Status of optics modeling at the MLS and at BESSY II

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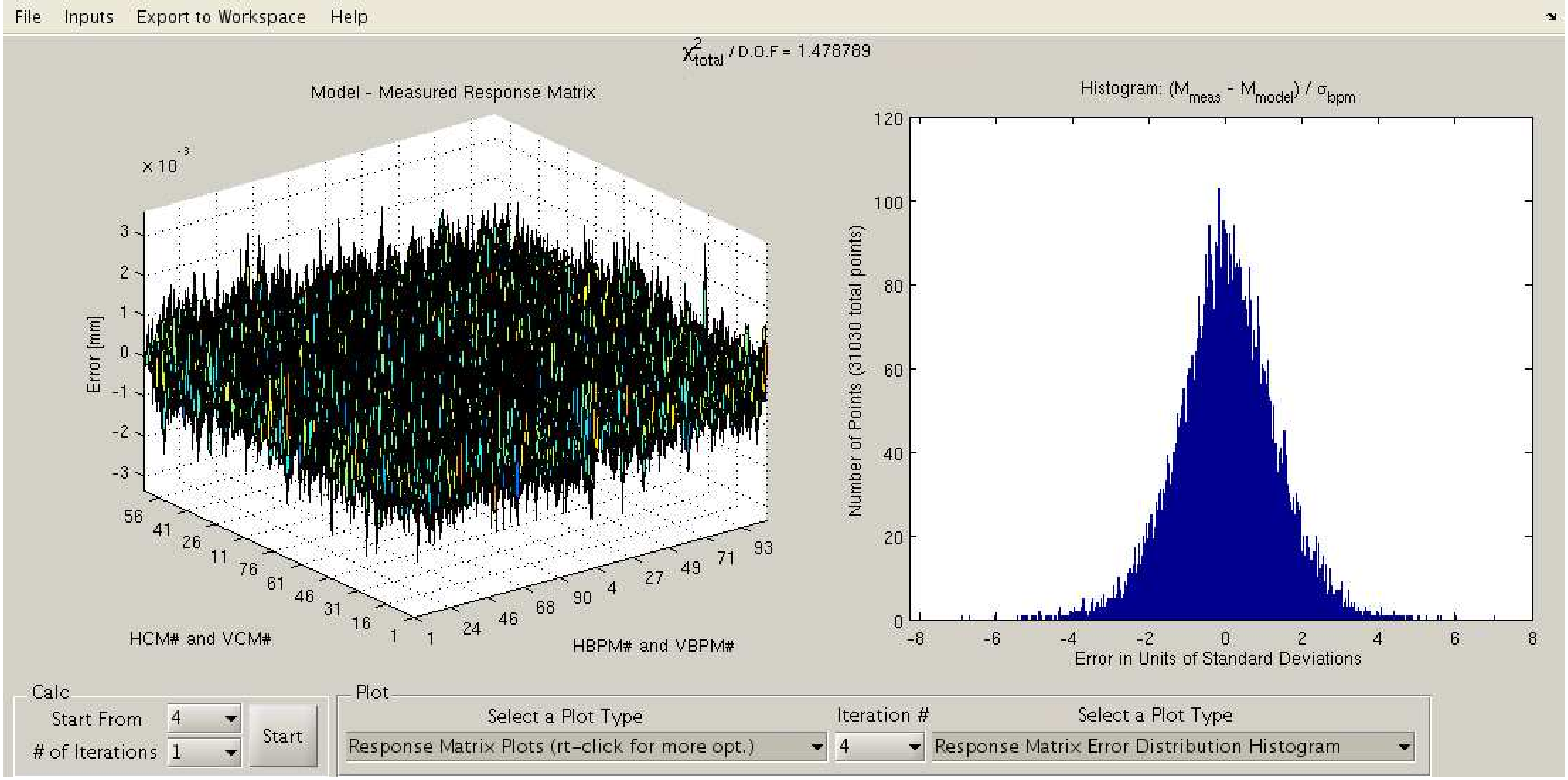
- ☐ LOCO
- ☐ Status of optics' studies
- ☐ Reducing the coupling
- ☐ Symmetrizing the optics
- ☐ Results

Linear Optics from Closed Orbits (*LOCO*)



χ^2_{total} / D.O.F = 1.478789

Start From: 4

\# of Iterations: 1

Select a Plot Type: Response Matrix Plots (rt–click for more opt.)

Iteration #: 4

Select a Plot Type: Response Matrix Error Distribution Histogram

Introduction

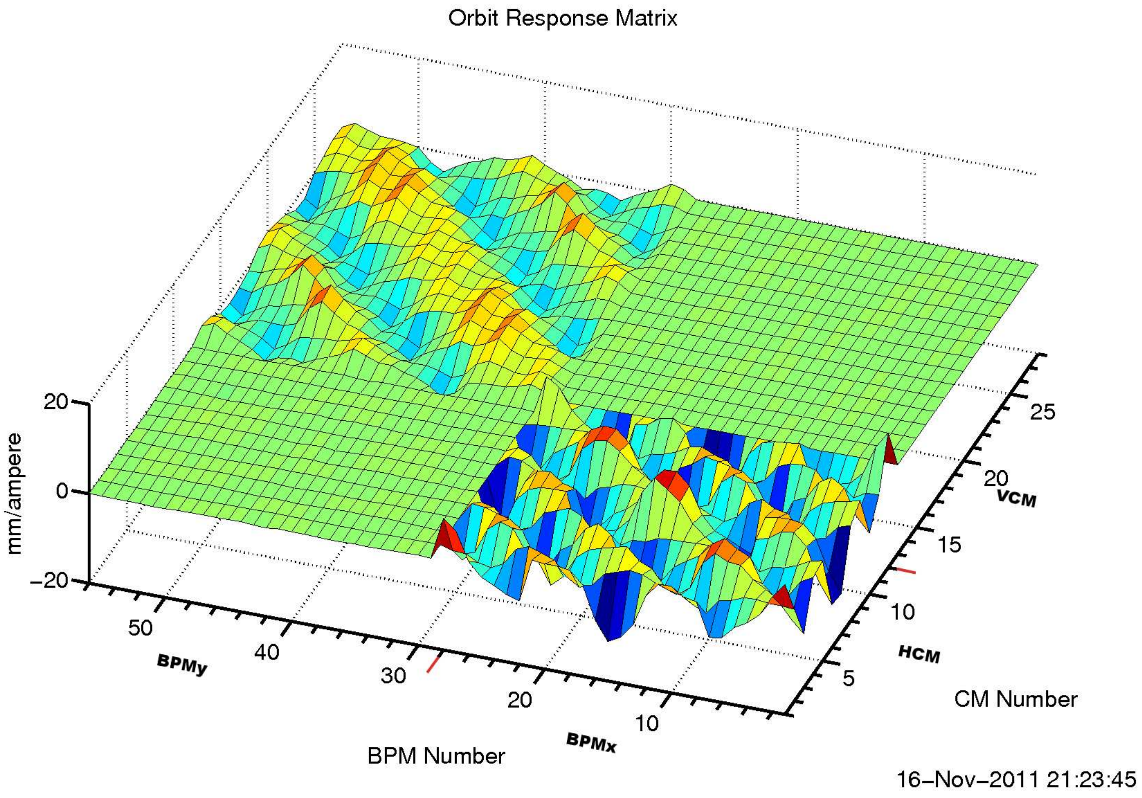
- LOCO: Linear Optics from Closed Orbits.
- Simulation programs (e. g. MAD) can compute response matrices for a given lattice.
- LOCO uses the opposite approach: Attempt to reconstruct the linear optics from measured response matrices.
- A successful LOCO analysis helps improving the understanding of the status of the storage ring.

Objective

Determining the

- quadrupole gradients.
- BPM *gains*.
- calibration factors of the steerer magnets.
- conversion factors of the skew quadrupole gradients.
- BPM coupling.
- quadrupole roll.
- focusing properties of IDs.

Plot of a Response Matrix



- Kick the beam horizontally/vertically and record the response at the BPMs.

Response matrix of the model

Response matrix M_{ij}:

change in orbit at BPM i depending on the strength θ_j of the corrector magnet j

$$\begin{bmatrix} x \\ y \end{bmatrix} = M \begin{bmatrix} \theta_x \\ \theta_y \end{bmatrix}$$

- Vertical response matrix:

$$M_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cos\left(|\phi_i - \phi_j| - \pi\nu\right)$$

- Horizontal response matrix:

$$M_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cos\left(|\phi_i - \phi_j| - \pi\nu\right) - \frac{\theta_j \eta_j}{\alpha_c L_0} \eta_i$$

Dispersive term in the horizontal plane:

The length of the orbit is determined by the RF frequency:

→ The change in path length caused by the kick has to be offset by a change in energy keeping the revolution time constant.

- β_i beta function
- ϕ_i phase advance
- η_i dispersion
- ν tune
- α_c momentum compaction factor
- L_0 length of the ring

Method

- The parameters in the model are varied.
- Goal: Minimizing the difference between measured and simulated response matrix.

Figure of merit

$$\chi^2 = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{\left(M_{ij}^{\text{meas}} - M_{ij}^{\text{model}}\right)^2}{\sigma_i^2} = \sum_{k=i,j}^{N} E_k^2$$

The error vector is minimized by iteration. (SVD, Gauß-Newton method)

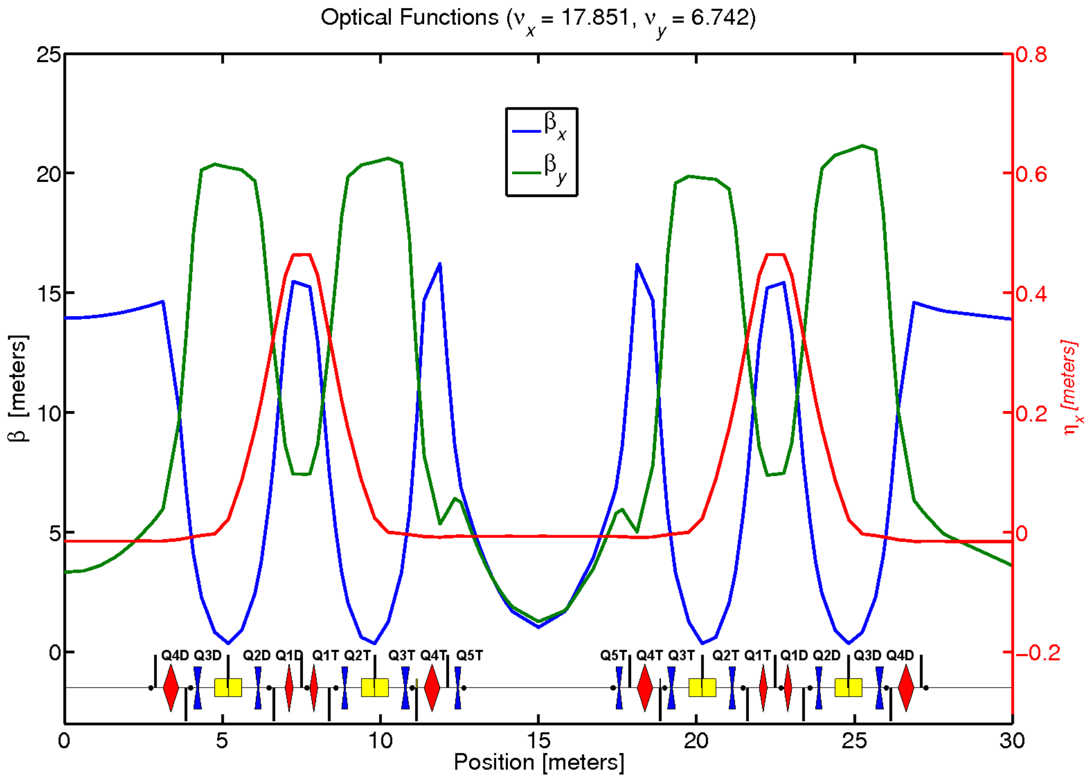
$$E_k^{\text{new}} = E_k + \frac{\partial E_k}{\partial K_l} \Delta K_l$$

$$-E_k = \frac{\partial E_k}{\partial K_l} \Delta K_l$$

The response matrix is not a linear function of the quadrupole gradients. Fit needs to be iterated until convergence occurs.

- σ_i: noise level of the BPMs
- E_k: error vector
- K_l: fit parameter; gradient, gain, etc.
- $\sigma(\text{model} - \text{meas}) :=$ standard deviation $\left(M_{ij}^{\text{model}} - M_{ij}^{\text{meas}}\right)$

BESSY II



- ❑ Double bend achromat lattice
- ❑ eight super cells
- ❑ Circumference $L = 240\,\mathrm{m}$.
- ❑ Nominal Energy $E = 1.72\,\mathrm{GeV}$.
- ❑ Emittance $\epsilon_x = 6\,\mathrm{nm\,rad}$.
- ❑ Emittance $\epsilon_x = 4\,\mathrm{nm\,rad}$ including super conducting devices.

Fit parameters for BESSY II

- 108 horizontal BPM gains
- 108 vertical BPM gains
- 80 horizontal corrector magnet gains
- 64 vertical corrector magnet gains
- 44 circuits (quadrupole gradients)

in total: M = 404 fit parameters

Measurement data:

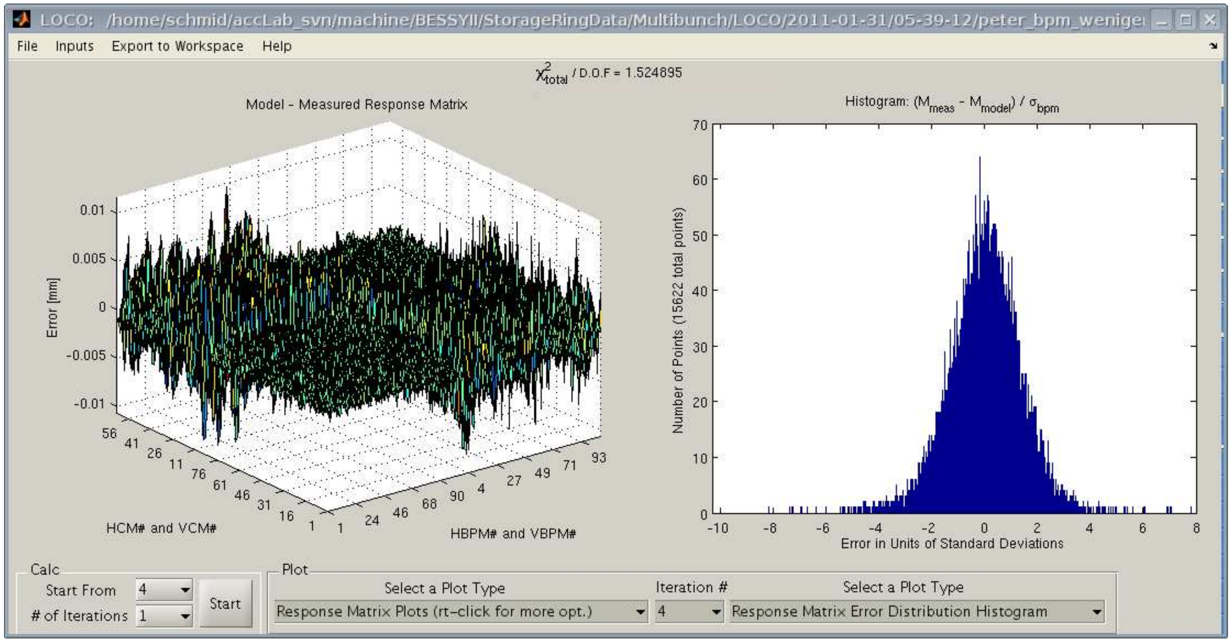
- $108 \times 80 + 108 \times 64$ data points included in the response matrix
- 108 dispersion measurements

in total: N = 15660 data points
number of degrees of freedom $N - M = 15256$

$$\chi^2 = N - M \pm \sigma, \quad \sigma = \sqrt{2(N - M)}$$

Predictor for the statistical error if $N - M$ is asymptotically large.

Best fit



LOCO: /home/schmid/accLab_svn/machine/BESSYII/StorageRingData/Multibunch/LOCO/2011-01-31/05-39-12/peter_bpm_wenige

χ^2_{total} / D.O.F = 1.524895

Calc

Start From: 4

# of Iterations: 1

Plot

Select a Plot Type: Response Matrix Plots (rt–click for more opt.)

Iteration #: 4

Select a Plot Type: Response Matrix Error Distribution Histogram

- The predictor for the precision of the fit, $\sigma(\text{model} - \text{measurement})$, reaches (almost) the noise level of the BPMs

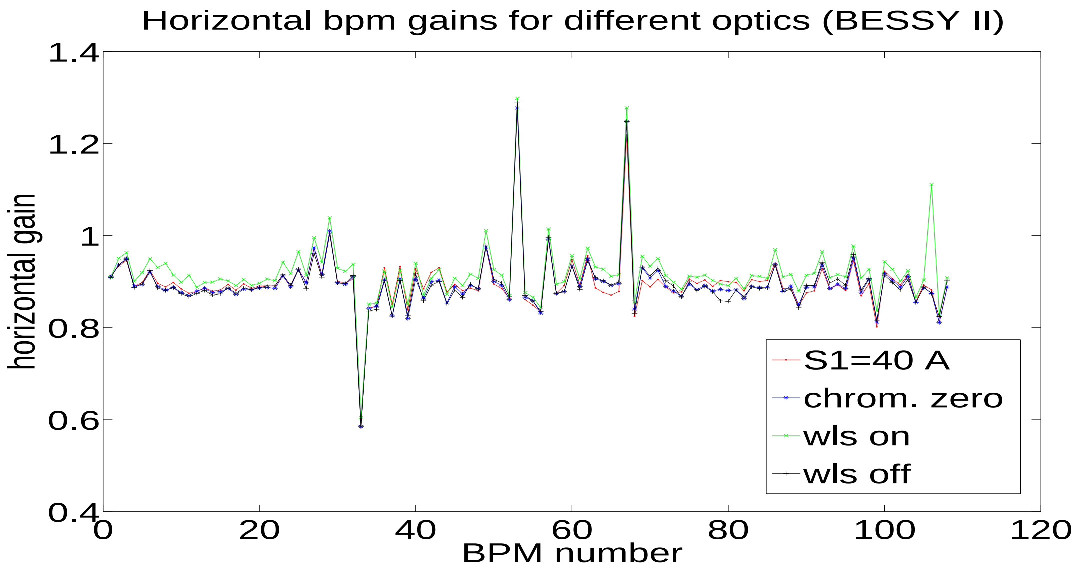
- Only sextupole family S1 is excited, $I_{S1} = 40$ A
- $\sigma(\text{model} - \text{measurement}) = 0.69\,\mu\text{m}$
- Average of the BPM σs: horizontal: $0.59\,\mu\text{m}$, vertical: $0.54\,\mu\text{m}$

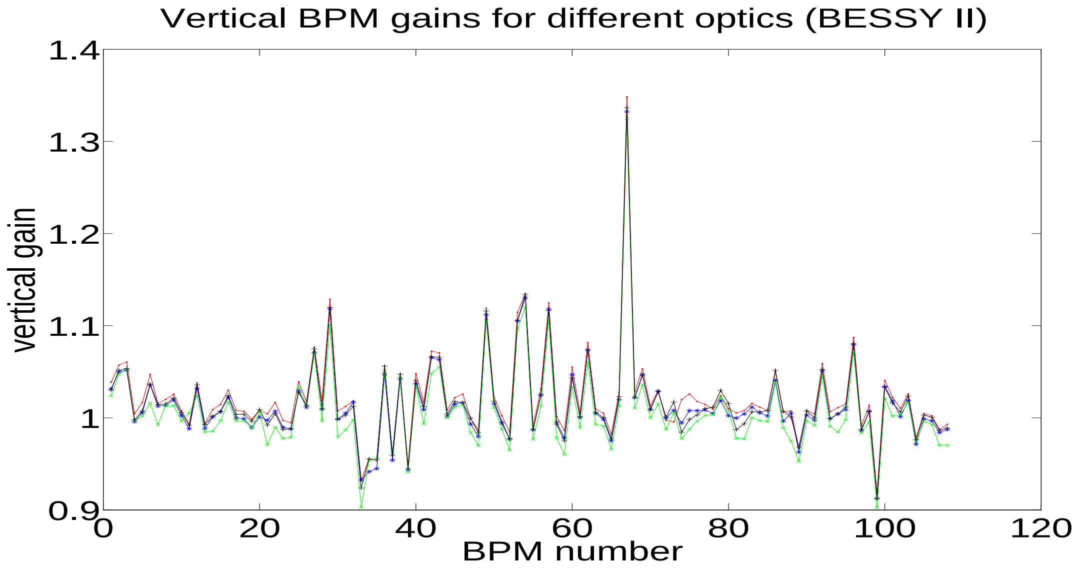
Analysis for different machine settings

Setting	$\frac{\chi^2}{DOF}$	$\sigma(\mathrm{model} - \mathrm{meas.})$
only S1 minimal	1.525	$0.687\,\mu\mathrm{m}$
+ skews	1.479	$0.672\,\mu\mathrm{m}$
user optics	3.975	$0.746\,\mu\mathrm{m}$
+ skews	9.138	$1.046\,\mu\mathrm{m}$
user optics w/ WLS/FFF	4.350	$0.805\,\mu\mathrm{m}$
+ skews	8.019	$1.002\,\mu\mathrm{m}$

- WLS: Wave Length Shifter.
- FFF: Fast Feed Forward (IDs).
- CQS: Skew Quadrupoles.
- User optics: All sextupoles including harmonic ones are at standard settings.
- Average of the BPM σs:
  horizontal: $0.59\,\mu\mathrm{m}$,
  vertical: $0.54\,\mu\mathrm{m}$

BPM gains for different optics





- Fitting the BPM gains substantially improves the quality of the fit.
- BPM gains deviate considerably from the nominal value.
- $\langle \mathrm{gain}_x \rangle \approx 0.9$ $\langle \mathrm{gain}_y \rangle \approx 1.$
- BPM readings become nonlinear for large orbit excursions.

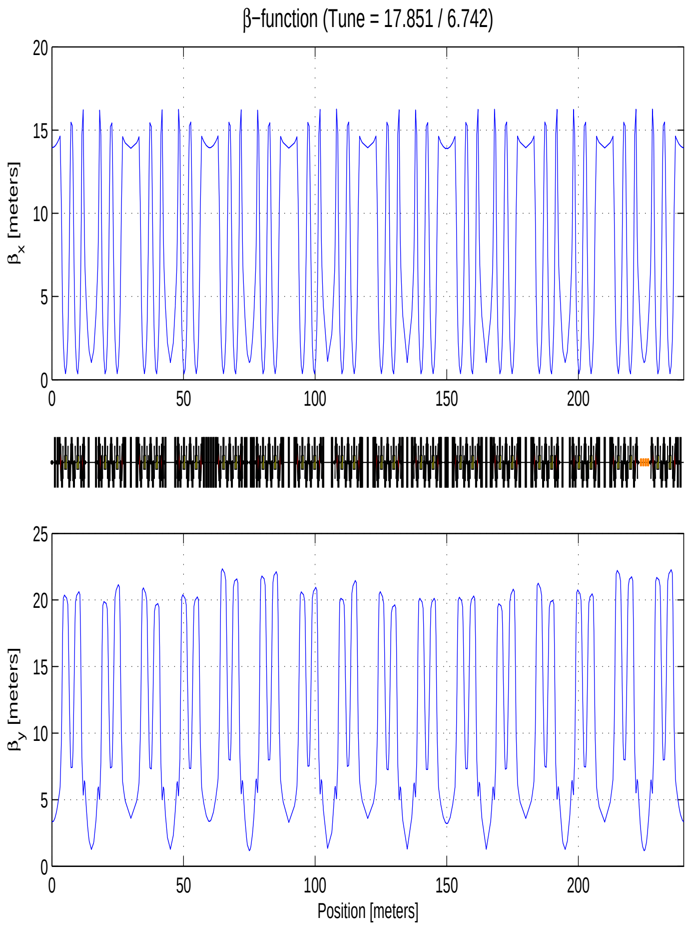
Modeling the impact of the WLSs

- Wave length shifters (WLS) focus *only* vertically
  → quadrupoles cannot absorb this effect.
- Modeling of WLS as thin “cylinder lenses” focusing only in the vertical plane.
- Wiggler: modeled as a sequence of dipoles.

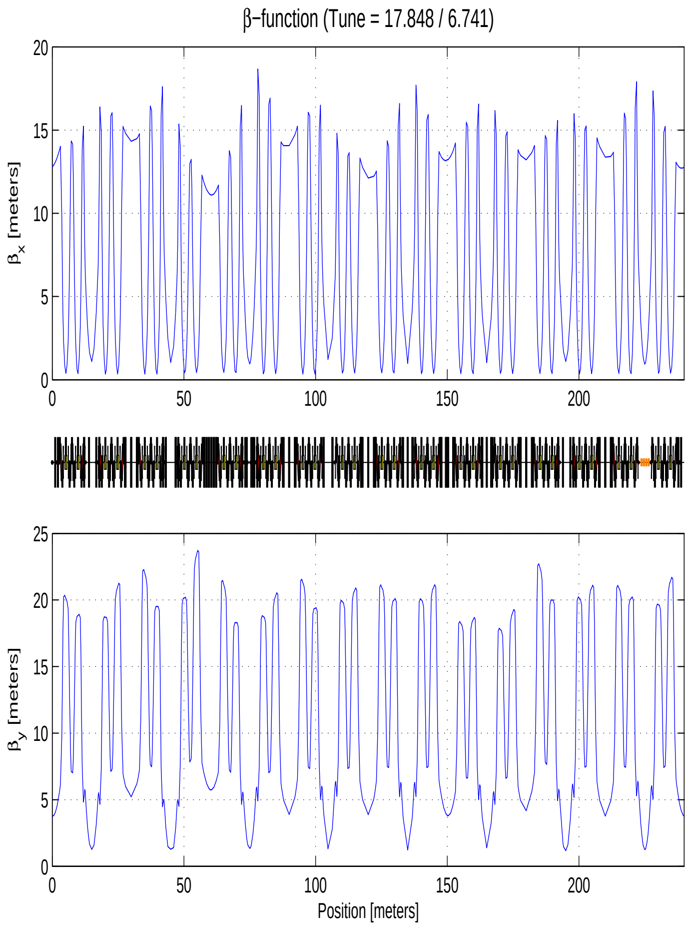
Results – in comparison with an analysis only employing quadrupoles:

- χ^2 / DOF reduces by a factor of 50.
- $\sigma(\mathrm{model} - \mathrm{measurement})$ decreases by an order of magnitude.

Beta functions: design- and user optics



Design optics



User optics

Checking the predictions of the model

Chromaticity:

Determining of chromaticities for the user optics without WLS and skew quadrupoles.

- measured $\xi_x = 3.49$ and $\xi_y = 3.95$
- from the calibrierten model:
  $\xi_x = 3.89$ und $\xi_y = 3.86$ (thin sextupoles) or $\xi_x = 3.70$ und $\xi_y = 3.76$ (sextupole with effective length.

Determining emittances via simulations

Problem:

- small vertical emittances cannot be determined with the diagnostic tools available.

Approach:

- Fit a skew quadrupole gradient at the location of each sextupole.
- Get the emittances from the Ohmi-Envelope ("coupled" optical functions).

Minimizing the coupling – procedure

Approach:

Try to minimize the vertical dispersion *and* the vertical emittance simultaneously employing the available skew quadrupoles.

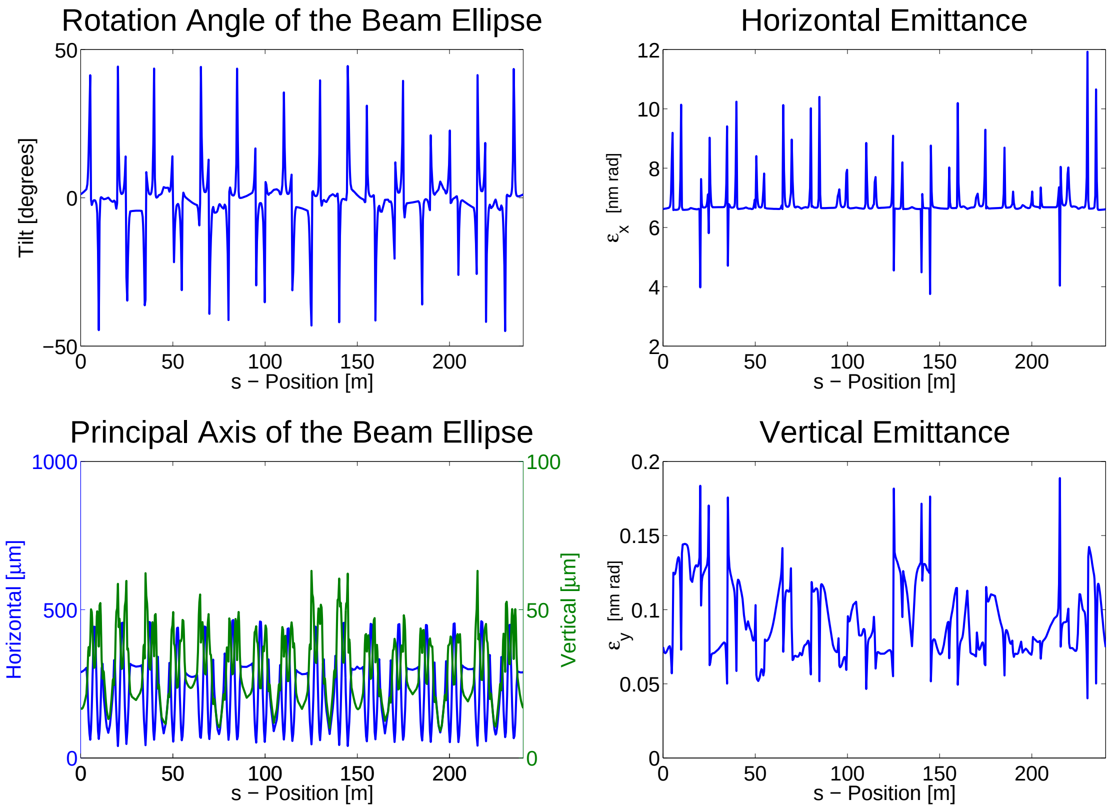
Caveats:

- At BESSY II only three skew quadrupoles are located at dispersive sections.

  → Increasing the number of skew quadrupoles in dispersive sections would help in minimizing the vertical dispersion.
- The 15 skew quadrupoles are located only in about one half of the ring.

  → A more even distribution could reduce the local coupling at important locations.
- Four BPMs couple, only three buttons are functional.

Determining the emittances: example



Emittance Ratio = 1.378447%

- ❏ user optics including all WLSs and FFF, CQS are off.
- ❏ the horizontal emittance ϵ_x and the vertical ϵ_y vary considerably along the ring.
- ❏ WLS: Wave Length Shifter
- ❏ FFF: Fast Feed Forward (IDs)
- ❏ CQS: Skew Quads

Coupling for given machine settings

Optics	$\langle\epsilon_y\rangle$ [pm rad]	$\kappa = \frac{\epsilon_y}{\epsilon_x}$ [%]	$\eta_{y\mathrm{RMS}}$ [mm]
only S1 minimal	14.3	0.22	5.40
only S1/S2 chrom. 0	18.0	0.28	6.78
user optics w/o WLS	74.6	1.13	7.66
user optics w/ WLS/FFF	93.3	1.38	9.91
user optics w/WLS/FFF u. CQS	99.8	1.48	7.90

❏ The coupling is mainly induced by the orbit excursions in the harmonic sextupoles and not by the settings of the skew quadrupoles.

❏ Average vertical emittance $\langle\epsilon_y\rangle$

❏ Coupling $\kappa = \epsilon_y/\epsilon_x$

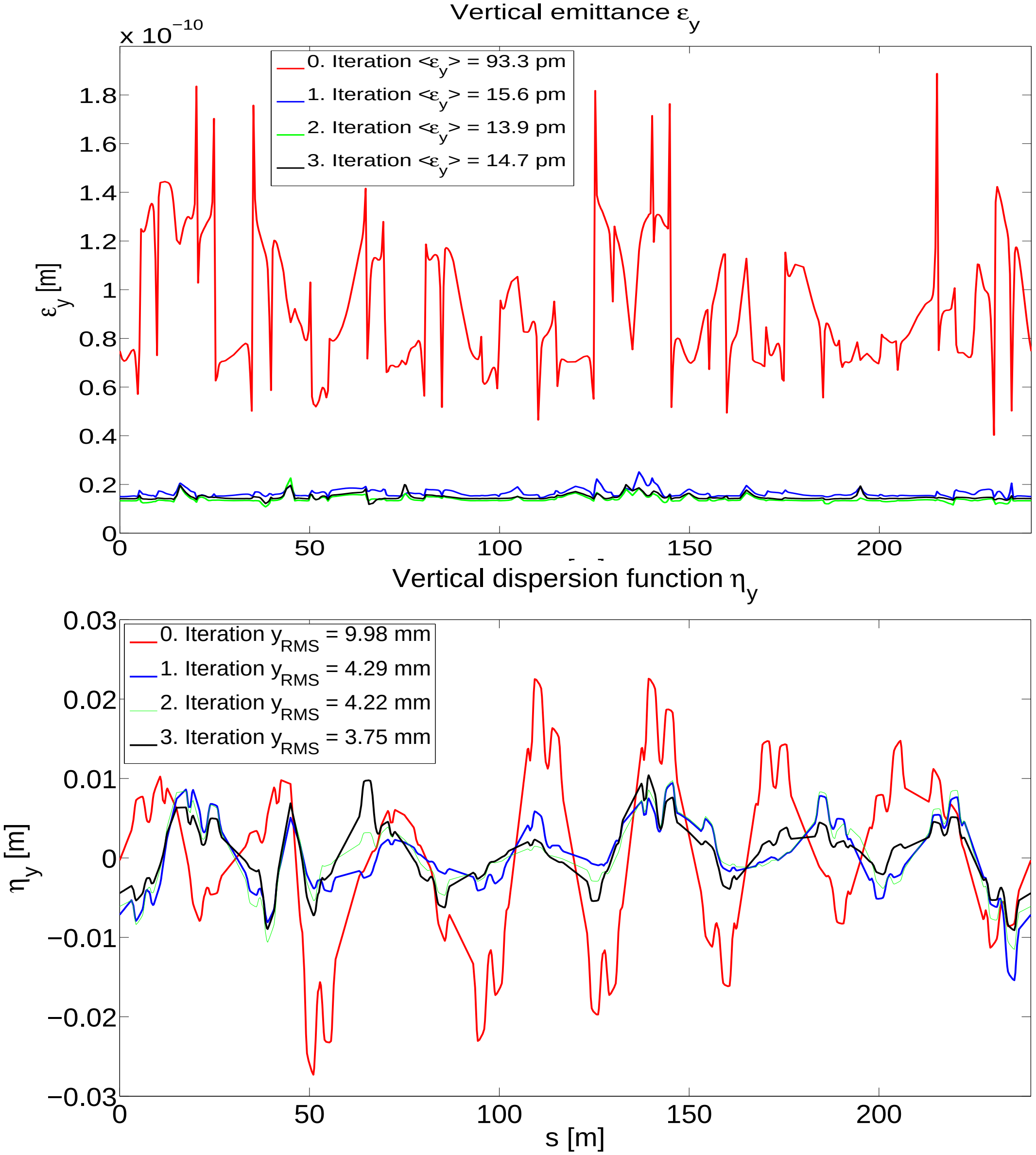
❏ Vertical Dispersion (RMS) $\eta_{y\mathrm{RMS}}$

❏ WLS: Wave Length Shifter

❏ FFF: Fast Feed Forward (IDs)

❏ CQS: Skew Quads

Decoupling – iterative process



- Iteration steps while decoupling
- (top panel) vertical emittance
- (bottom panel) vertical dispersion
- user optics including all WLSs and FFF
- 15 CQS available.
- only three CQS in dispersive regions

Decoupling – comparing the results with measurements

Criterion: reduction of the (Touschek) life time at large beam current ($I \approx 300\,\mathrm{mA}$)

mode	life time
3rd iteration	$6.9\,\mathrm{h}$
2nd iteration	$7.0\,\mathrm{h}$
1st iteration	$7.7\,\mathrm{h}$
CQS off	$11.9\,\mathrm{h}$
CQS standard	$10.7\,\mathrm{h}$

→ The life time can be reduced by 40%.

- ❏ All Sextupoles and the WLS are at their standard settings. (user optics)
- ❏ The ellipse at the beam profile monitor assumes normal orientation.

Symmetrizing the optics

Objective:

- Restoring the dynamic aperture.
- Dialing in the reference optics in a reproducible fashion.

Approach:

- Determine the normalized quadrupole gradients per circuit.
- Changing the quadrupole settings according to

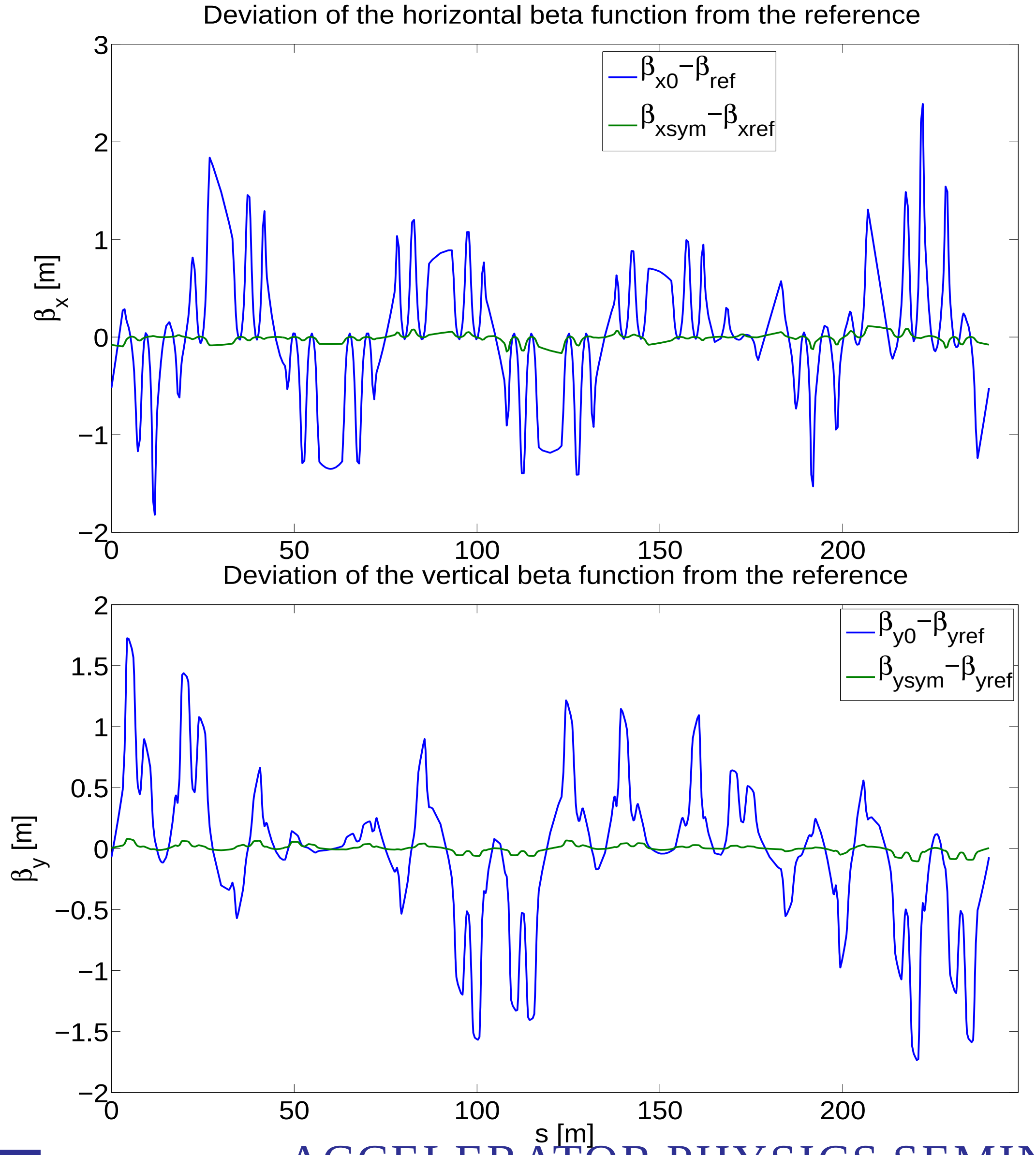
$$\frac{\Delta I_n}{I_n} = -\frac{K_{\mathrm{fit},n} - K_{\mathrm{ref},n}}{K_{\mathrm{ref},n}}$$

employing offset channels at the quadrupole power supplies.

Caveats:

- Quadrupoles at BESSY II cannot be powered individually.
- Q1D/T and Q2D/T: 16 quadrupole each are ganged together.
- Q3D/T, Q4D/T and Q5T can be powered in pairs.

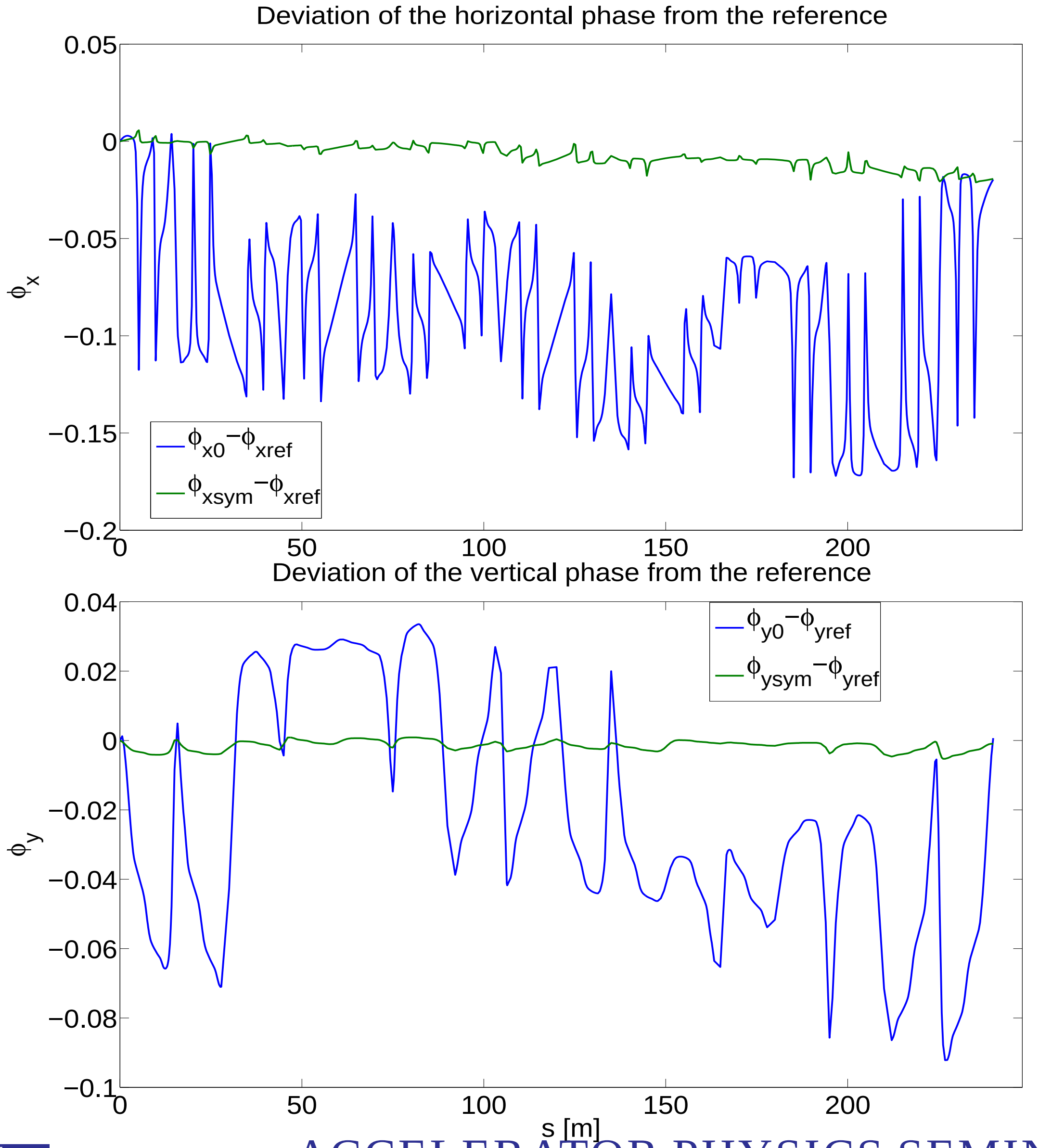
Restoring the beta functions



- ❑ User optics without WLSs
- ❑ β_{iref}: β function of the reference.
- ❑ β_{isym}: β function of the symmetrized optics
- ❑ β_{i0}: β-function before symmetrizing.

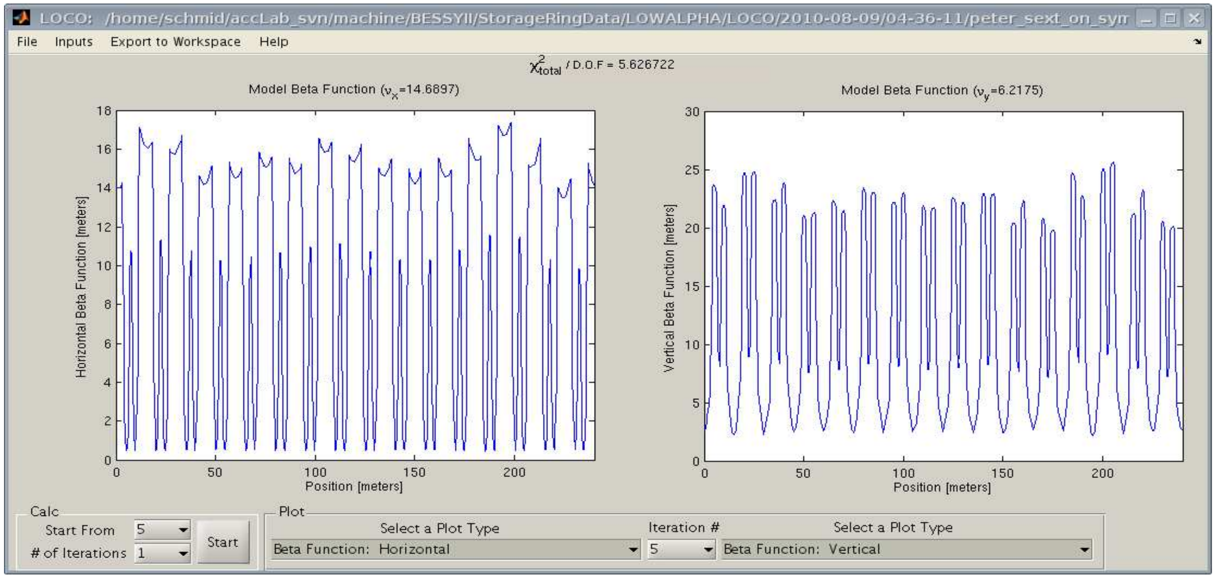
Iteration	Beta beat RMS	
	x	y
0.	6.95%	4.39%
1.	0.80%	0.97%
2.	0.44%	0.22%

Restoring the phase



- user optics without WLSs
- ϕ_{iref}: phase of the reference.
- ϕ_{isym}: phase of the symmetrized optics (2nd iteration).
- ϕ_{i0}: phase before symmetrizing.

LOCO – Low alpha optics



LOCO: /home/schmid/accLab_svn/machine/BESSYII/StorageRingData/LOWALPHA/LOCO/2010-08-09/04-36-11/peter_sext_on_sym

χ^2_{total} / D.O.F = 5.626722

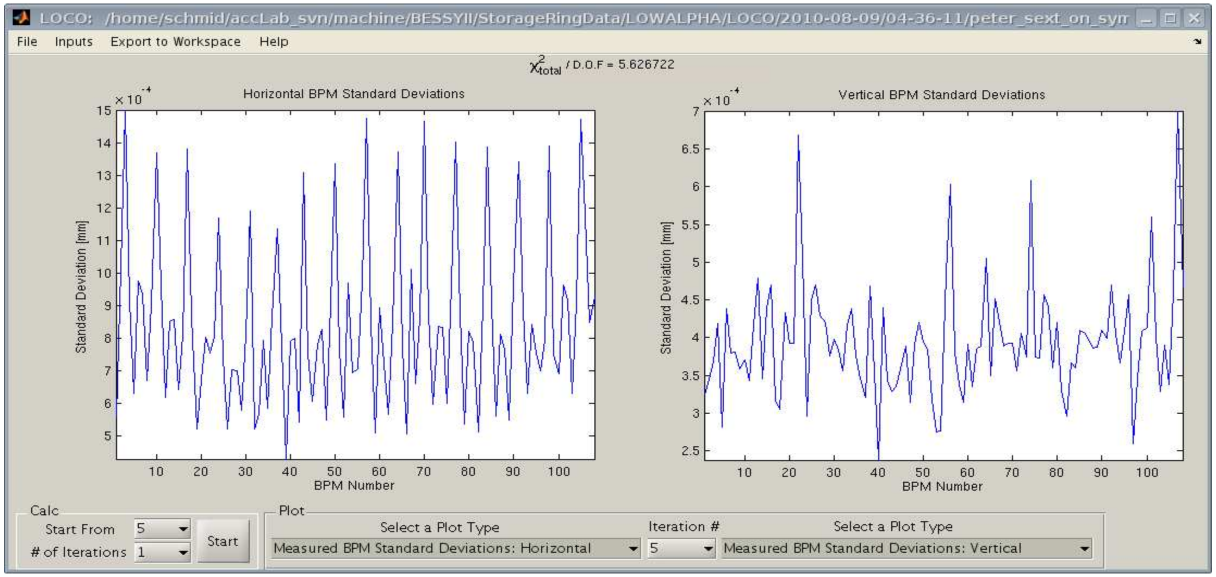
Start From 5

\# of Iterations 1

Select a Plot Type: Beta Function: Horizontal

Iteration # 5

Select a Plot Type: Beta Function: Vertical



LOCO: /home/schmid/accLab_svn/machine/BESSYII/StorageRingData/LOWALPHA/LOCO/2010-08-09/04-36-11/peter_sext_on_sym

χ^2_{total} / D.O.F = 5.626722

Start From 5

\# of Iterations 1

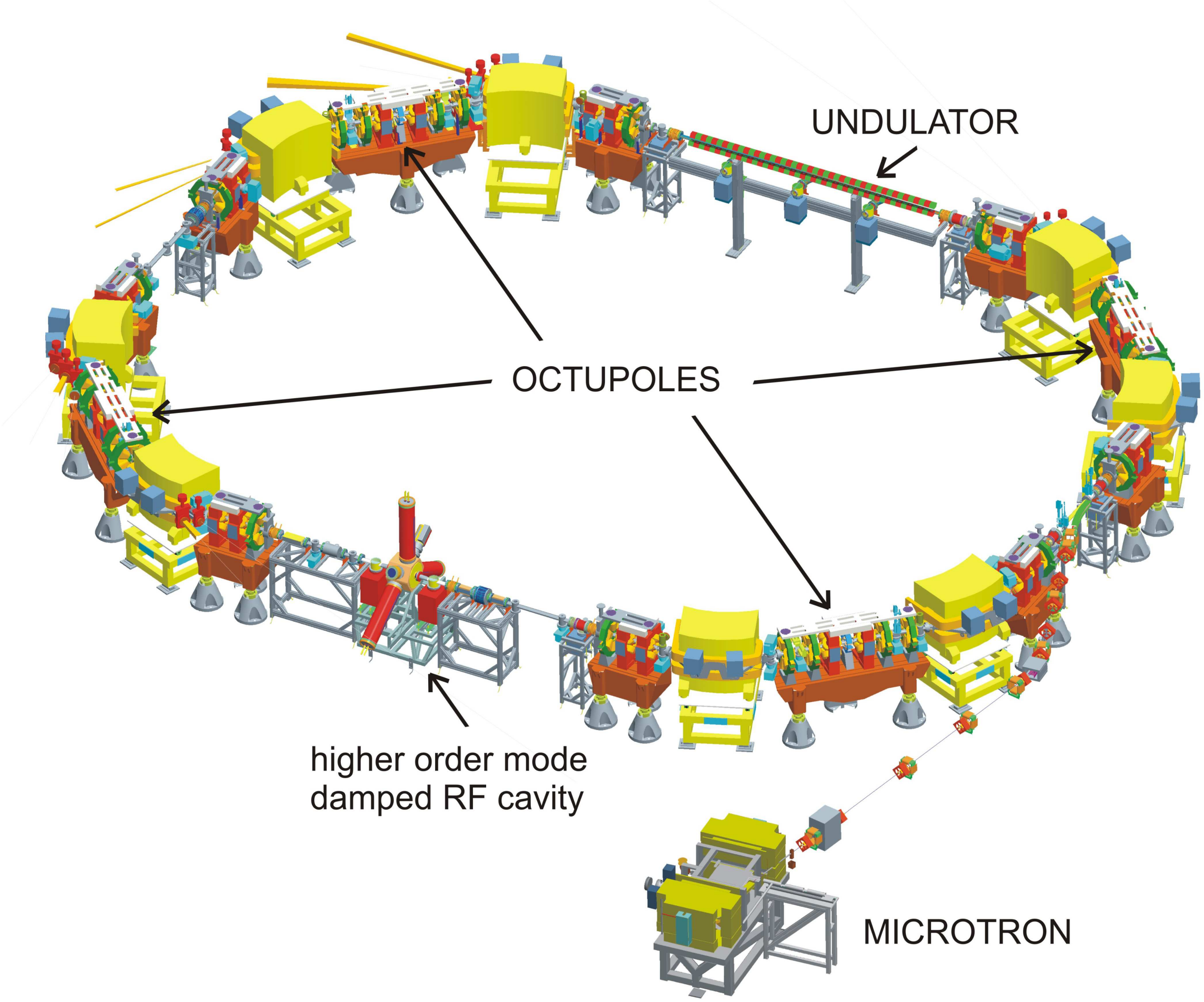
Select a Plot Type: Measured BPM Standard Deviations: Horizontal

Iteration # 5

Select a Plot Type: Measured BPM Standard Deviations: Vertical

- $f_s = 1.75\,\mathrm{kHz}$.
- $\chi^2/DOF = 5.625$.
- $\sigma(\mathrm{model} - \mathrm{meas.}) = 1.34\,\mu\mathrm{m}$.
- BPM noise: $\langle\sigma_x\rangle = 0.9\,\mu\mathrm{m}$, $\langle\sigma_y\rangle = 0.4\,\mu\mathrm{m}$
- Orbit drifts during the measurement.

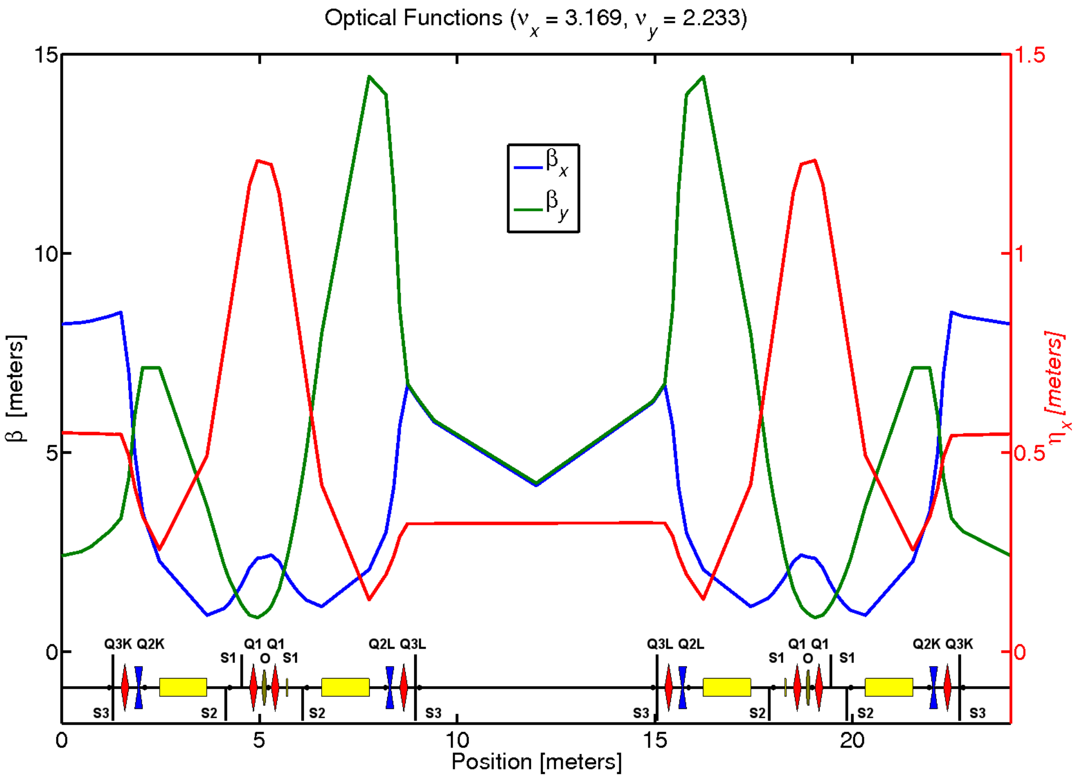
The Metrology Light Source



- ❑ Double Bend Achromat Lattice
- ❑ two super cells
- ❑ Circumference $L = 48\,\mathrm{m}$.
- ❑ Nominal Energy $E = 629\,\mathrm{MeV}$.
- ❑ 8 Bending Magnets $L_B = 1.2\,\mathrm{m}$.
- ❑ Emittance

  $\epsilon_x = 120\,\mathrm{nmrad}$.

The Metrology Light Source



- ❑ Double Bend Achromat Lattice
- ❑ two super cells
- ❑ Circumference $L = 48\,\mathrm{m}$.
- ❑ Nominal Energy $E = 629\,\mathrm{MeV}$.
- ❑ 8 Bending Magnets $L_B = 1.2\,\mathrm{m}$.
- ❑ Emittance $\epsilon_x = 120\,\mathrm{nmrad}$.

Fit parameters for the MLS

- 28 horizontal BPM gains
- 28 vertical BPM gains
- 12 horizontal corrector magnets
- 16 vertical corrector magnets
- 24 quadrupole gradients

in total: M = 100 fit parameters

Measuring data:

- $28 \times 12 + 28 \times 16$ data points included in the response matrix
- 28 dispersion measurements

in total: N = 784
number of the degrees of freedom $N - M = 684$

$$\chi^2 = N - M \pm \sigma, \quad \sigma = \sqrt{2(N - M)}$$

Predictor for the statistical error if $N - M$ is asymptotically large.

Fitting the focusing effect of the dipole

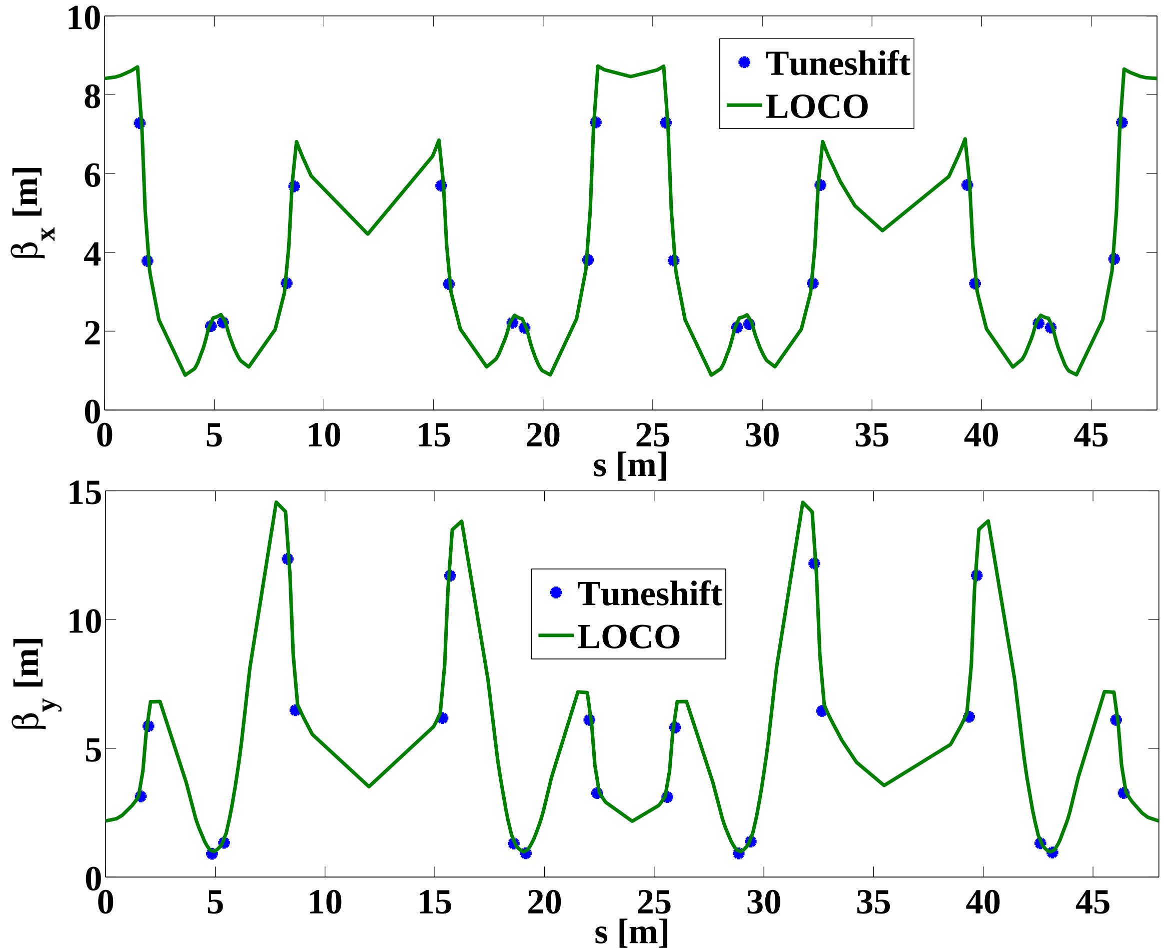
Dipole model	$\frac{\Delta\text{Frac.Tune}}{\text{kHz}}$	$\frac{\chi^2}{DOF}$	$\frac{\sigma(\text{mod.}-\text{mea.})}{\mu m}$
a) RBEND	[28.6, 233]	307.5	5.32
b) ditto, fit grad.	[5.6, 0.2]	9.38	0.849

c) $f_{\text{int}} = 0.5$	[14.4, 96.3]	67.1	2.48
d) ditto, fit f_{int}	[0.4, 4.2]	2.92	0.499
e) ditto, fit grad.	[2.0, 3.4]	2.45	0.459
f) ditto, fit grad. and fit f_{int}	[1.5, 3.9]	2.24	0.441

- Energy $629\,\text{MeV}$
- ΔFrac.Tune: Deviation between measured fractional tune and the one predicted by LOCO
- length of the dipole $1.2\,\text{m}$

- Fitting fringe field or the gradient of the bending magnet dramatically improves the quality of the LOCO fit.

Comparing LOCO's predictions with tune shift measurements



- Both the dipole gradient and the fringe field were varied during the LOCO analysis.
- $\chi^2/DOF = 2.24$
- $\sigma(\text{model} - \text{meas.}) = 0.44\,\mu\text{m}$
- BPM noise: $0.33\,\mu\text{m}$

The undulator U180

The undulator U180:

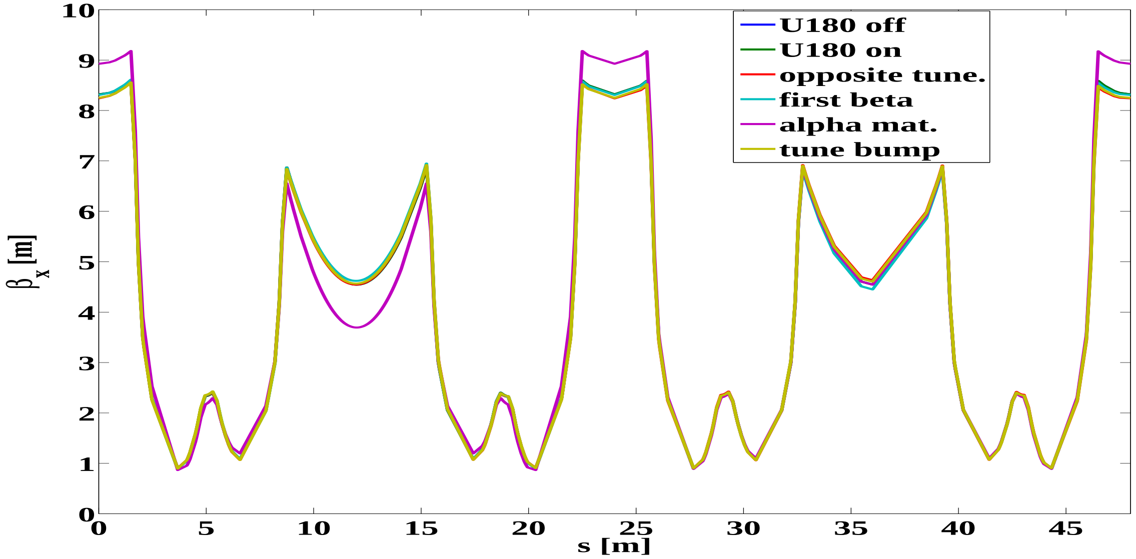
- Electro magnetic undulator with a period length of $\lambda_P = 180\,\mathrm{mm}$.
- causes considerable tune shift at lower energies.
- modeled as a sequence of dipole magnets.

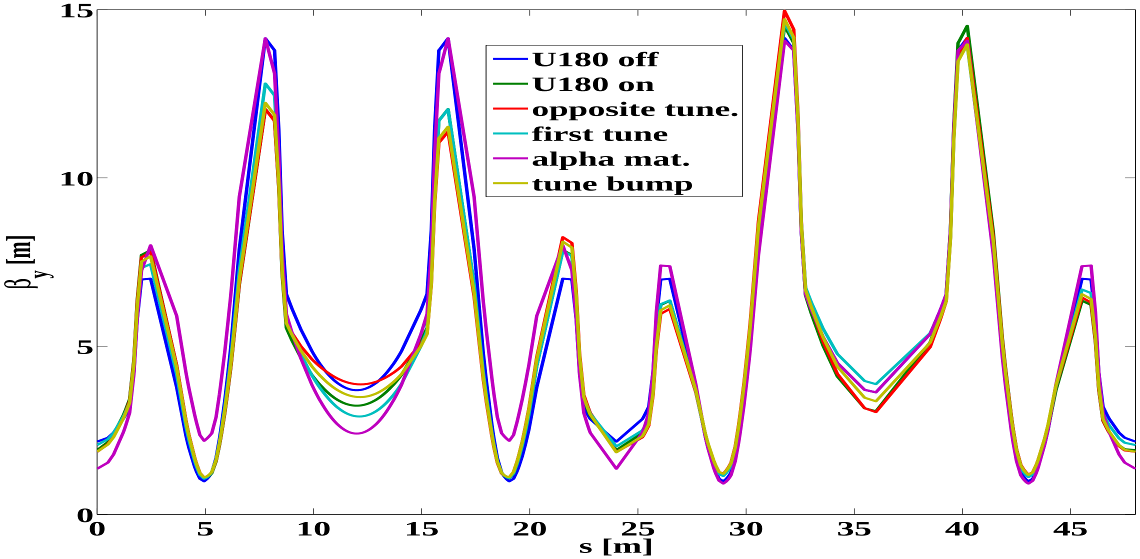
Energy	$\Delta\nu_y$	Beta beat	
MeV		max [%]	RMS [%]
629	0.034	18	11
450	0.060	34	20
200	0.223	360	96

Compensation schemes investigated:

- *opposite tune*
- *first tune then beta*
- *“alpha matching”*
- *tune bump*

Compensating the U180

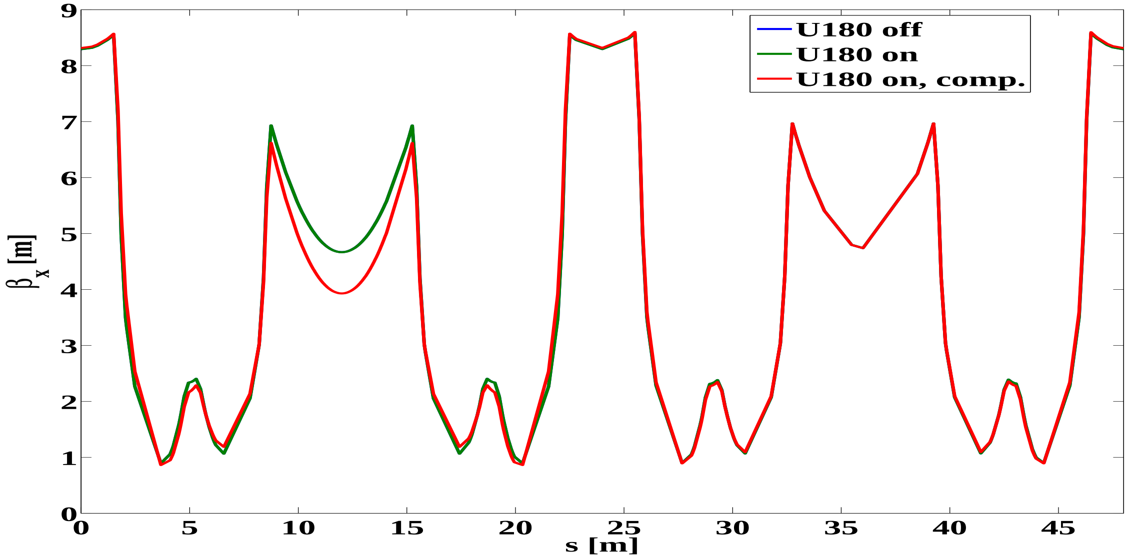


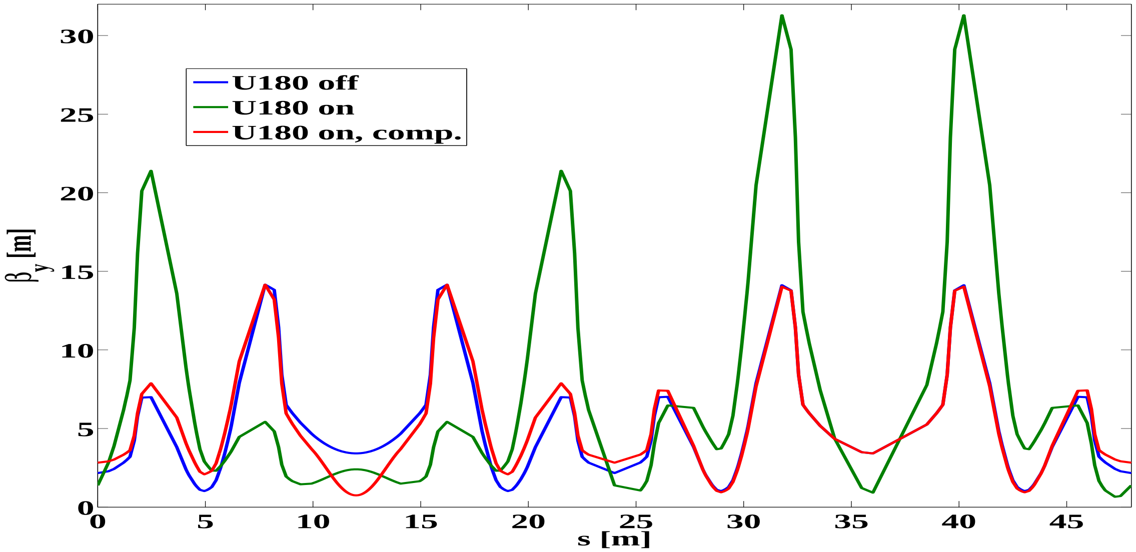


- Beam Energy is at 629 MeV

mode	current	life time
	mA	h
standard user mode	135.0	13.9
undulator on	133.3	12.5
opposite tune	132.5	14.6
first tune then beta	131.5	12.6
alpha matching	130.6	14.0
tune bump	128.0	14.4

Compensating the U180 at 200 MeV





- ❏ Energy: 200 MeV.

Results

- Optics calibration works reliably both at the MLS and at BESSY II.
- Fitting almost down to the noise level of the BPMs was achieved.
- Calibrated Model can be employed for realistic simulations.
- An orbit correction program including the focusing effects of IDs was build upon the model.
- Decoupling and symmetrizing the optics was successful at BESSY II.
- The focusing properties of IDs and the mitigation measures by the TFF were analyzed for the first time.