Determination of the APS Machine Model and Exploitation of the Results

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Acknowledgements
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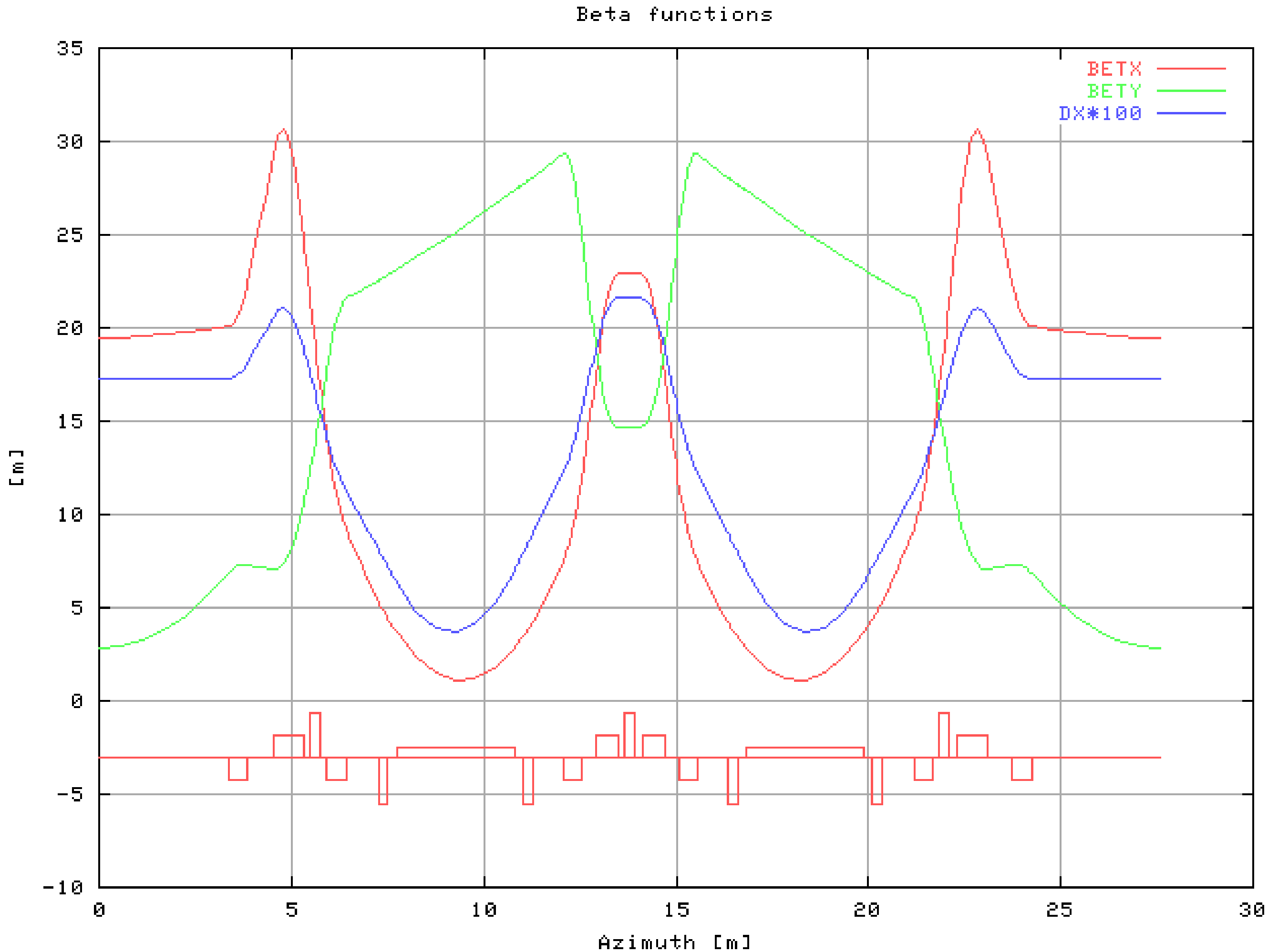
APS lattice functions

2.4 nm×rad lattice, one sector



Motivation

- 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. Altogether, small perturbations could significantly change the linear optics and seriously affect performance of the storage ring.
- From the beginning of the APS storage ring operation there was a substantial difference between the model and the real storage ring.
- The difference presents difficulties when tuning the machine to new lattices such as low-emittance or converging β-function.

Motivation

Experimental fact:

When we take quadrupole currents and transform them into quadrupole gradients using measured excitation curves, we get a different machine with different betatron tunes and beta functions.

When we were changing the machine, we had to choose between different approaches:

- Use excitation curves
- Use "ratio" model adjustment
- Use "difference" model adjustment

Creating a new lattice was a time-consuming process. 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

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

- 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 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.

Orbit response matrix fit

The main idea of the analysis is to adjust all the variables that the response matrix depends on in order to solve the following equation:

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

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

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 and at ALS. 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 measured response matrix depends on the following parameters:

- Quadrupole gradients
- Steering magnet calibrations
- BPM gains
- Energy shift associated with steering magnets
- BPM nonlinearity
- Steering magnet and BPM longitudinal positions
- etc.

} Main parameters (the first three items)

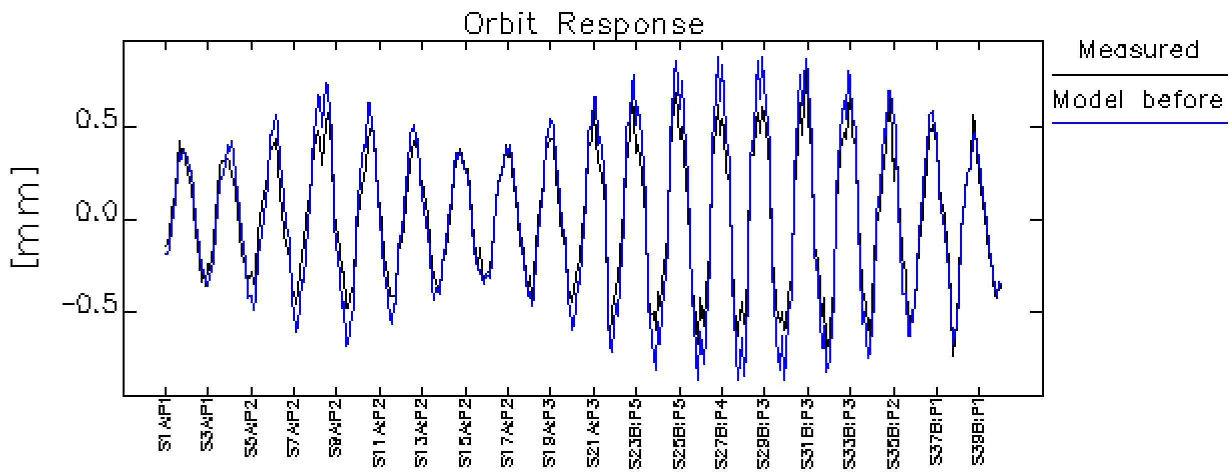
Measurements and fitting

- APS has 320 steering magnets and 400 BPMs in each plane plus 400 quadrupoles and 280 sextupoles.
- For our measurements we use 40 steering magnets in each plane and all BPMs. We do not vary sextupoles. The resulting response matrix has 32,000 elements, and the number of variables is 1320.
- Finally we solve the following equation (by iterations):

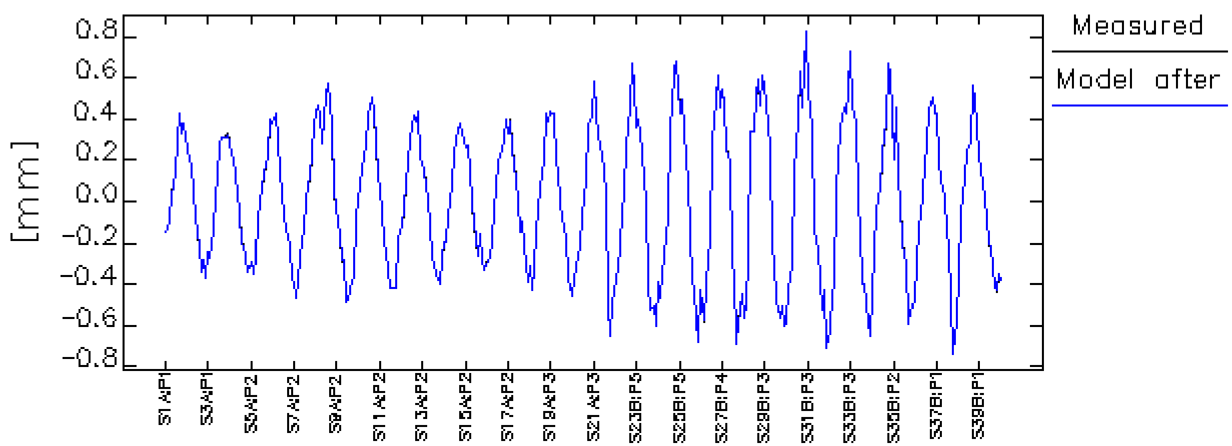
$$X = M^{-1} \cdot V$$

$$\begin{pmatrix} 1 \\ \times \\ 1320 \end{pmatrix} = \begin{pmatrix} 1320 \\ \times \\ 32000 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \times \\ 32000 \end{pmatrix}$$

Measurements and fitting



Typical rms error before the fit: 80 µm

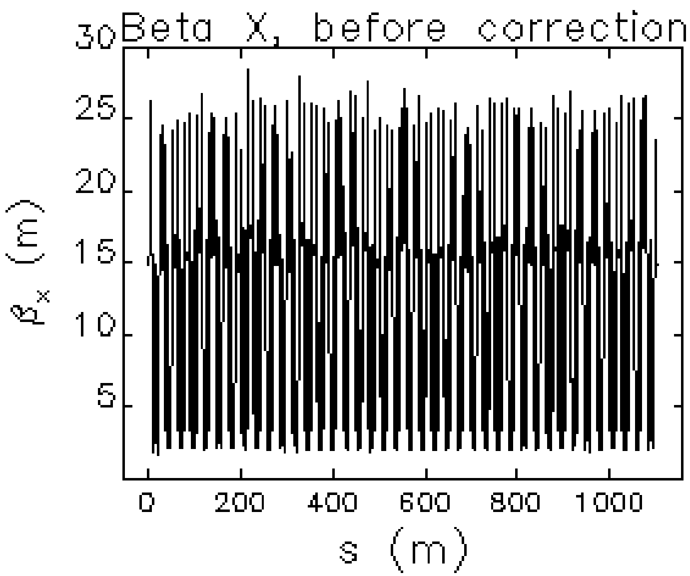


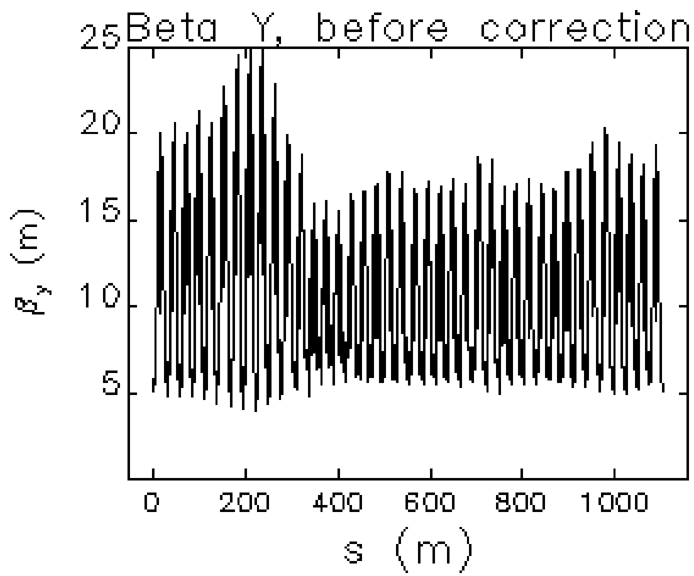
Typical rms error after the fit: < 2 µm

After the fit is done…

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

Beta functions calculation (08/08/2001):



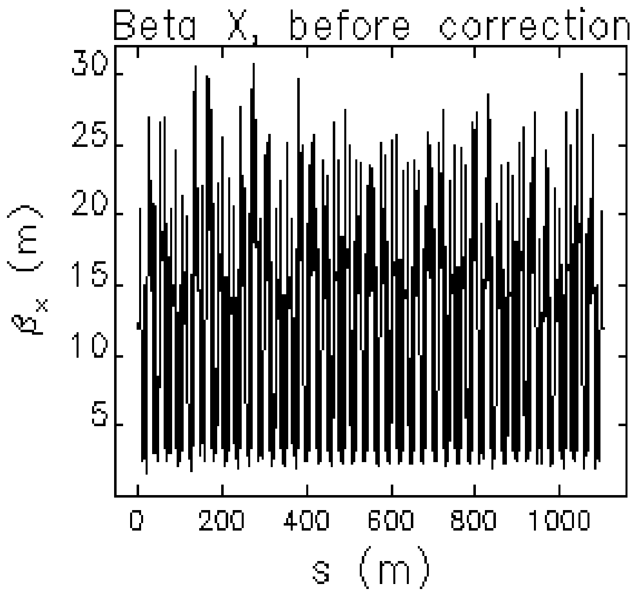


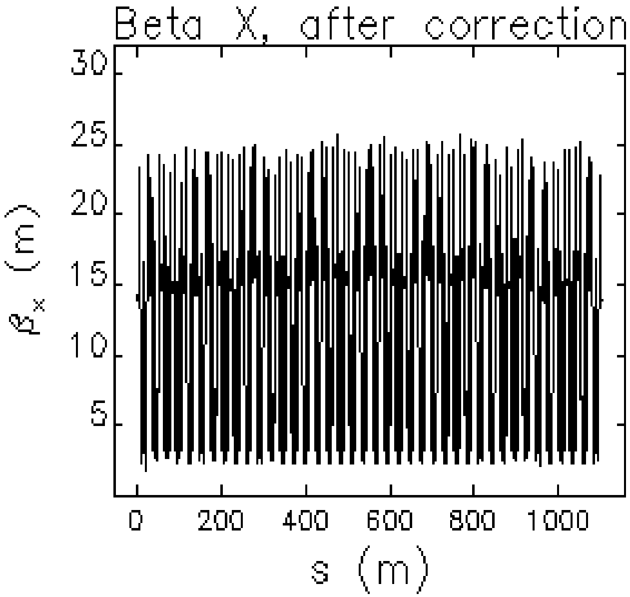
Exploitation of the model

- 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:
    - Longitudinal injection to decrease beam motion during injection
    - Converging beta function to increase x-ray flux density
- Learning new things about the machine
  - Local impedance distribution

Beta function beating correction

Horizontal beta function for the low-emittance lattice before and after beta function correction (November 2001):



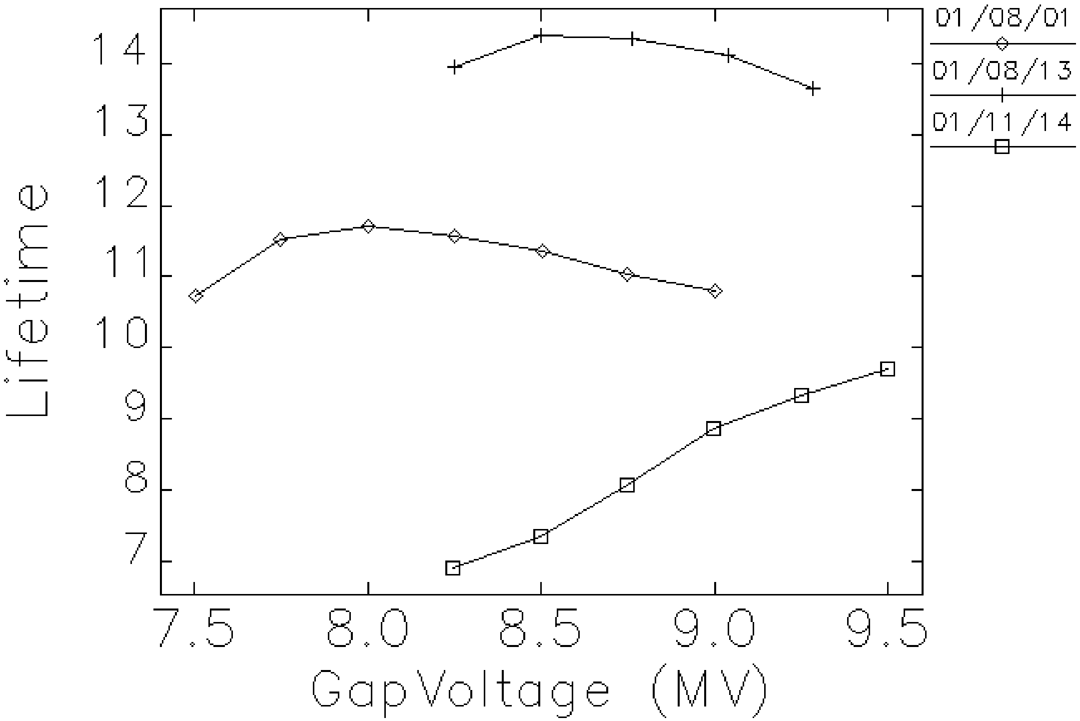


As a result of the correction, the lifetime increased from 6 hours to 9 hours. The lifetime increase was crucial for top-up operation.

Nonlinear energy acceptance increase

At APS the lifetime is defined by the nonlinear energy acceptance. The lattice correction improved the acceptance from 1.8% to 2.5%.

RF Voltage Scan



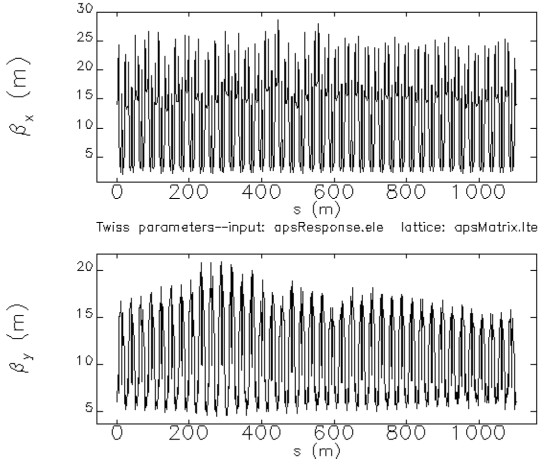
Lifetime improvement in the low-emittance lattice

June 2002

Before correction → Lattice correction → After correction → Sextupole reduction → Weaker sextupoles

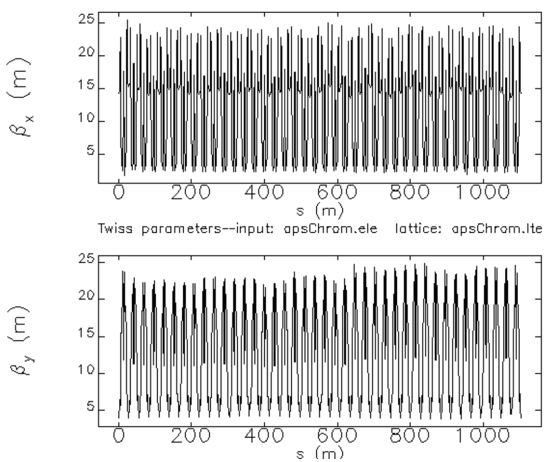
Lifetime – 6 hours

Lifetime – 10 hours



Chromaticity:

Natural:	ξ_x=-73.0
	ξ_y=-28.2
With sextupoles:	ξ_x=7.1
	ξ_y=7.2



Chromaticity:

Natural:	ξ_x=-71.5
	ξ_y=-33.9
With sextupoles:	ξ_x=7.5 (8.3 measured)
	ξ_y=12.0 (11.9 measured)

Beta functions are the same

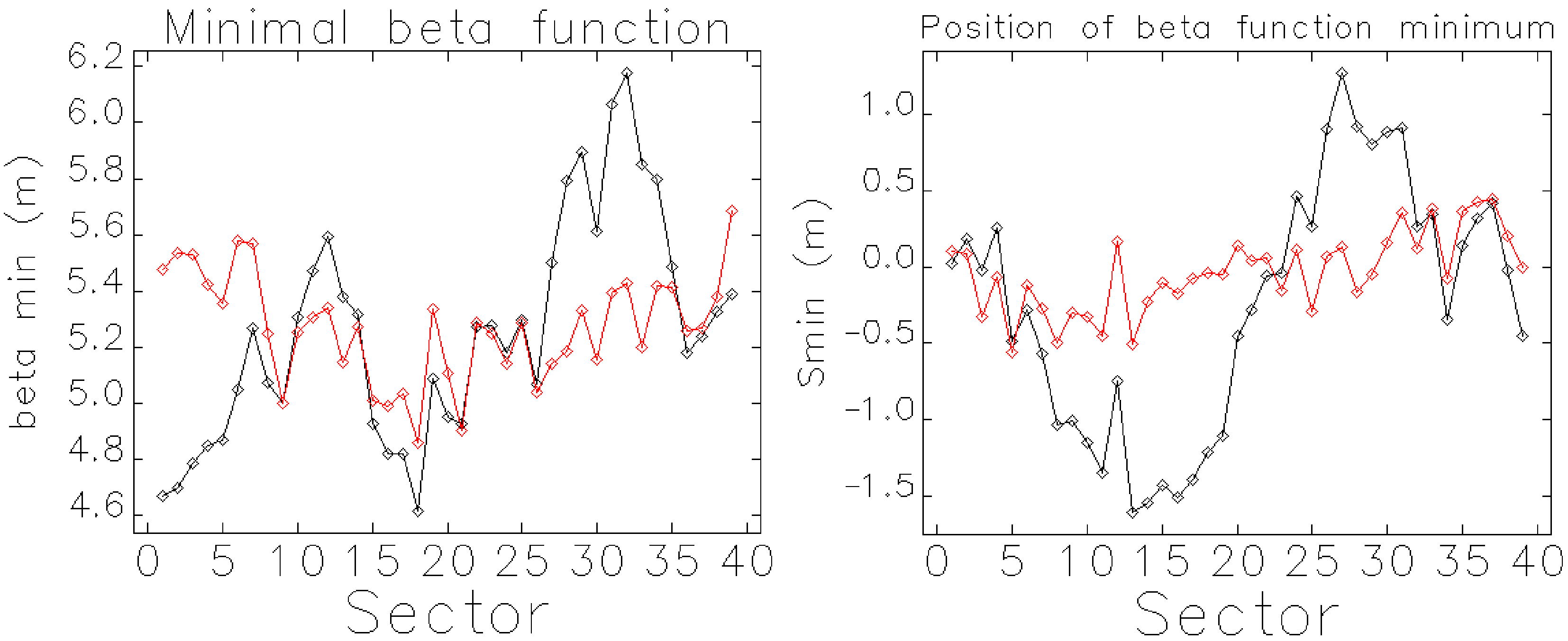
Chromaticity:

Natural:	same
With sextupoles:	ξ_x=3.2 (2.7 measured)
	ξ_y=5.0 (4.9 measured)

Summary:
Lattice correction not only improved the symmetry of the machine but also improved the sextupole efficiency in the chromaticity correction. This allowed us to substantially decrease the sextupole strengths (for example, S3 from 250 A to 184 A). As a result of these two steps, the lifetime increased significantly from 6 to 10 hours.

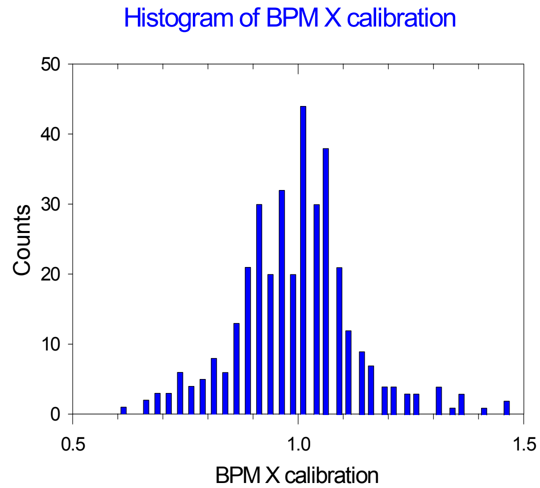
Improvement of uniformity of radiation points

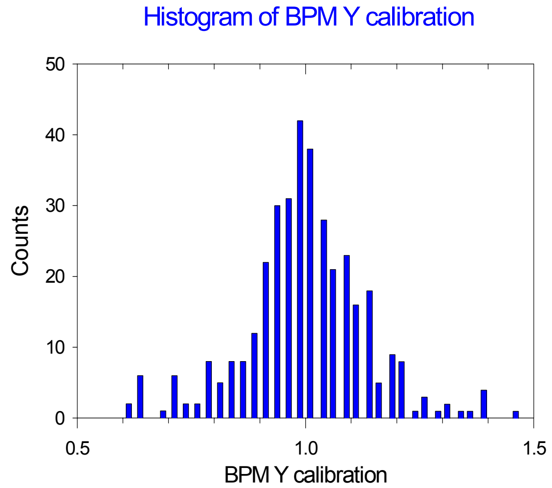
The minimal of the beta function and its position define the radiation source size and its location for the user of undulator radiation. The minimal beta function and its position in each ID straight section is presented in the figure (before and after correction):



BPM gain calibration

Method allows us to calibrate the gain of all storage ring BPMs





Dispersion after the BPM gain correction shows smoother behavior

Creating new lattices

- Before the precise model of the APS storage ring was created, the process of creating a new lattice was taking many study shifts.
- Now it is possible to try a new lattice in just one shift. For example, the creation of the new “lower-emittance” lattice took only five shifts from scratch to user-available lattice (including beta function correction and user orbit restoration).

Increasing brightness of x-rays

- 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
11/7/2001

→

Lattice:
"Lower emittance"
2.4 nm×rad
10/15/2002

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

"Exotic lattices"

They are just ideas: most of them change just one sector but this change is dramatic:

- ❑Longitudinal injection
- ❑Converging beta function
- ❑10 meter long ID straight section
- ❑Low horizontal beta ID straight section

After the storage ring model is calibrated, the implementation of the new lattices becomes straightforward.

Local impedance

Change in phase advance between lattices derived from the response matrix fits made for 5 mA and 1 mA