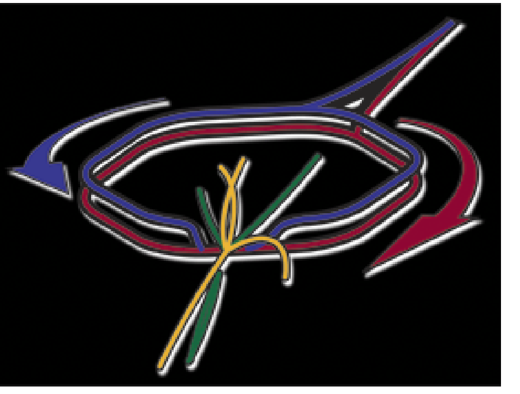
# Optics measurement, modeling, and correction - PEP-II experience

Yiton Yan
SLAC

# Outline

- PEP-II - *Asymmetric B Factory*
- Orbit excitation - resonance driving leads to non-modified betatron oscillation
- PEP-II optics measurement for modeling
- PEP-II optics modeling - Green's functions
- PEP-II optics correction
- Implication to model non-modified LHC optics

# *PEP-II: Asymmetric B Factory*



- The PEP-II facility consists of two independent storage rings, one located atop the other in the PEP tunnel.
- The high-energy ring (HER) stores a 9-GeV electron beam.
- The low-energy ring (LER) stores 3.1-GeV positrons beam.
- The optics complication mainly comes from IR, especially the detector solenoid causes strong PEP-II LER coupling.
- Peak luminosity is about 1.2 e34 $cm^{-2}s^{-1}$

# Orbit excitation - resonance driving leads to non-modified betatron oscillation

- Proton storage ring, with Little damping, needs non-resonance ac driving which leads to modified Betatron oscillation as if a quad (1-D linear case) is inserted at the driving location.

$$M_{insert} = \begin{pmatrix} 1 & 0 \\ -k & 1 \end{pmatrix},$$

*where*

$$k = \frac{2(\cos\mu - \cos\mu_d)}{\beta \sin\mu}$$

- Electron storage ring, with strong synchrotron radiation damping, uses sinusoidal resonance driving by shaking dipoles easily. Betatron motion is not modified.

$$\mu_d = \mu \Rightarrow k = 0 \Rightarrow M_{insert} = 0$$

# PEP-II optics measurement for modeling - BPM buffer data acquisition

- The PEP-II modeling was centered on the program MIA.
- Resonance excitation at the horizontal betatron (eigen) tune and then at the vertical tune and the synchrotron tune, each for about 1000 turns to get a complete set of linear optics data.
- Buffer data are stored in three sets of matrices, each set has two matrices, one for the x data and the other for y data.

# Validation of BPM data –symplecticity and noise check

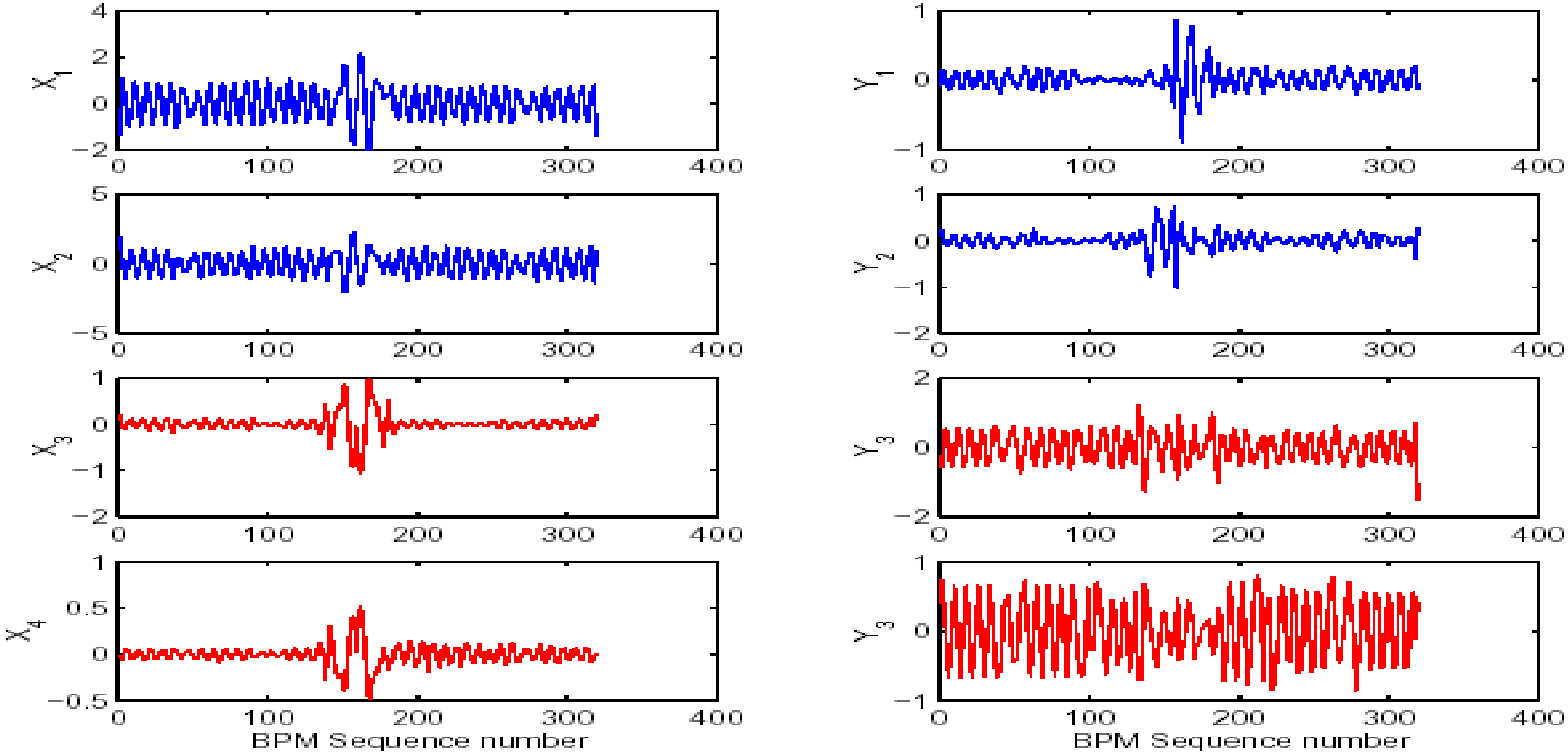
- Considering BPM aberration only for linear gain and linear cross coupling, we can check BPM data symplecticity by calculating and comparing the invariant ratio without the need to know the BPM aberrations – a strong criterion.

- We also check BPM data correlation (SVD) to rank the BPM noise level – a weak criterion.

- So we have good bases for selecting reliable BPM data. Through years, we have helped PEP-II correct and improve BPM performance.

# Four independent orbits and dispersions

- Obtaining three pairs of conjugate (sine- and cosine-like) orbits from zooming FFT (focuse on individual component FFT).
- Calculating phase advances and Green's functions among BPMs as well as dispersions (to a proportional scale) at BPMs.




A typical high-resolution 4 orbits for LER, showing strong couplings. The top two orbits, the cosine-like orbit, $(x_1, y_1)$, and the sine-like orbit, $(x_2, y_2)$, are from eigen-plane-1 resonance excitation while the bottom two orbits, the cosine-like orbit, $(x_3, y_3)$, and the sine-like orbit, $(x_4, y_4)$, are from eigen-plane-2 resonance excitation. Assuming no BPM coulings, phase advances can readily obtained from these orbits.

4 independent orbits determines the linear optics.

# Phase Advances

- If there is no BPM cross couplings, one can calculate the orbit betatron phase at each BPM location by simply taking the arctangent of the ratio of the imaginary part to the real part of the resonance excitation focused FFT mode.
- Phase advance between two adjacent BPMs can then be calculated by subtraction.
- The BPM gains, if there is, cancelled but not the BPM cross couplings.

# The linear Greens functions

$$(x_1^a x_2^b - x_2^a x_1^b)/Q_{12} + (x_3^a x_4^b - x_4^a x_3^b)/Q_{34} = \mathcal{R}_{12}^{ab} .$$

$$(x_1^a y_2^b - x_2^a y_1^b)/Q_{12} + (x_3^a y_4^b - x_4^a y_3^b)/Q_{34} = \mathcal{R}_{32}^{ab} .$$

$$(y_1^a x_2^b - y_2^a x_1^b)/Q_{12} + (y_3^a x_4^b - y_4^a x_3^b)/Q_{34} = \mathcal{R}_{14}^{ab} .$$

$$(y_1^a y_2^b - y_2^a y_1^b)/Q_{12} + (y_3^a y_4^b - y_4^a y_3^b)/Q_{34} = \mathcal{R}_{34}^{ab} .$$

They, along with the phase advances are used for SVD-enhanced fitting to obtain a virtual accelerator

Where, in the measurement frame, *R* is a function of BPM gain and BPM cross-plane coupling.

Q12 and Q34 are the two invariants representing the excitation strength

MIA does not trust the BPM accuracy – MIA figures out BPM gain and cross coupling errors.

# The Coupling Ellipses

For each double-view BPM, one can trace the MIA extracted high-resolution real-space orbits to obtain a coupling ellipse in real space for each resonance (Eigen) excitation. Shown in Figure 2 are typical Eigen ellipses projected in the real X-Y plane.

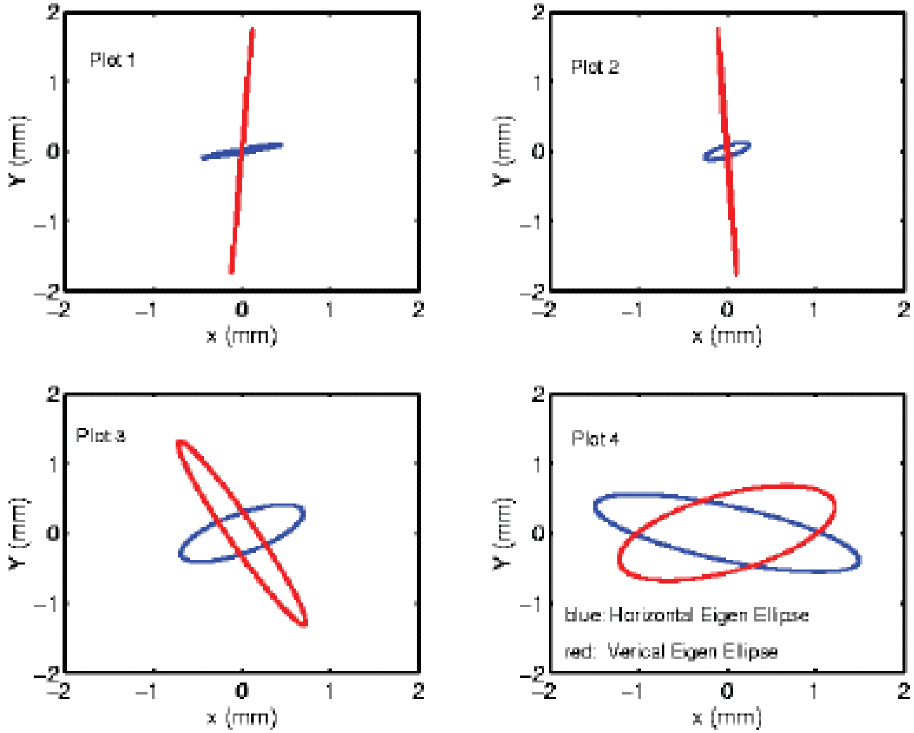



**Figure 2:** Eigen-mode coupling ellipses projected on the transverse x-y plane at 4 double-view BPM locations of PEP-II LER. The top 2 are at the two BPMs beside the IP, which show little coupling, while the bottom 2 are at the tenth BPMs from IP in each side, which show large couplings as the axis ratios of the short axis vs the long axis are large. (data acquired on September 30, 2003).

# Auto SVD-enhanced Least-Square fitting for Green functions and phases

- Treating normal quad family strengths, individual skew quad strengths, normal and skew strengths for sextupole feed-downs, BPM linear gains and linear cross couplings and one invariant as well as one energy scale as variables, we update the lattice model and calculate Green's functions, phase advances, coupling ellipses, dispersions, etc. among/at BPMs.

- Essentially Unlimited Green's functions (no worry about degeneracy), providing overwhlming constraints to guarantee Least-Square fitting convergence.

- Orbits updated by linear BPM aberrations during fitting offers self-consistent phase advances and dispersions.
  - phase advances are independent from linear BPM gain but not from BPM cross coupling because BPM cross coupling and lattice coupling are not distinguishable.

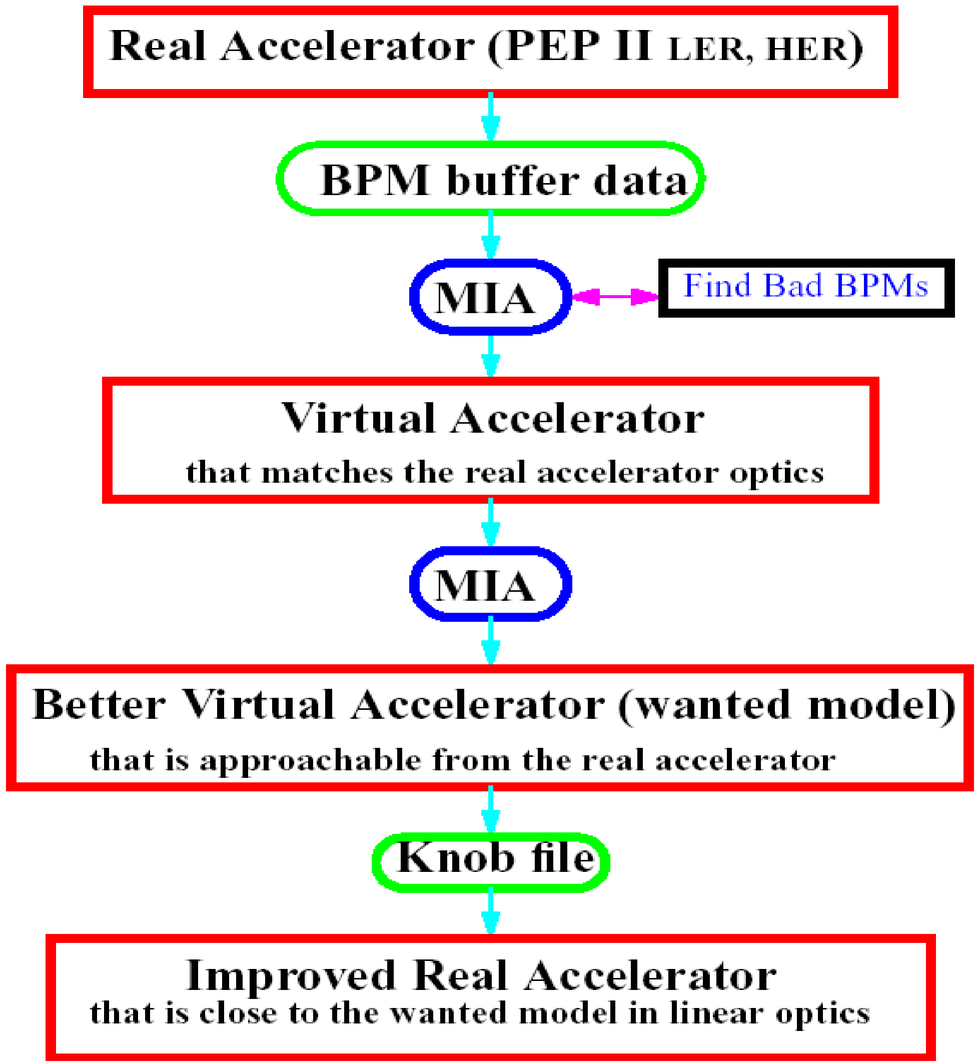
- Auto optimal selection of SVD modes for fitting iterations. Unstable modes are automatically avoided to guarantee convergence – no problem for near half-integer tune cases.

# Virtual machine and correction

- We reserve eigen-plane projected (to the real x,y) coupling ellipses’ tilt angles and axis ratios without fitting to see if they are automatically matched for accuracy checking.

- Once we are satisfied with the fitting accuracy, we call the updated lattice model the virtual machine (Virtual LER, Virtual HER).

# Summary chart for PEP-II measurement, modeling, and correction procedures



# PEP-II optics correction (some cases) – LER to half integer working tune in 2003

- We tried MIA optics correction for PEP-II for the first time in late 2002. PEP-II luminosity (then at about 3 – 4 x $10^{33}$ $cm^{-2}s^{-1}$) increased 20%. But then followed by two consecutive failures in trying to increase PEP-II luminosity.
- The 1st milestone overcome: MIA successfully brought LER to a half integer working tune and improve LER beta beats and linear coupling. Instantly, LER beam became the stronger one of the two (LER and HER beams). {Without MIA, this was difficult because of strong LER coupling.}
- *Consequently, PEP-II luminosity more than doubled in the year after Decker's online tweak with symmetric and anti-symmetric orbit corrector bumps.*

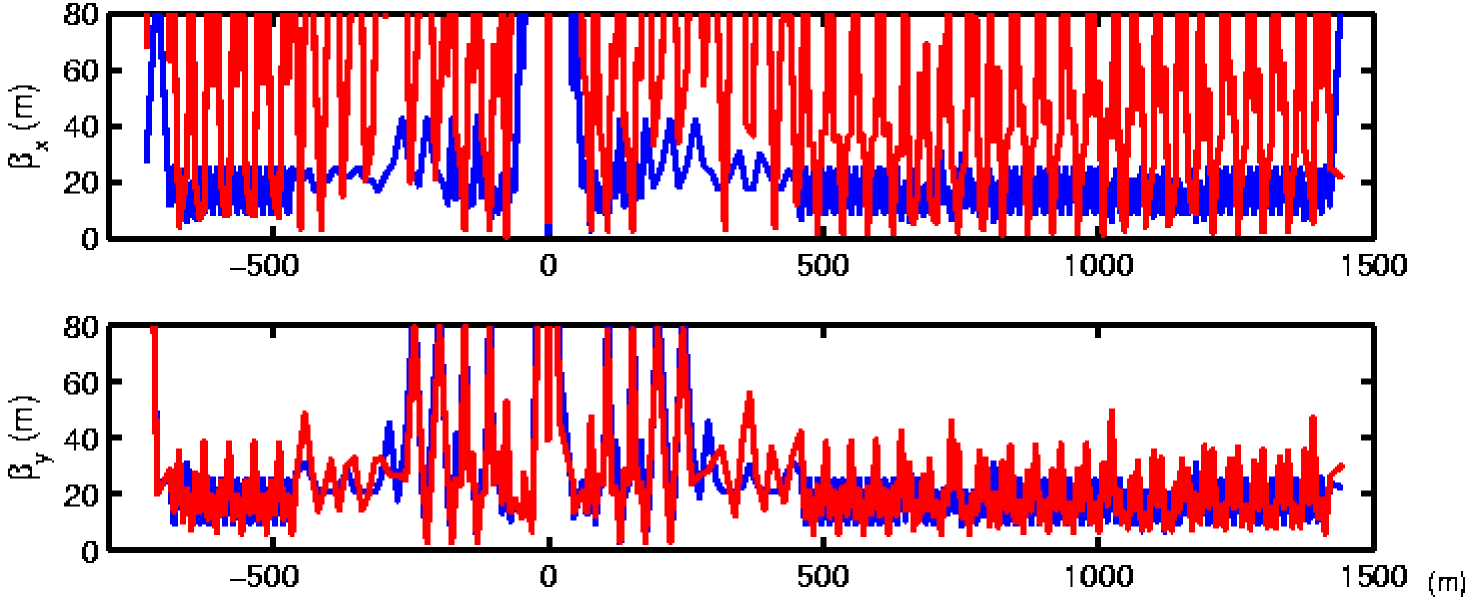
# PEP-II crisis

- After we enjoyed good 2003, 2004 for bringing PEP-II luminosity up to $10^{34}$ $cm^{-2}s^{-1}$, we had a PEP-II crisis in 2005 due to accident. PEP-II was shut down for about half a year in 2005.

- We faced the so-called P-5 reviews both in 2005 and 2006. Even worse, when we turned on PEP-II again, our machines were not cooperating. We had very bad HER.

# Virtual HER – Feb 1, 2006

comparing beta function bewteen the machine and the ideal lattice

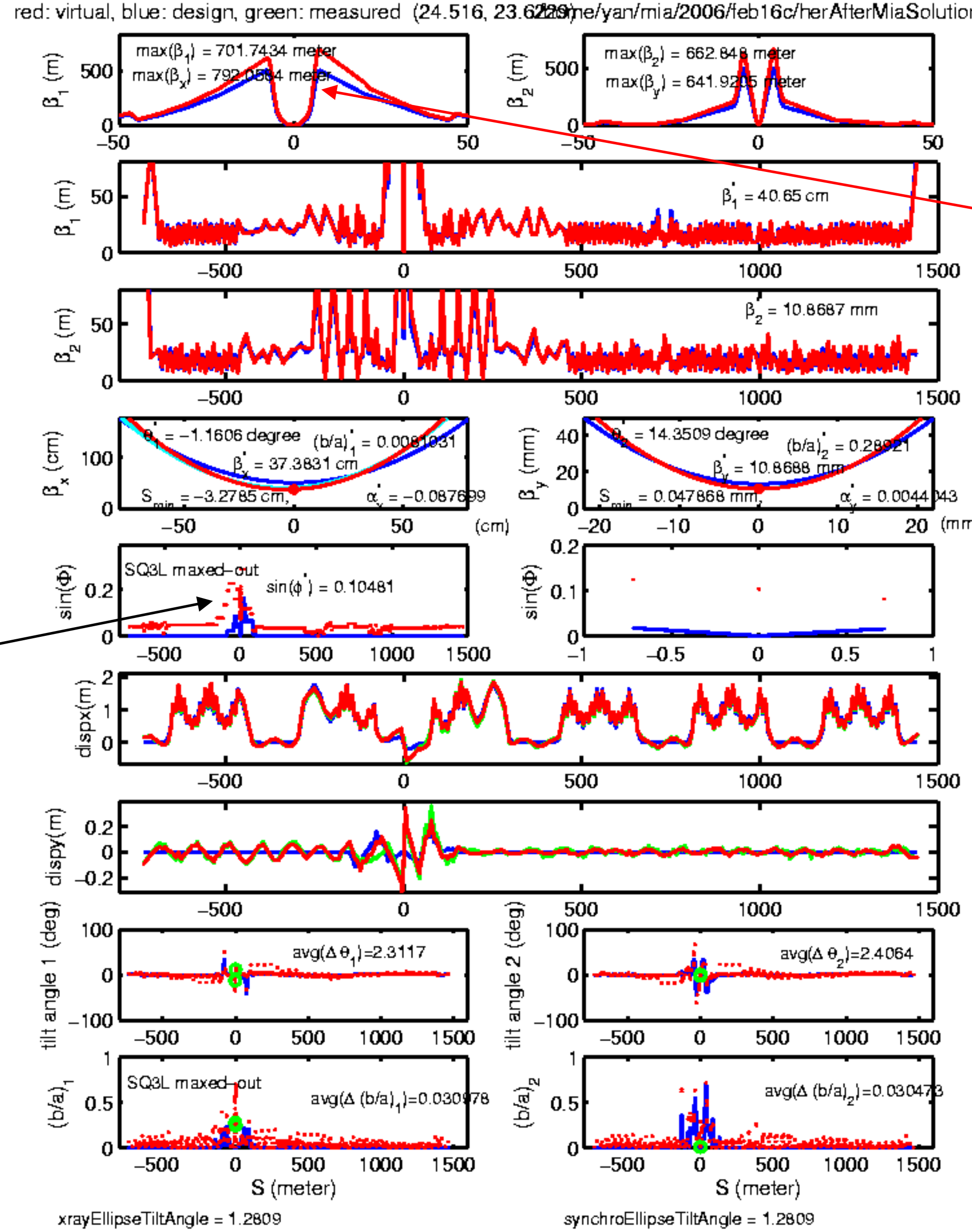



**We had a very strong HER X beta beat during the beginning period of 2006 run. We could have fixed it right away, however, due to more urgent problems, this high beta beat fixing was postponed till mid-February, 2006.**

# Virtual HER after one-shot MIA correction– Feb 16, 2006

mac2006

- Beta beating fixing mainly from QF5 (we use only the left one).
- We had also added trombones, local and global skews to simultaneously improve couplings, dispersion, and IP optics.
- We had a max-out of SQ3L that caused an imperfection of the offline solution. Thanks to Pantalio Raimondi who helped me find this max-out then.
- Since then we had enjoyed an HER record-low residual from the ideal lattice till we ramped the currents at later stage of the run.




**We had an updated ideal lattice at BetaX* =33 cm.**

# Successful LER major orbit steering in 2006

- One of the key improvement for PEP-II optics in 2006 run was the successful LER major orbit steering.

- It was usually difficult to correct the optics after a major steering for the coupled LER.

- We rely on offline modeling (MIA) after the steering to generate wanted approachable optics model and dial in the solution for restoring the linear optics.

# MIA for HER emittance improvement in 2007

**Table 1:** Emittance comparison for PEP-II HER

| PEP-II HER | X emittance (nm) | Y emittance (nm) |
|---|---|---|
| Virtual HER Feb. 6, 2007 | 94 | 0.59 |
| Virtual HER Feb. 8, 2007 (after 50% MIA solution in) | 64 | 0.24 |
| Wanted model for the new half solution derived from Virtual HER Feb. 8, 2007 after 50% MIA solution | 52 | 0.24 |
| Ideal Lattice emittance calculated from MIA program | 51 | 0.13 |

# Summary

- We had been, for years, able to get accurate models for PEP-II with MIA.
- MIA could provide wanted model for optics correction such as beta beat correction, bringing operation to half integer, linear coupling reduction, IP optics improvement, and catastrophic converting into a new configuration.
- Symmetric and anti-symmetric orbit corrector bumps performed by F.-J Decker were very helpful in improving PEP-II optics online, especially after one-shot optics correction with MIA.
- PEP-II is no longer operation

# Implication to model non-modified LHC optics

- Use of only Green's functions for fitting, one may still excite modified betatron oscillation, however, can  directly modeling non-modified optics.

- Two measurements, each with a pair of ac dipoles can obtain a complete set of Green's functions for modeling non-modified optics.