Optics Measurements in the FNAL Booster and the CERN PSB

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Outline of Talk

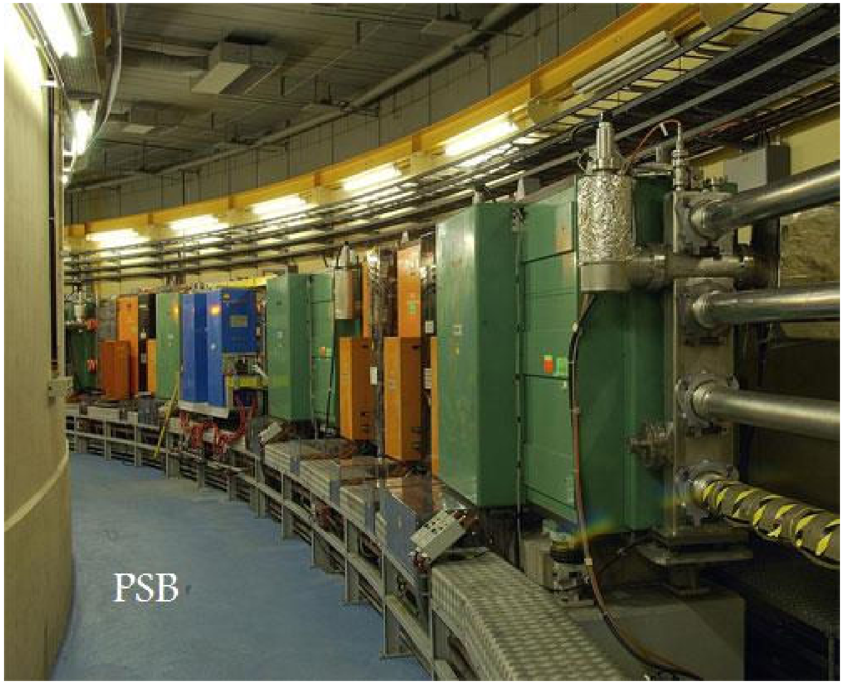
I. HL-LHC requirements for CERN PSB

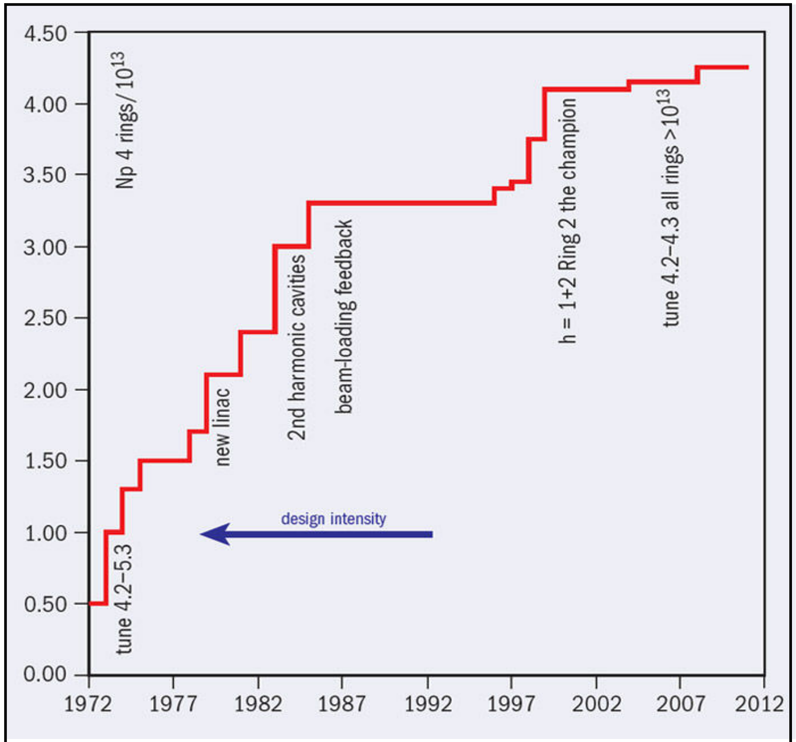
II. Planned optics measurements in CERN PSB
   - Two optics measurement methods will be used:
     - Linear Optics from Closed Orbit (LOCO)
     - Turn-by-turn trajectories
   - Goals are to fully characterize linear and nonlinear optics, and to compensate for measured imperfections

III. Optics measurements in FNAL Booster
   - Lattice model was calibrated and linear optics were measured using LOCO
   - Transverse coupling and beta beating were corrected

The Proton Synchrotron Booster

- 4 stacked rings simultaneously accelerate beam
- 16 period lattice structure with triplet focusing structure
- Accelerate protons from 50 MeV to 1.4 GeV (will be 160 MeV to 2 GeV after Linac4 commissioning)
- Maximum intensity has increased by a factor of four since commissioning in 1972

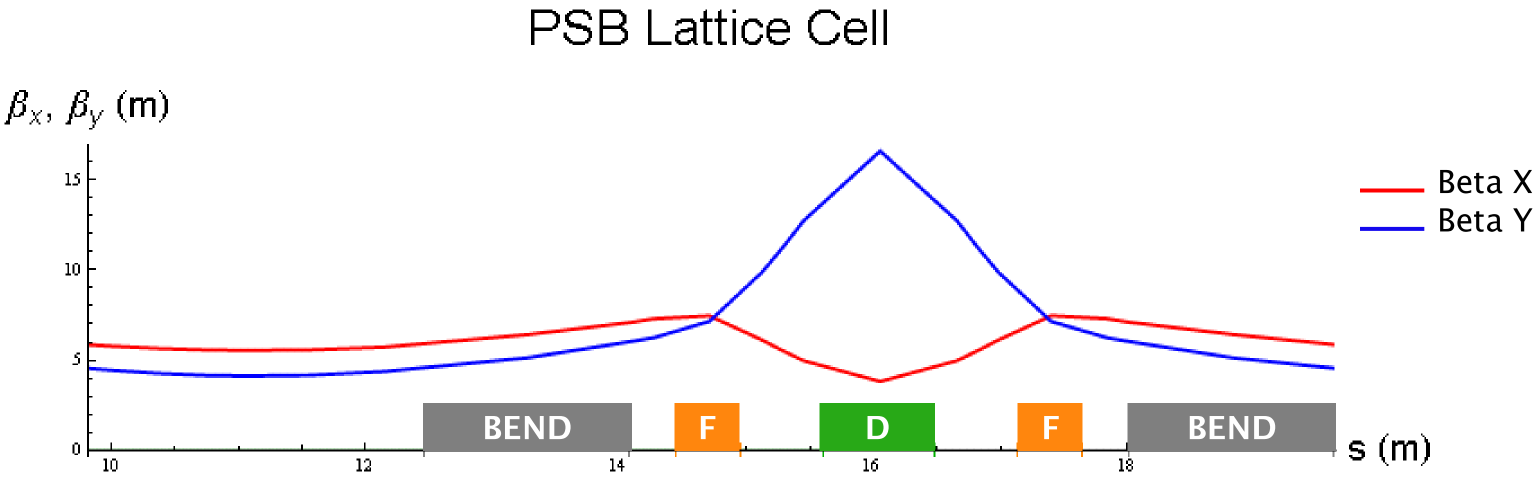




Intensity increase since the commissioning of the PSB in 1972

PSB Parameters and Lattice Structure

	CERN PSB
Energy	50 MeV-1.4 GeV
Ramp time	525 ms
Circumference	157 m
Qx, Qy	4.2, 4.3



Requirements for beam delivered to the LHC from the PSB

		N (10^{11} ppb)	ϵ (μm)	E_inj (GeV)	E_ext (GeV)
Post LS1	50 ns	12.4	1.4	0.05	1.4
	25 ns	17-22	2.1-2.6	0.05	1.4
Post LS2	50 ns	12.5	0.8	0.16	2
	25 ns	24.9	1.7	0.16	2
HL-LHC	50 ns	27.2	1.9	0.16	2
	25 ns	34.2	1.5	0.16	2

Increasing intensity while maintaining small emittance will require effective correction of resonances, as well as precise knowledge of optics for accurate beam modeling.

Source:

Summary of the LIU Beam Studies Review

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25 October 2012
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First Optics Measurement Method: Linear Optics from Closed Orbit (LOCO)

- Measure the linear response of the orbit to *j* dipoles at *i* BPMs
- Find the set of hidden model parameters (quad errors, dipole and BPM gains, etc.) that minimizes the difference between measurement and model:

$$F = \sum_{i,j} \left(\left(\frac{\partial x_i}{\partial \theta_j} \right)_{Meas} - \left(\frac{\partial x_i}{\partial \theta_j} \right)_{Model} \right)^2 \frac{1}{\sigma_{ij}^2}$$

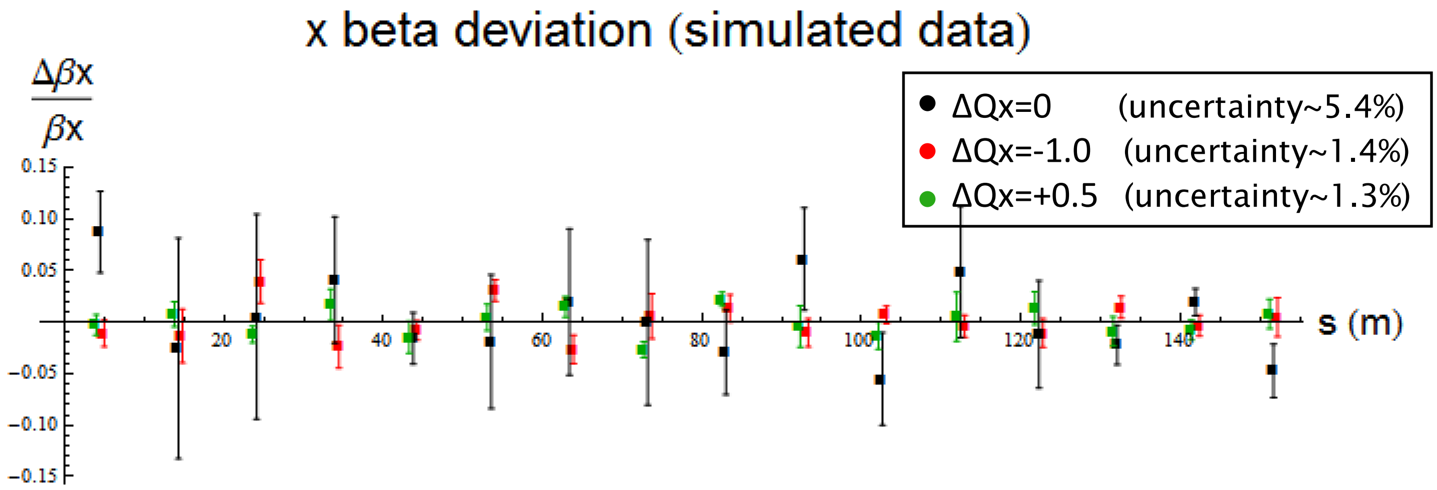
Each of the PSB's four rings contains 16 BPMs and 14 dipoles that can be used to measure the Orbit Response Matrix.

Method 2: Resonance Measurements from Turn-by-turn Trajectory

- Nonlinear optics are measured by analyzing the frequency spectra of coherently oscillating beam
- A test of optics analysis using trajectory data from three of the PSB’s BPMs will be completed by the end of this year
- After LS1, all BPMs will be capable of turn-by-turn acquisition

Effect of tune on TBT measurement precision

- With present tunes, Δψ≈90° between BPMs
- Changing working point would improve precision of optics calculation from turn-by-turn measurements



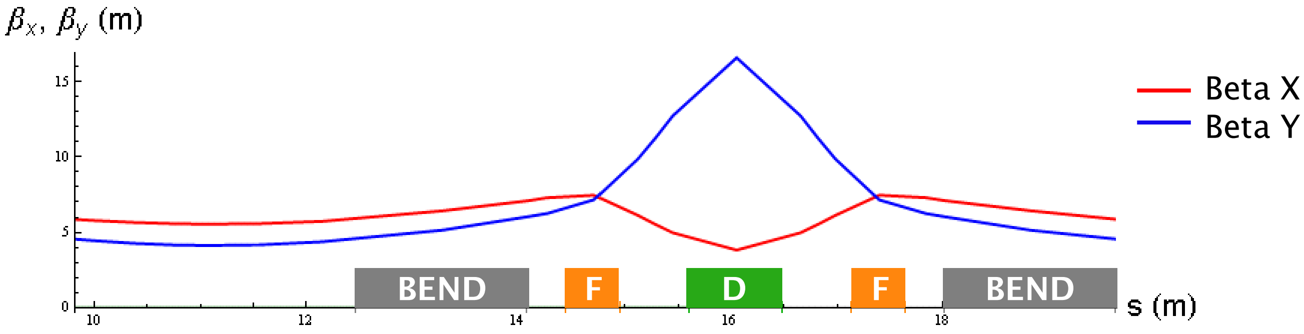
Beta beating reconstructed from PTC tracking, using three tune working points: ΔQx=0, ΔQx=-1.0, ΔQx=+0.5. Model included 0.1% random error added to quads and 0.1 mm noise to BPMs.

Optics Measurements in the FNAL Booster

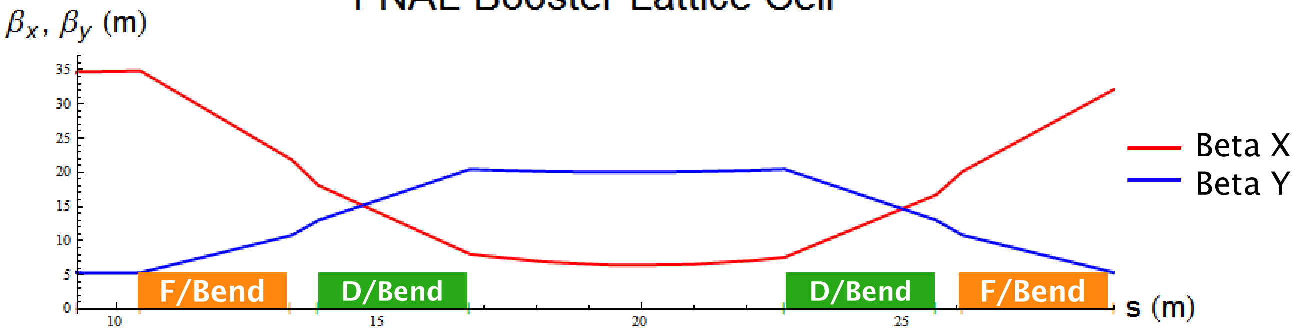
CERN and FNAL Booster Comparison

	CERN PSB	**FNAL Booster**
Energy	50 MeV-1.4 GeV	400 MeV-8 GeV
Ramp time	525 ms	33 ms
Circumference	157 m	474 m
Qx, Qy	4.2, 4.3	6.7, 6.8

PSB Lattice Cell

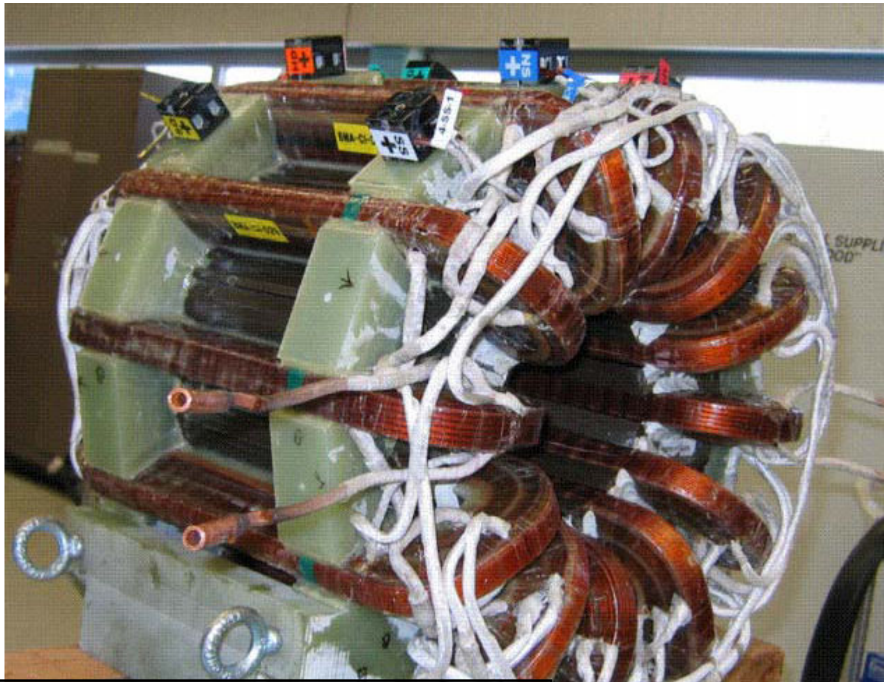


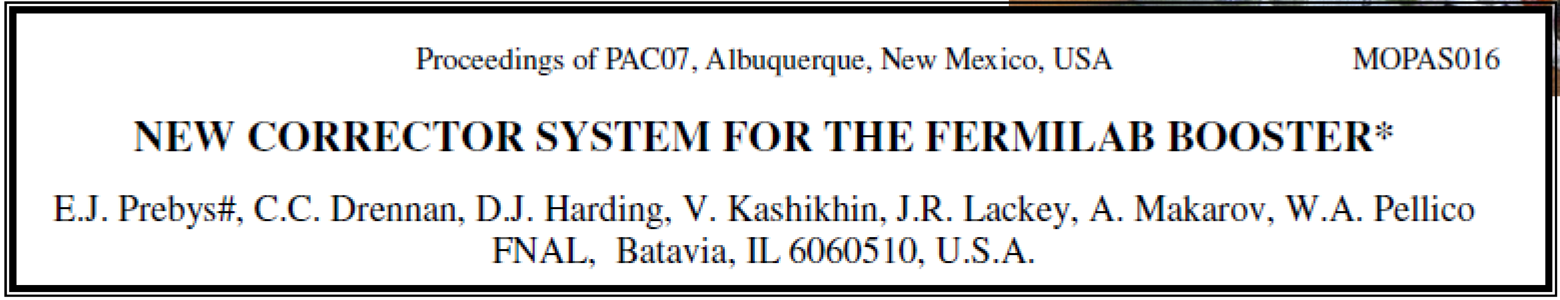
FNAL Booster Lattice Cell



Booster Corrector Magnet Packages

- The Booster's system of 48 ramping corrector magnets provides flexibility for making optics measurements and implementing corrections
- each corrector package contains an integrated BPM and six independently-powered elements:
  - horizontal and vertical dipoles
  - normal and skew quadrupoles
  - normal and skew sextupoles





Proceedings of PAC07, Albuquerque, New Mexico, USA MOPAS016

NEW CORRECTOR SYSTEM FOR THE FERMILAB BOOSTER*

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Linear Optics from Closed Orbit (LOCO) Analysis in FNAL Booster

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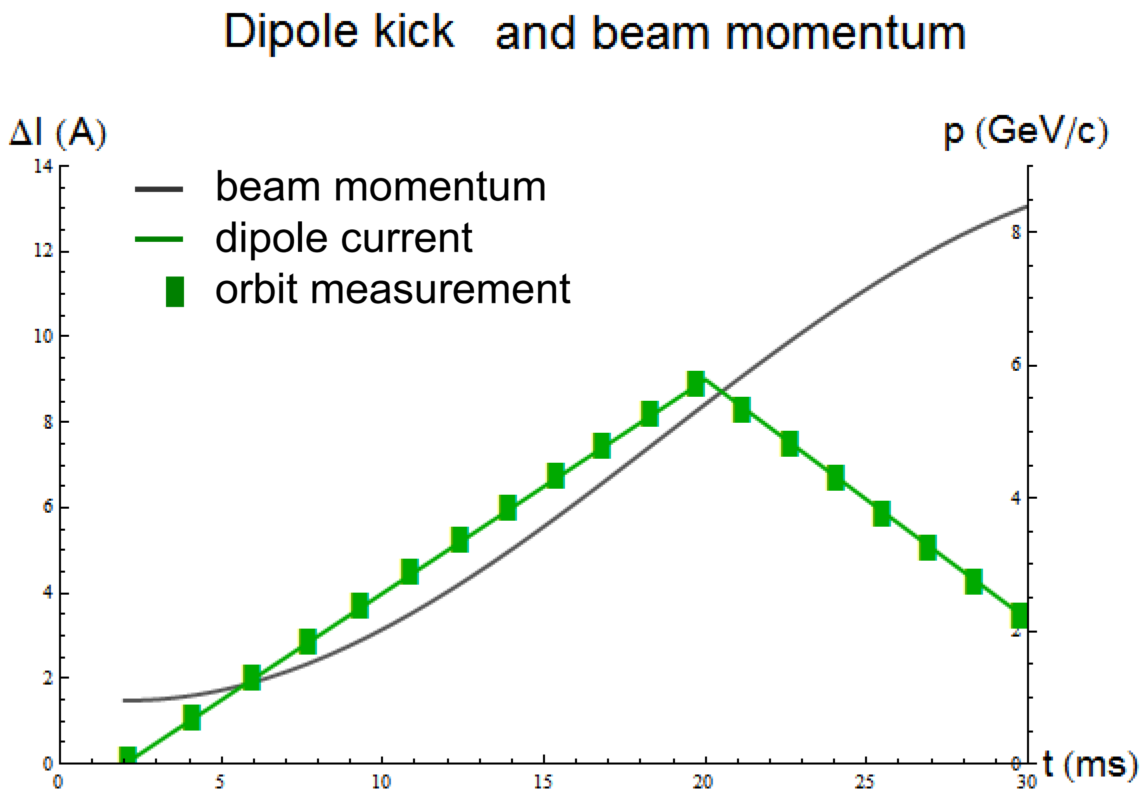
- Orbit response to i=48 dipoles at j=48 BPMs (in each plane) was measured
- Chosen model calibration parameters were normal and skew pseudo-quad errors located at positions of corrector packages, and BPM and dipole gain and roll
- Optics were measured and corrections were implemented throughout the acceleration ramp

Orbit response in a fast-ramping synchrotron

- Dipoles were ramped to keep an approximately constant angular kick as beam momentum increased
- Eddy currents had a significant effect on magnet strengths

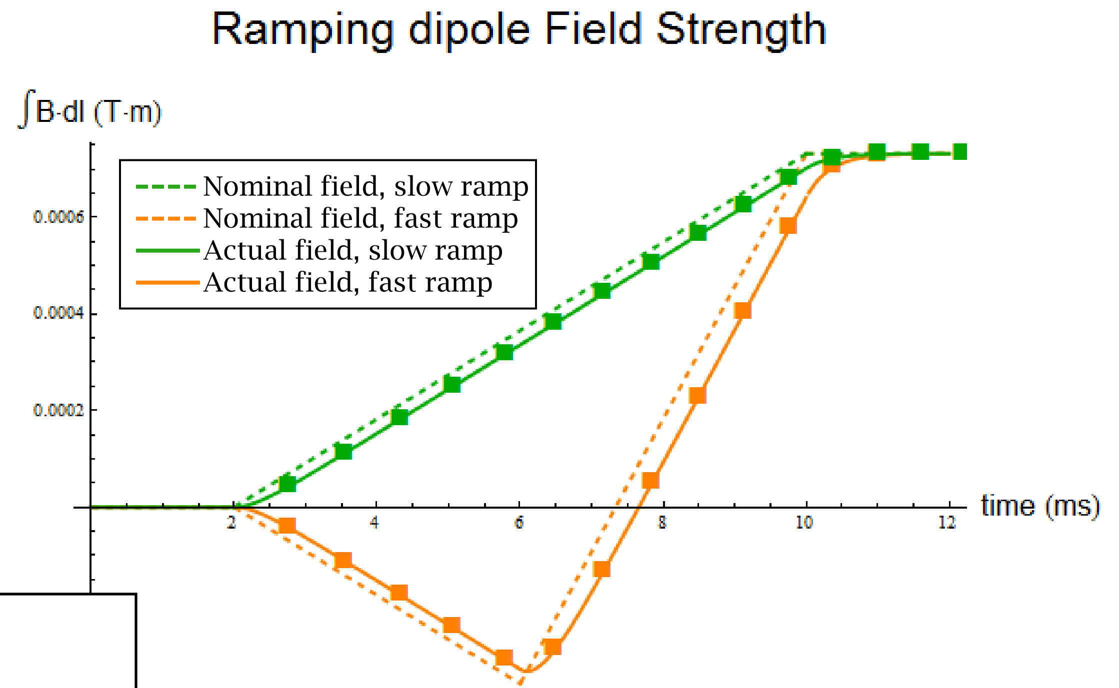


During Orbit Response Matrix measurements the strength of the dipole kick is increased as momentum increases, and the orbit is measured at 20 points during the acceleration cycle.

Measurement of eddy currents

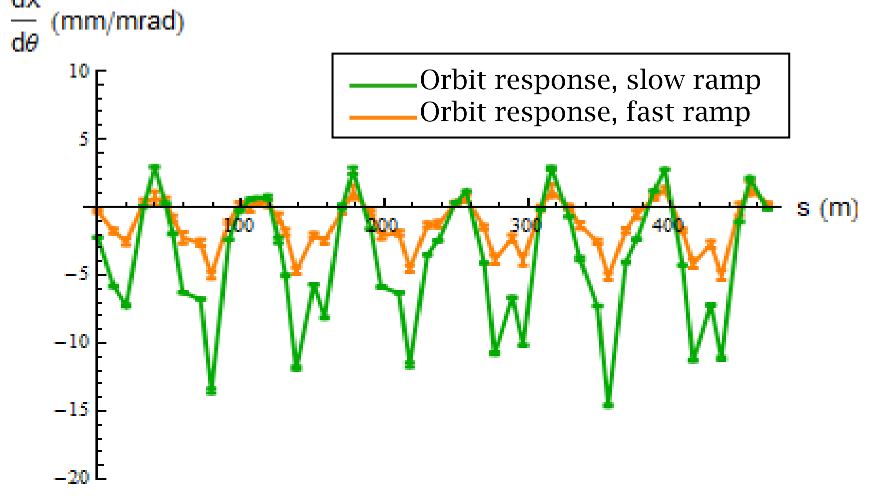
Eddy current effects were measured by comparing orbit response with fast and slow magnet ramps, and fitting for the field lag time constant τ:

$$\tau \frac{dB}{dt} + B(t) = B_0(t)$$



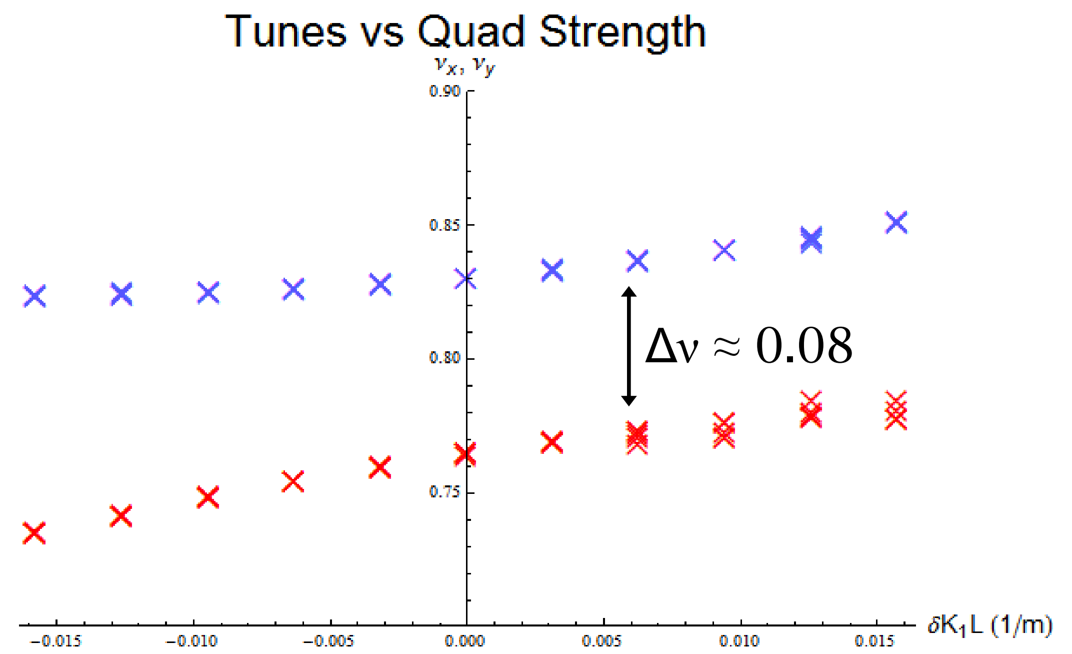
We measured the orbit response to both a quickly-ramping and a more slowly-ramping dipole current, and fit the ratio of these responses to find the lag time constant τ

Orbit Response, t= 7.84 ms

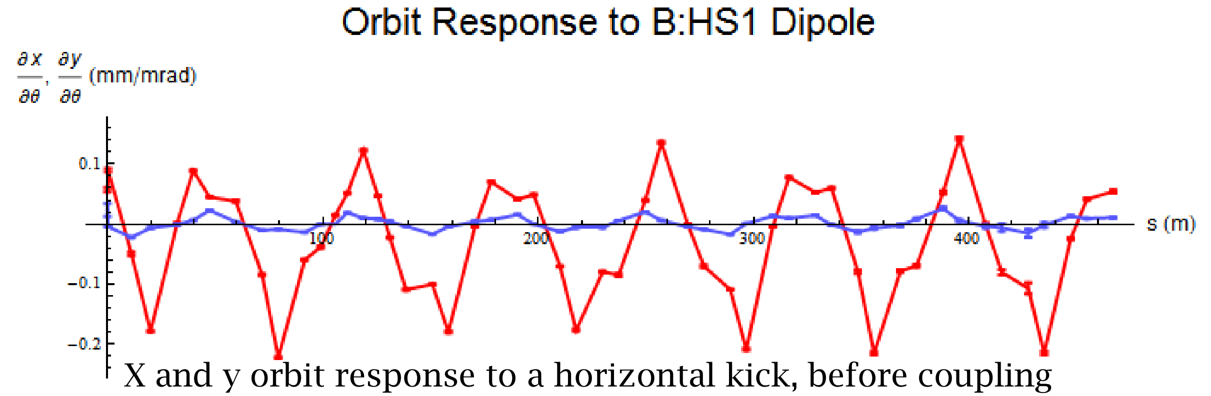


Transverse Coupling

- The booster has significant transverse coupling during normal operation
- Some coupling is caused by magnet misalignments, and skew quad fields are also added in order to suppress transverse instabilities



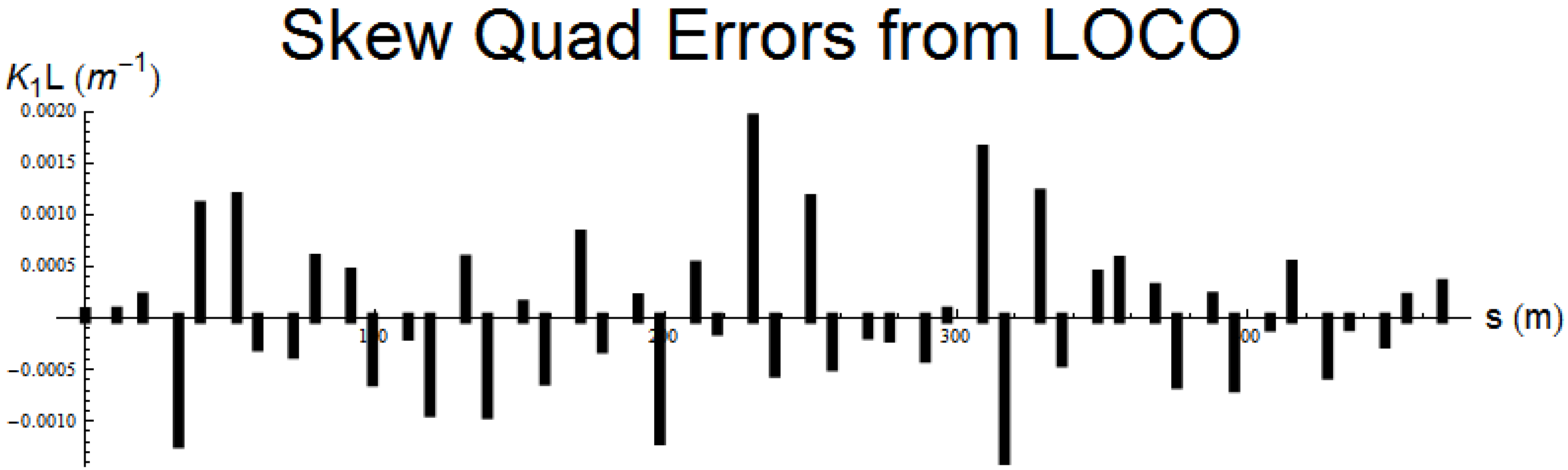
Change in x and y tunes vs quad strengths, before coupling correction; minimum tune separation is ~0.08.



X and y orbit response to a horizontal kick, before coupling correction; response in unkicked plane is not zero.

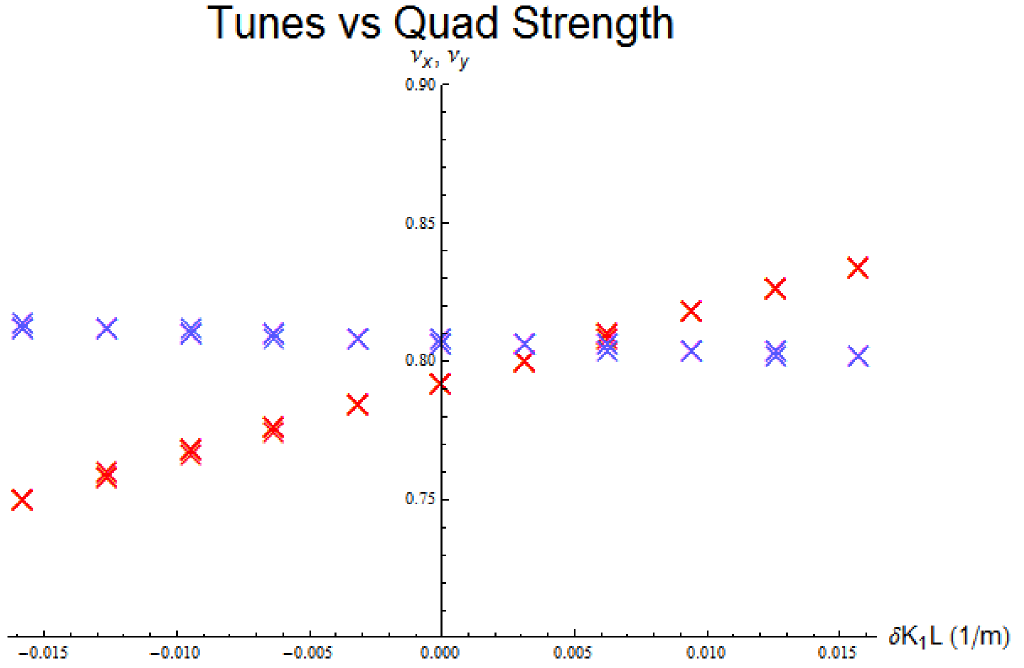
Correction of Transverse Coupling

- The set of skew pseudo-quad errors around ring was found using LOCO, and then compensated with skew quad corrector magnets to remove transverse coupling
- ORM measurements were then repeated on the uncoupled machine

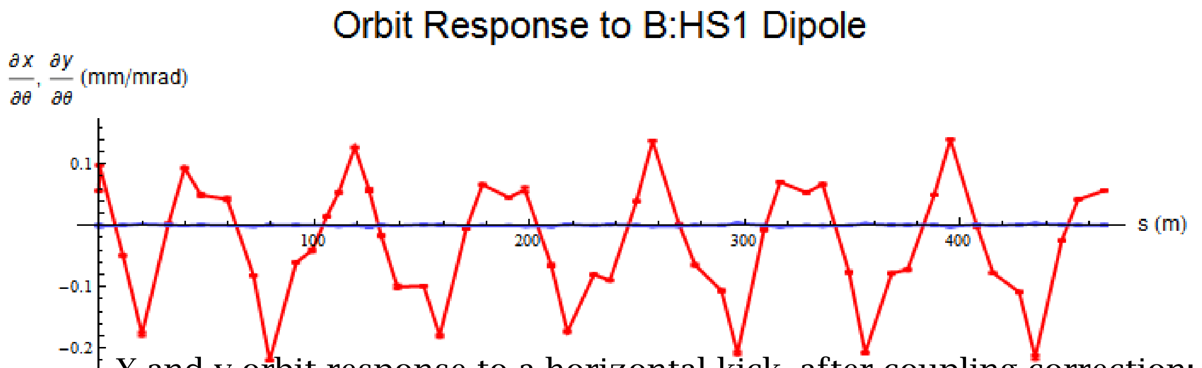


Transverse Coupling After Correction

- Minimum tune separation and orbit response in non-kicked plane are virtually eliminated
- Transverse instability isn't present at the relatively low intensity we used (~50% of normal intensity)

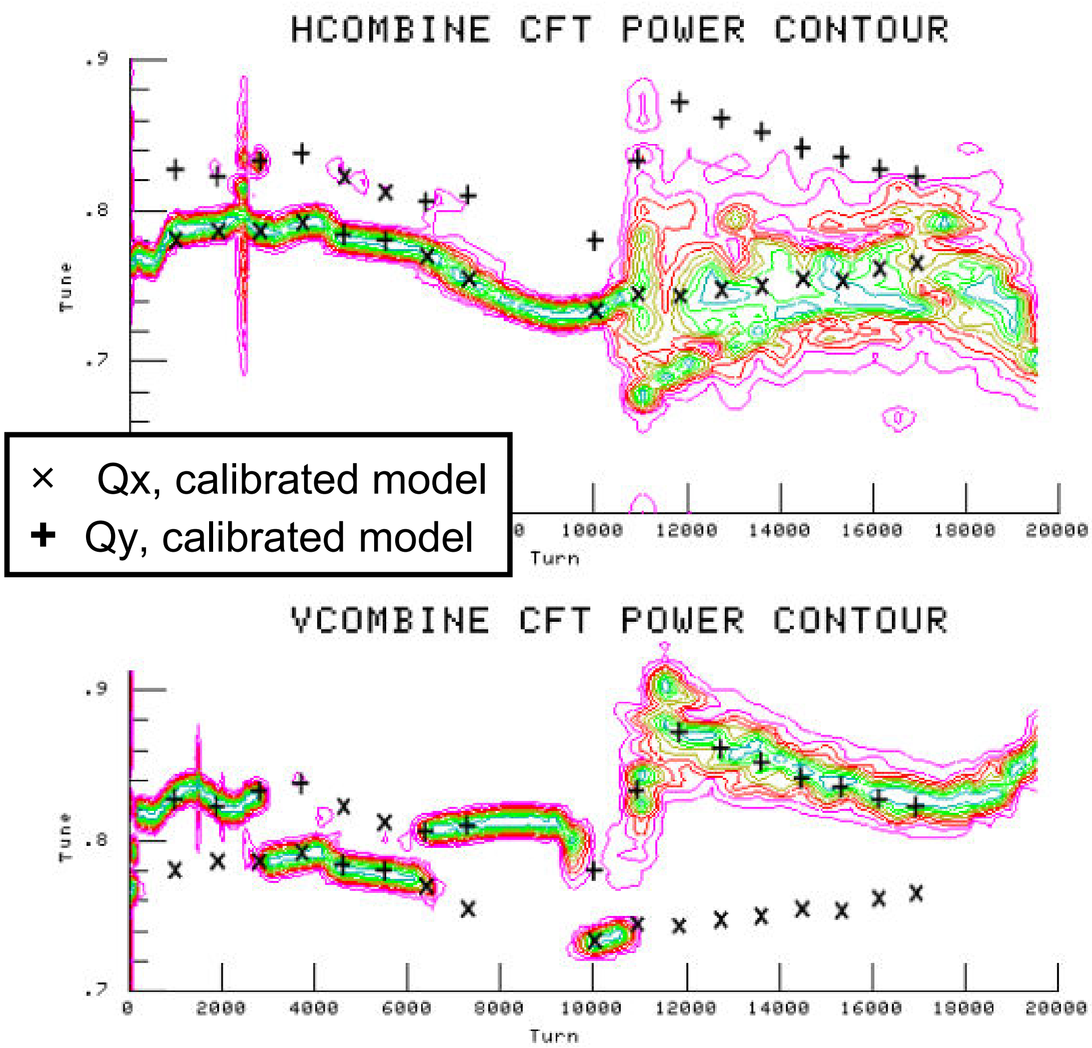


Change in x and y tunes vs quad strengths, after coupling correction; ΔQmin is smaller than measurement resolution.



X and y orbit response to a horizontal kick, after coupling correction; response in unkicked plane is nearly zero.

Calibration of Model

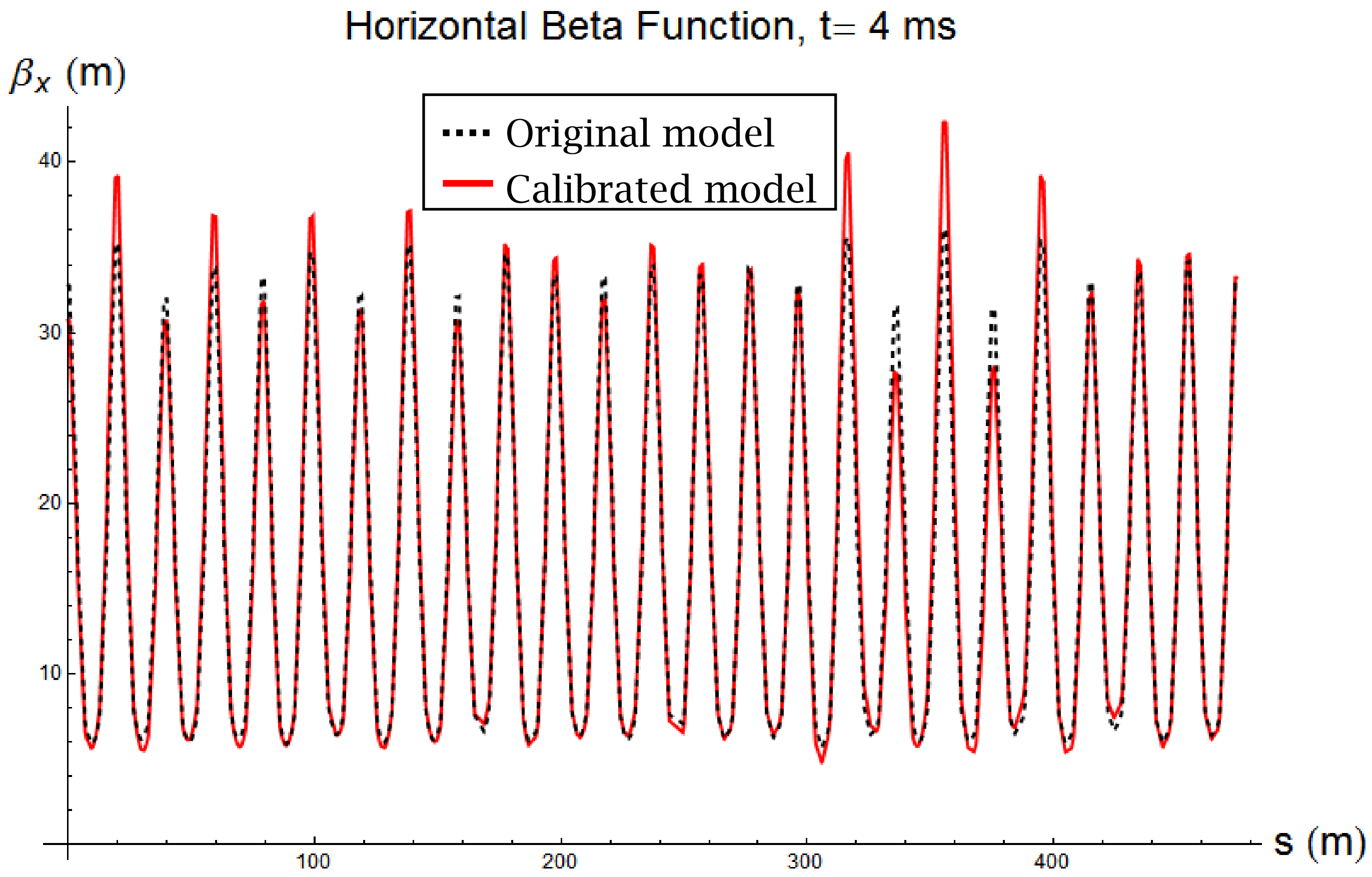


Comparison of coupled tunes given by calibrated model, and measured spectra from horizontal (top) and vertical (bottom) BPMs.

- Booster lattice model was calibrated by adding thin quad errors found from LOCO
- After calibration, the model tunes agree with the measured coupled tunes
- Measured tune is not input in LOCO algorithm, so tune of calibrated model helps to verify the validity of the method

(Image from A. Petrenko)

Measured Beta Beating

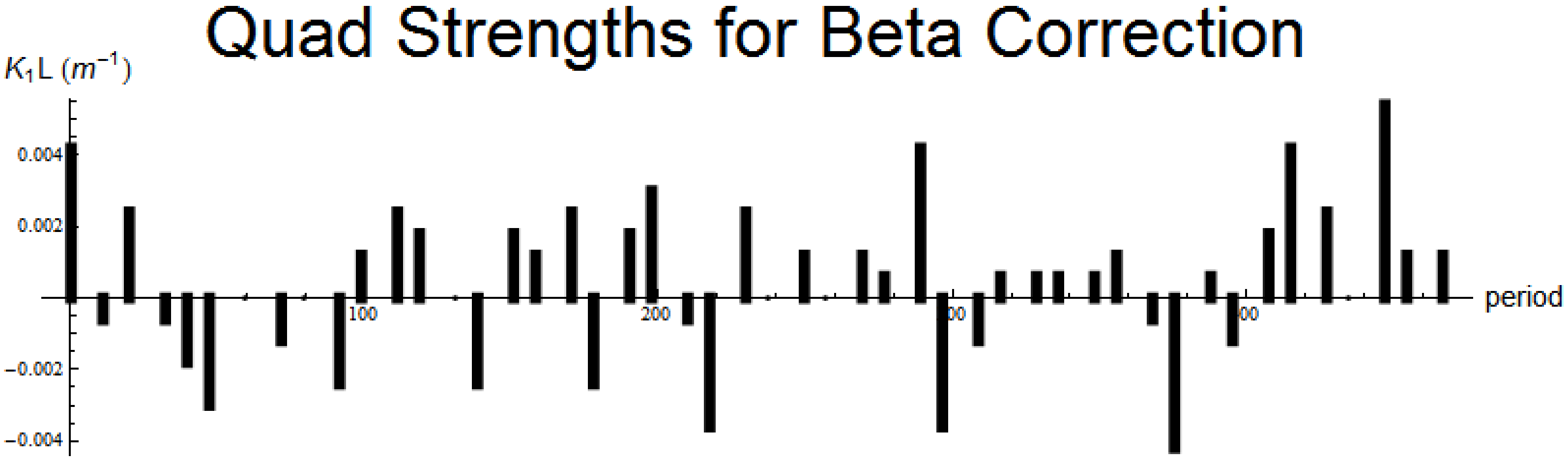


Horizontal beta function as given by both the original MAD Booster model and the calibrated model.

- Beta beating is nearly 30% early in the acceleration cycle, smaller later in the cycle
- Standard MAD model shows only ~10% beta beating at injection

Correction of beta beating

- Because lattice imperfections are very irregular, beta-beating corrections were calculated "by hand" using OptiM*
- All 48 corrector quads were used for correction, ramped to make appropriate corrections throughout the acceleration cycle
- To minimize orbit distortion, dipole corrections were calculated to negate the quad steering effects in each corrector package



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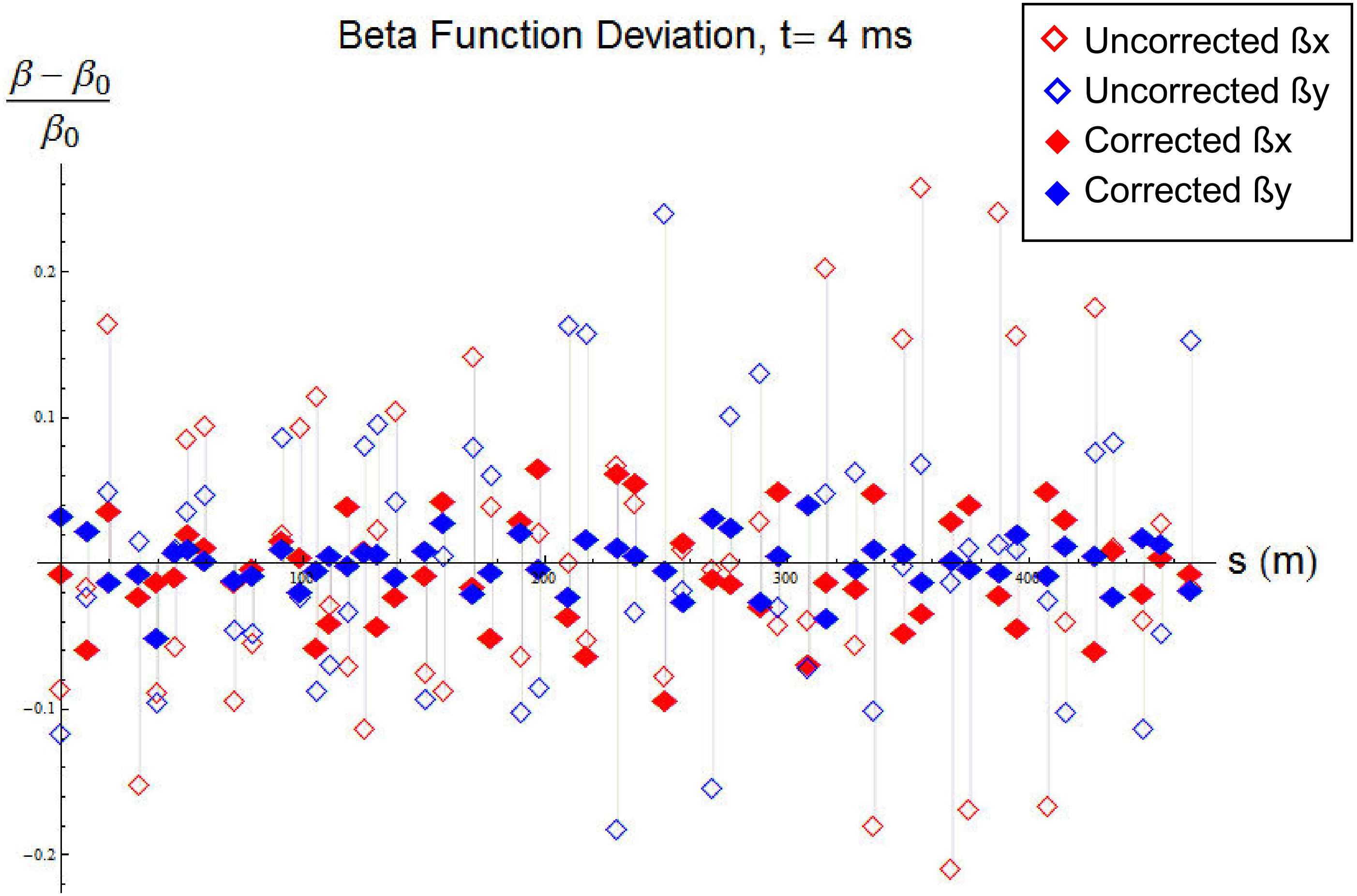
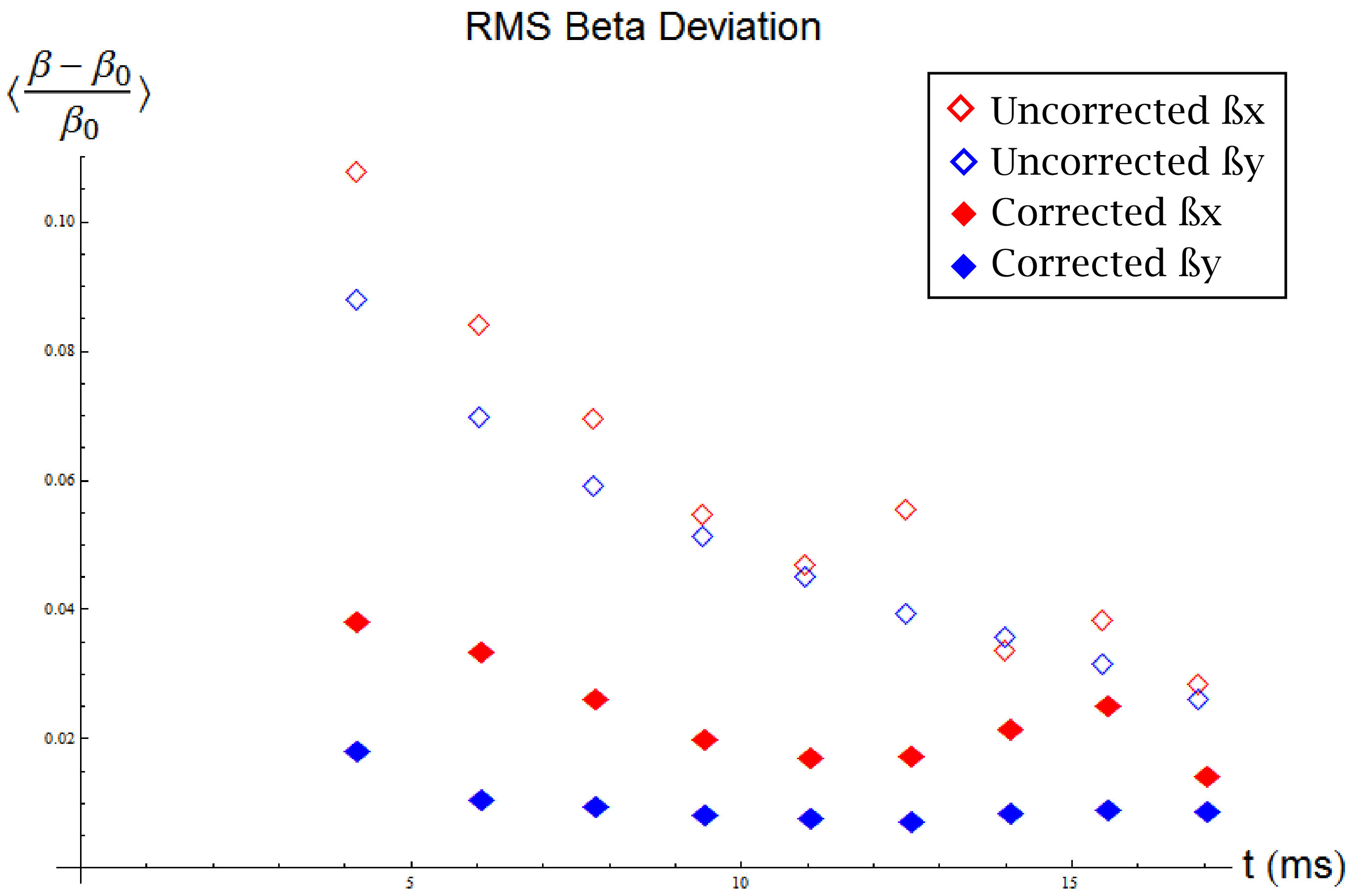
* V. Lebedev, "OptiM- Computer code for linear and non-linear optics calculations," 2009

Beta beating after correction



Deviation of the x and y beta functions from ideal values near beginning of the acceleration cycle, before and after beta beating corrections.

RMS beta deviation after correction



RMS deviation of the x and y beta functions from ideal values throughout the acceleration cycle, before and after beta beating corrections.

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