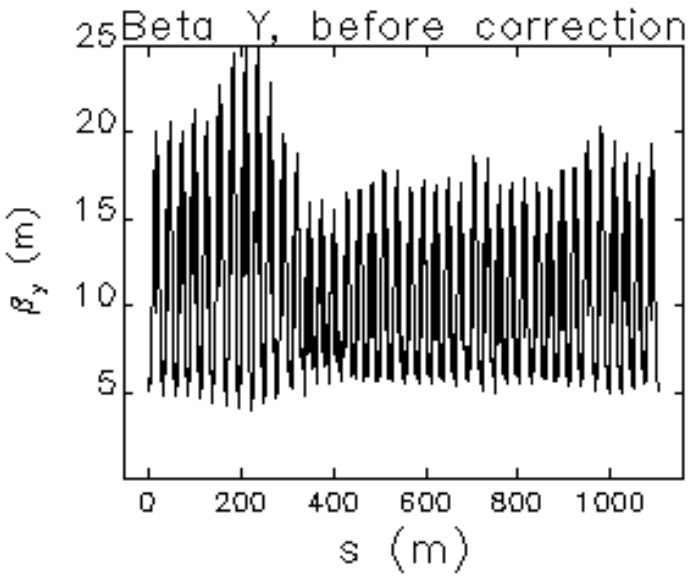
Typical rms error after the fit: < 2 μm

After the fit is done…

The result of the fit is the "parameter" file for `elegant`. This file could be used for different kinds of calculations in elegant

Beta functions calculation:

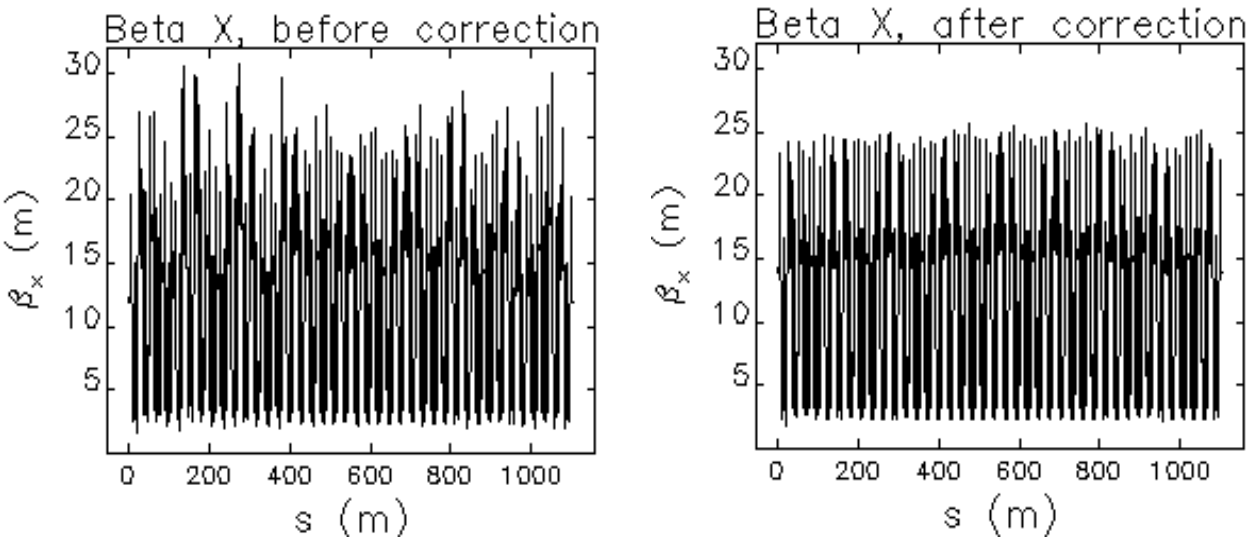




Beta function beating correction

After the beta functions are calculated using the created model, the *SRbetaCorrection* oag application is used to compute quadrupole corrections required to correct for the beta function beating

Horizontal beta function for the low-emittance lattice:

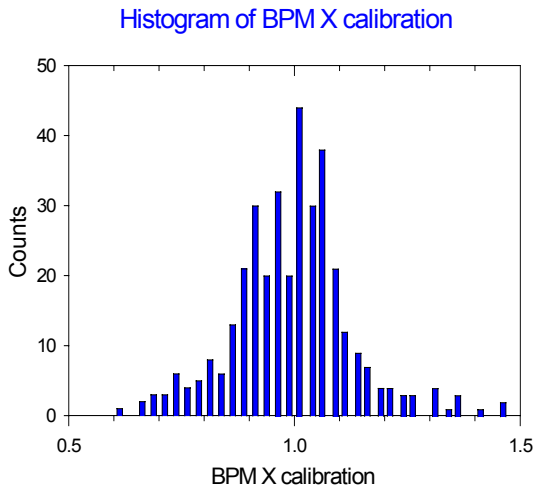


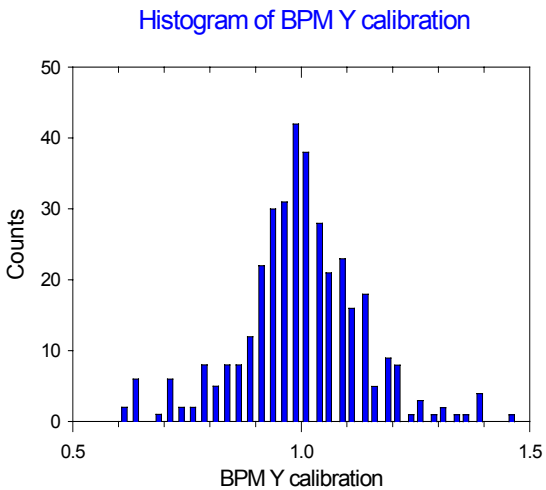
Lifetime increase

- Corrected beta functions improve the nonlinear dynamics of the machine
- After the corrections the lifetime for the low-emittance lattice was increased from 6 to 9 hours, and the injection efficiency was improved

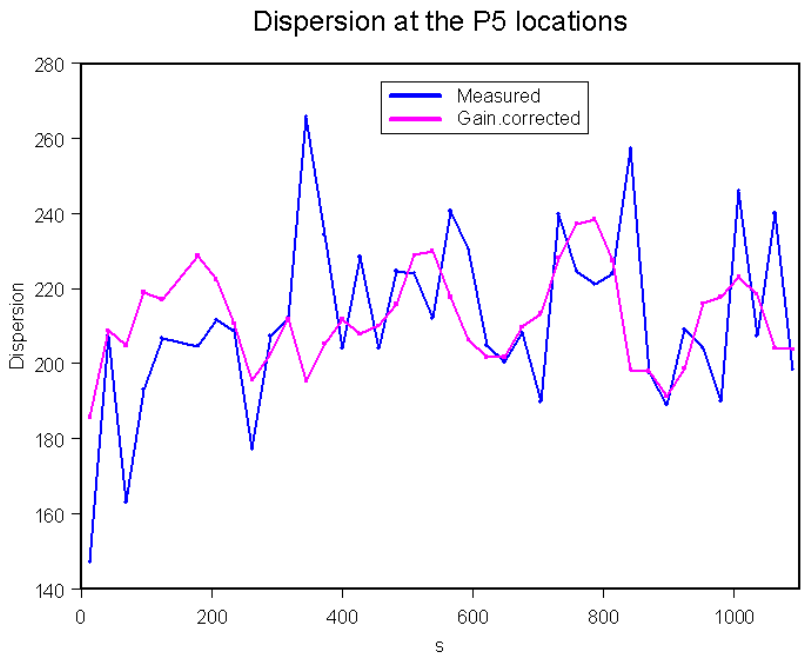
BPM gain calibration

Method allows for calibration of the gain of all storage ring BPMs





Dispersion after the BPM gain correction shows smoother behavior



Conclusions

- A method for calibrating the linear model of the storage ring has been developed → The model was used to correct the beta functions and improve the lifetime
- The method is particularly useful when modifying the storage ring lattice → The model was really helpful when we started working on the longitudinal injection lattice

The way for individual sector adjustments is now open (as far as lifetime permits)

Future plans

- Global and local linear coupling characterization and correction/control
- Include dispersion into the fit
- Simultaneous manipulation of the beta functions and dispersion
- Use the precise linear model to better understand nonlinear features of the ring