Measurement and Correction of Transverse Dispersion in PETRA III

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Outline

Need of Transverse Dispersion Correction

Dispersion Correction Strategy and Response Matrices

Theoretical Simulation and Results

Online Measurements, Corrections and Results

Summary

Need of Transverse Dispersion Correction

Design Horizontal beam emittance: 1 nm.rad with 1% coupling

	Horz. (mm)	Vert. (mm)
Wiggler section	18	5
Undulators (IDs)	20	3
FODO arc		58
DBA	22	31

$$\varepsilon_y = \frac{C_q \gamma^2 \left\langle \frac{\eta_y^2}{\overline{\beta}_y} \right\rangle}{J_y \rho}$$

Maximum horizontal rms dispersion distortion yielding 5% horizontal emittance growth and rms vertical dispersion yielding vertical emittance of 10pm.rad.

Need of Transverse Dispersion Correction

Alignment Tolerances (rms values)

Element(No.)	$\Delta x(\mu m)$	$\Delta y(\mu m)$	$\Delta\psi(mrad)$	$\Delta s(\mu m)$	Field Error
Monitors(219)	200	200			
Quadrupoles ((281)Old Octant)	250	250	0.2	500	$\frac{\Delta K}{K} = 0.001$
Quadrupoles ((105)New Octant)	100	100	0.2	500	$\frac{\Delta K}{K} = 0.001$
Dipoles(196+18)	250	250	0.2	500	$\frac{\Delta B}{B} = 0.0005$
Sextupoles(140)	250	250	0.2	500	

Values truncated at 2σ of a Gaussian distribution

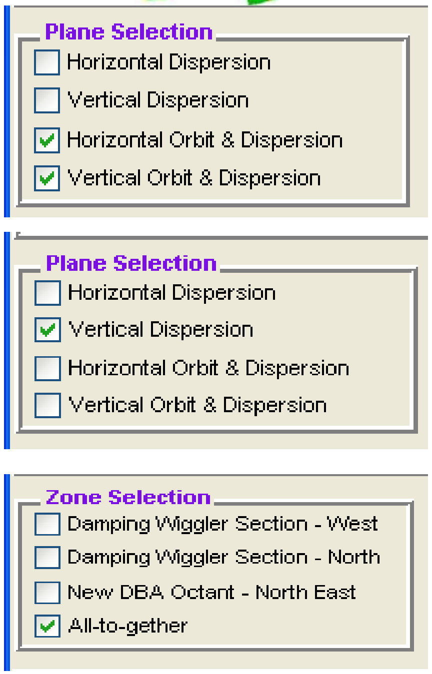
The misalignment errors in the old octants are considered according to the measurements, and in the new octant the misalignment errors are what were foreseen.

Dispersion Correction Strategy and Response Matrices

Combined orbit and dispersion correction:

$$\begin{pmatrix} \alpha \vec{u} \\ (1-\alpha)\vec{D_u} \end{pmatrix} + \begin{pmatrix} \alpha R \\ (1-\alpha) S \end{pmatrix} \vec{\theta} = \vec{0}$$

u measured orbit and D_u dispersion
R orbit and S dispersion response matrices
α weighting factor (1 Pure Orbit, 0 Pure Dispersion)



Modes of Dispersion Correction:

- Combined Orbit and Dispersion Correction in Transverse Planes with All BPMs(226) and Correctors(Horz.191, Vert.187)
- Vertical Dispersion Correction with PKVSU Type Correctors(21) Only
- Vertical Dispersion Correction with Skew Quadrupoles(12), (44BPMs)

Combined orbit and dispersion correction

Theoretical Response Matrices

The beam response is defined as $\mathbf{r}_j = d\mathbf{u}/d\theta_j$, where $\mathbf{u}$ is the vector of orbit distortion at the BPMs caused by a kick angle of θ by the steerer magnet j. The $\mathbf{rj}$ can be combined to a matrix $R_{ij} = d\mathbf{u}_i/d\theta_j$. The theoretical Orbit Response Matrix (**ORM**) is calculated as,

$$R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2Sin(\pi Q)} . Cos\left(\left| \varphi_i - \varphi_j \right| - \pi Q \right);$$

$$K_1 = \frac{1}{B\rho} \frac{dB}{dx}$$

$$K_2 = \frac{1}{B\rho} \frac{d^2 B}{dx^2}$$

For the dispersion response matrix, we consider two classes of perturbation, the ordinary chromatic terms and those due to field errors. Considering the perturbations at quadrupoles and the sextupole locations, the Dispersion Response Matrix (**DRM**) can be written as,

$$S_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2Sin(\pi Q)} \left[\begin{array}{l} -Cos\left(\left| \varphi_i - \varphi_j \right| - \pi Q \right) \\ \pm \sum_{k=1}^{N_{quadrupoles}} \frac{\beta_k . (K_1 l)_k}{2Sin(\pi Q)} . Cos\left(\left| \varphi_i - \varphi_k \right| - \pi Q \right) Cos\left(\left| \varphi_k - \varphi_j \right| - \pi Q \right) \\ \mp \sum_{k=1}^{N_{sextupoles}} \frac{\beta_k . (K_2 l)_k . \eta_k}{2Sin(\pi Q)} . Cos\left(\left| \varphi_i - \varphi_k \right| - \pi Q \right) Cos\left(\left| \varphi_k - \varphi_j \right| - \pi Q \right) \end{array} \right]$$

Vertical Dispersion Correction Using Skew Quadrupoles

A horizontal orbit offset through a skew quadrupole will generate a deflection in the vertical plane through an angle $\Delta\theta_y = k_{1s} l x$. This will generate a vertical orbit distortion of Δy such that,

$$\Delta y_i = \frac{\sqrt{\beta_{yi}\beta_{yj}}}{2 \sin(\pi Q_y)} \cos\left(\left|\varphi_{yi} - \varphi_{yj}\right| - \pi Q_y\right) \left(K_{1s} l x\right)_j$$

With $x = D_x \Delta P/P$ and $y = D_y \Delta P/P$, one can write the Skew Quadrupole response matrix as

$$R_{ij} = \frac{D_{xj}\sqrt{\beta_{yi}\beta_{yj}}}{2 \sin(\pi Q_y)} \cos\left(\left|\varphi_{yi} - \varphi_{yj}\right| - \pi Q_y\right)$$

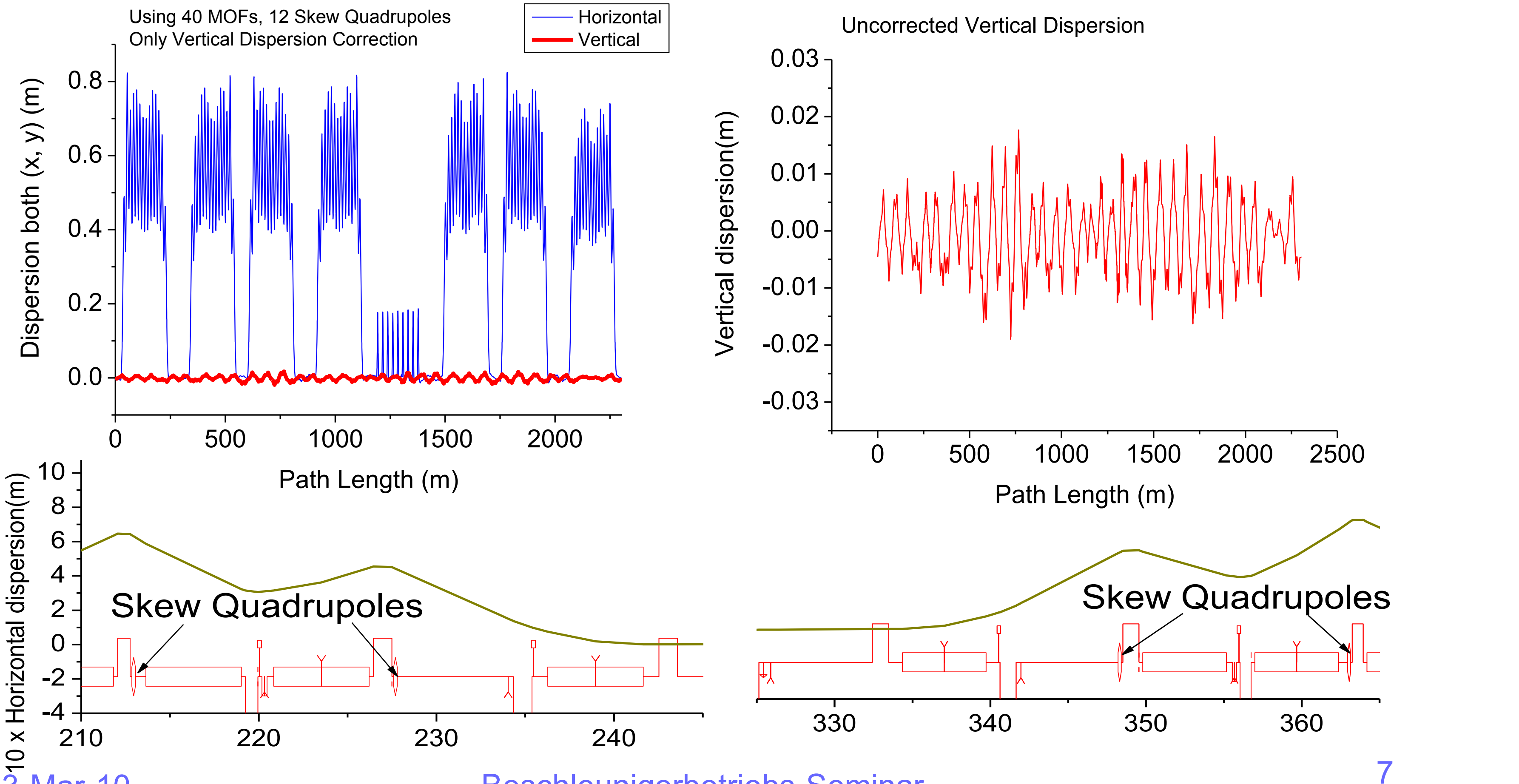
$$\Delta \eta_{yi} = R_{ij} \left(K_{1s} l\right)_j$$

Theoretical Simulation and Results

After Combined Horizontal Dispersion Correction

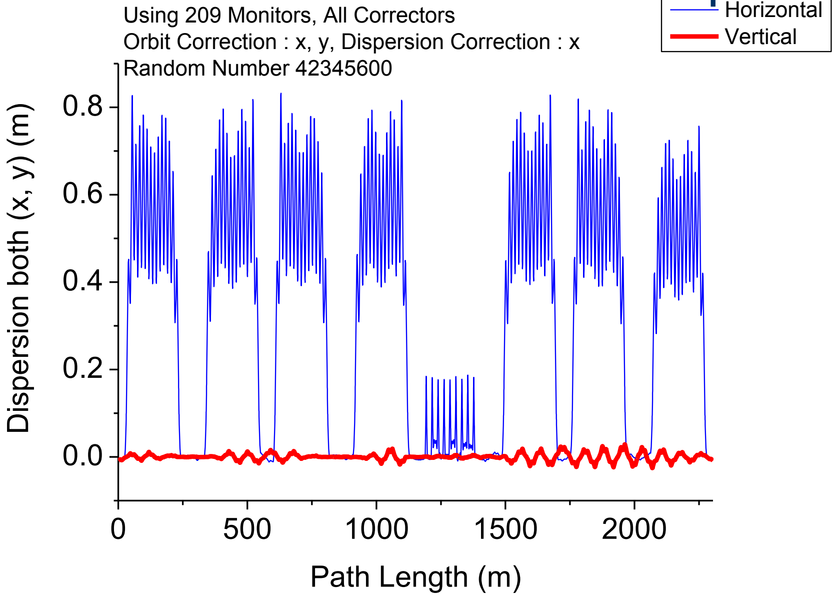
Using: 226 Monitors, 191 Horizontal Correctors and 187 Vertical Correctors

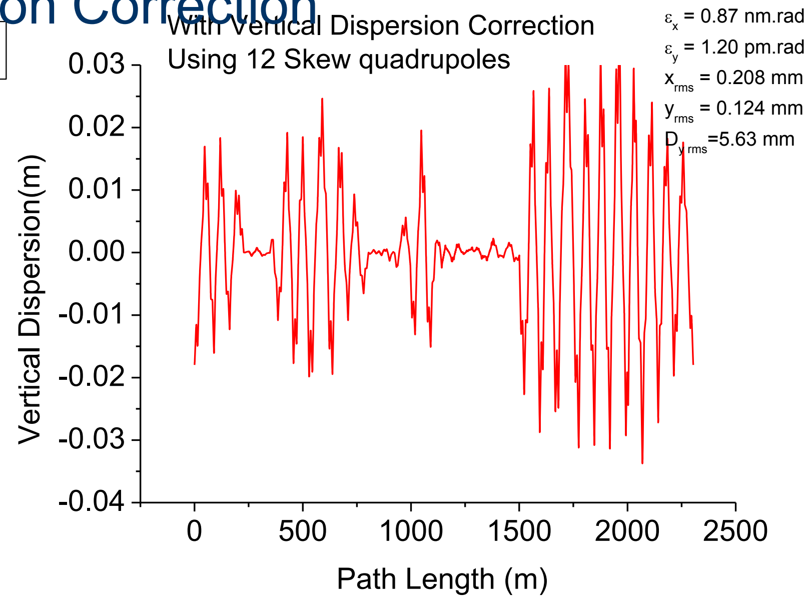
Corrected Horizontal Dispersion and Vertical Dispersion before its Correction



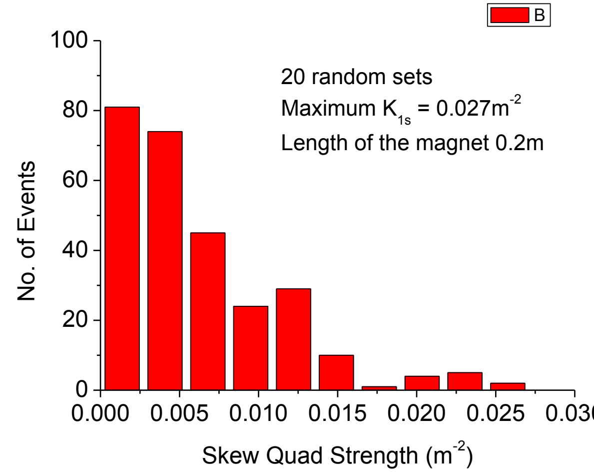
Theoretical Simulation and Results

Vertical Dispersion Correction

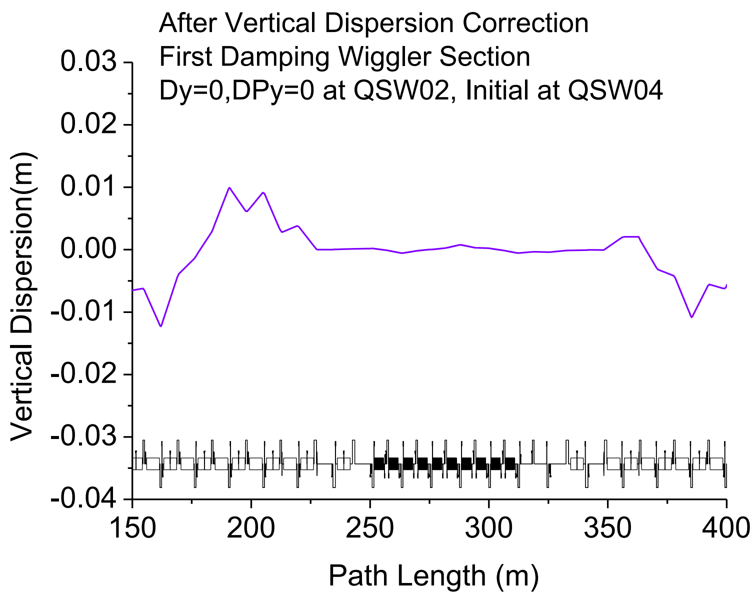


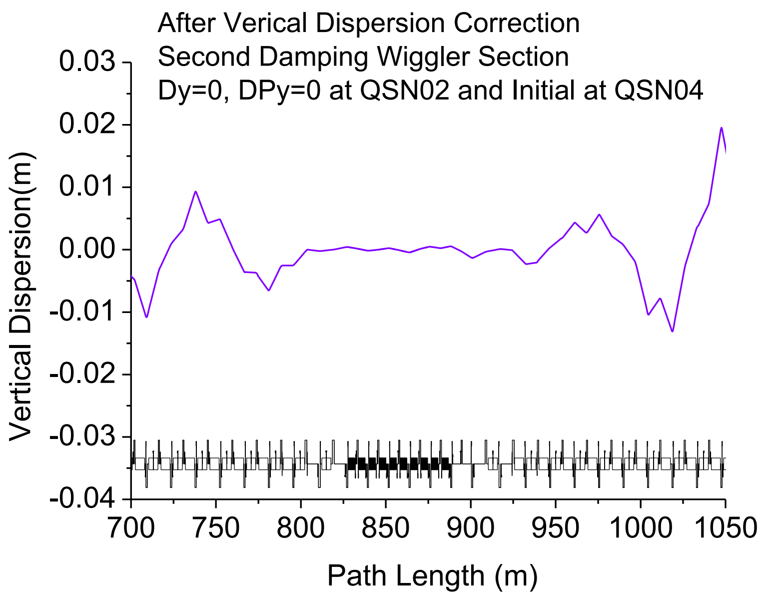


The skew quadrupoles are made with a gradient of 2T/m.



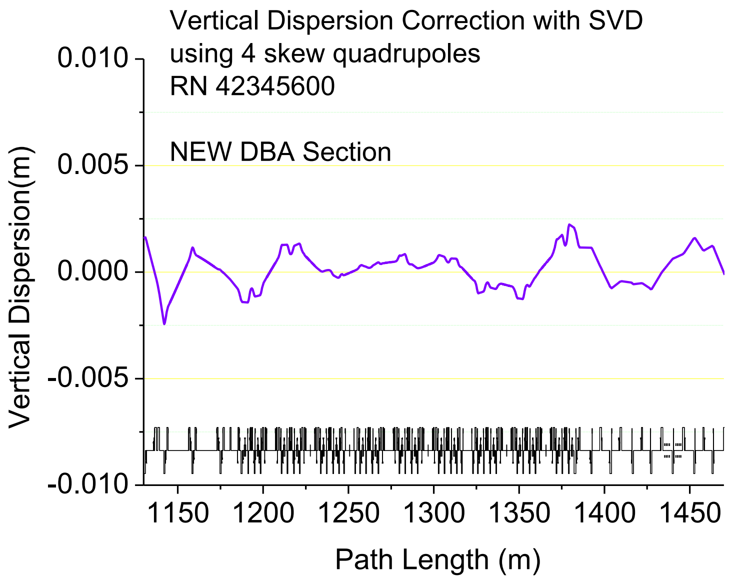
Local Vertical Dispersion Correction in DW Section

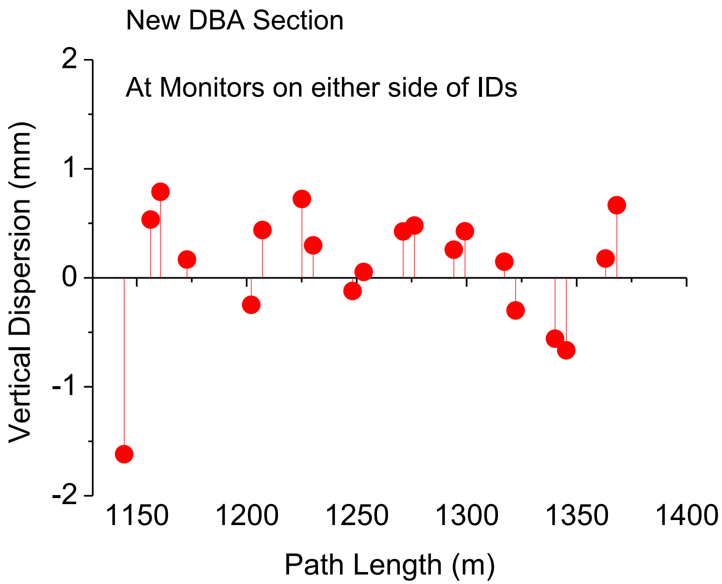




Vertical dispersion is locally corrected using 4 skew quadrupoles that form a local bump. It is performed by setting the dispersion and its derivative to zero at the second skew quadrupole in front, and closing the bump with the pair of skew quadrupoles in back.

Local Vertical Dispersion Correction in DBA Section

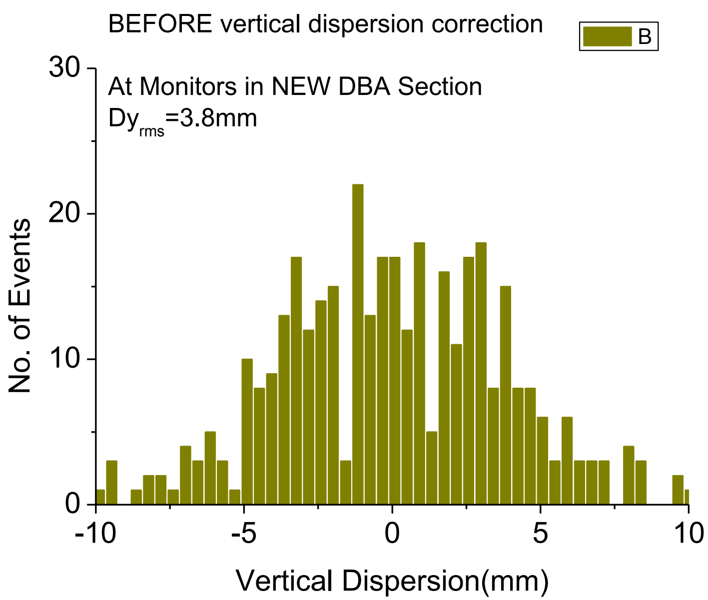


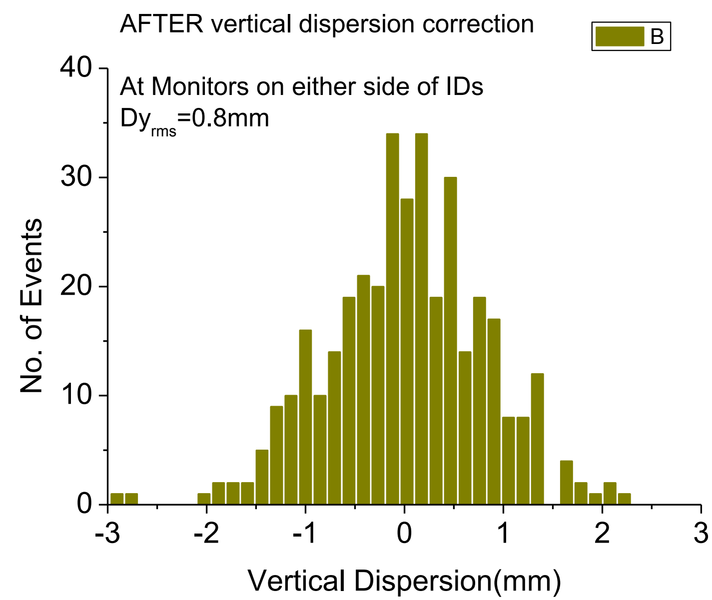


The vertical dispersion is minimized using 20 BPMs on either side of the insertion devices and 4 skew quadrupoles on either side of the new octant using SVD algorithm.

The results obtained from this correction procedure are encouraging as the orbit differences before and after dispersion correction are below 30μm and the vertical emittance can be maintained with different weighting factors given to BPMs. The skew quadrupole strengths are small such that it can impart small betatron coupling.

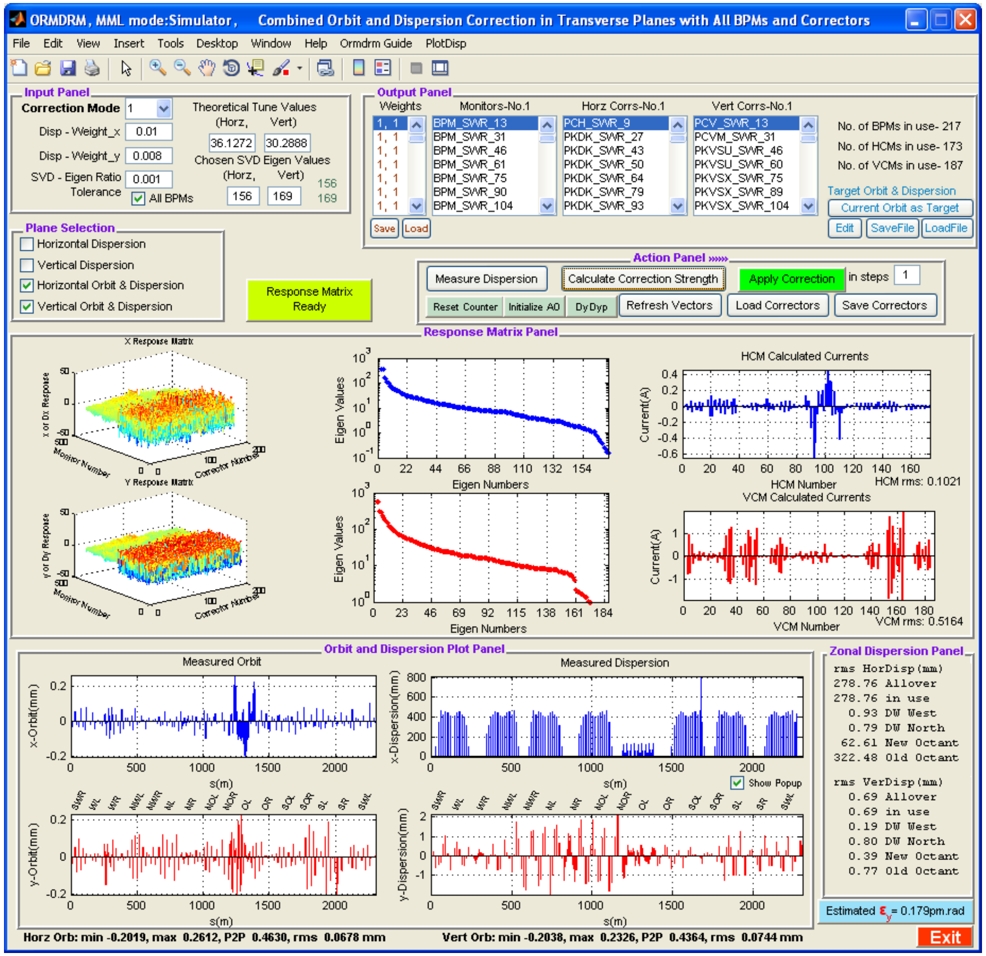
Vertical Dispersion at 5m Undulator Sections





From 20 random seed iterations results, it is seen that the vertical dispersion is well *maintained with in desired 3mm limits on either side of 5m undulator sections.*

Online Measurements, Corrections and Results



Can go offline for simulation / online for measurements

A graphics user interface (GUI) ORMDRM is developed in MATLAB using the Middle Layer as backbone under TINE control interface utility to measure and correct transverse dispersion to its theoretical values. The ORMDRM performs correction of transverse dispersion using monitor to corrector theoretical response matrices. It displays results in graphics as well as in text form in three modes of operation.

The modes are-

1. Combined Orbit and Dispersion Correction in Transverse Planes with All BPMs and Correctors.
2. Vertical Dispersion Correction with PKVSU Type Correctors Only
3. Vertical Dispersion Correction with Skew Quadrupoles.

In case of 1, one can correct the orbit and dispersion both in horizontal and vertical plane simultaneously or independently.

In case of 3, one can correct only vertical dispersion in individual zones viz. west/north damping wiggler sections or DBA section or all-together.

Online Measurements, Corrections and Results

The program starts with determination of theoretical orbit response matrix (ORM)/ dispersion response matrix (DRM) as desired by the mode of operation followed by measurements of orbits and dispersions using BPMs by varying RF frequency ~±1.5kHz in steps of 20Hz. The corrector strengths are determined for a pre-selected number of Eigen values. These correctors can be energised in a single step or in multiple steps. The cycle of measurement of dispersion and apply of corrector strengths to magnets iteratively continues to a number of times till the required convergence to theoretical values are achieved or a suitable tolerance is occurred before it corrects further with change in beam energy.

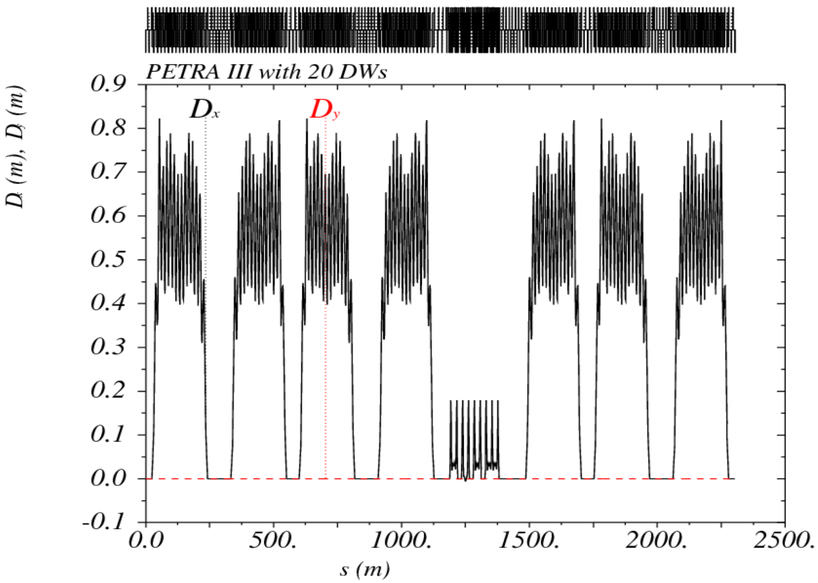
In addition provision is made to assign different weight factors to the BPMs, choose different number of BPMs and correctors depending on their availability, and editing of initial orbits and dispersion values. As it uses the theoretical optics of the lattice created in Middle Layer, it prints the betatron tune values which can be edited. The weight factor that decides the degree of orbit to dispersion correction in combined correction scheme can be chosen along with the Eigen values cut off factor which is the ratio of n^{th} Eigen value to most dominant Eigen value. Left click in graphs of dispersion pops up a separate figure with enlarged view. Similarly, left click on the list boxes of BPMs or correctors pop up the data in more details in a tabular form. The data can be used to compare readouts of different measurements and saved to files that can be opened with EXCEL.

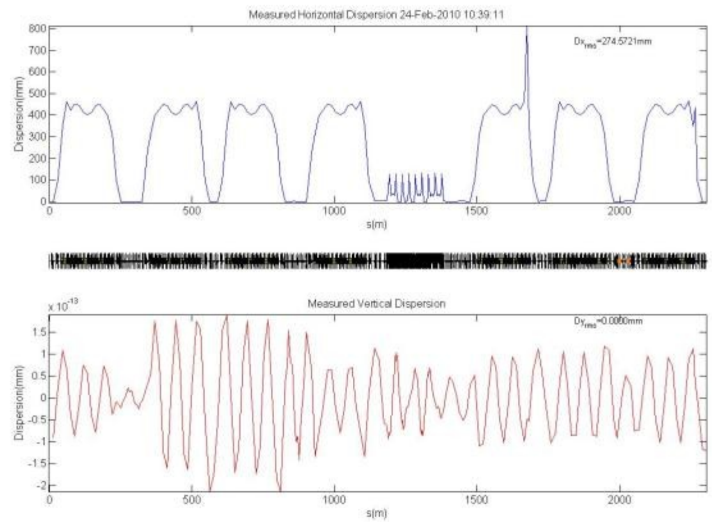
Online Measurements, Corrections and Results

The closed orbit is corrected after the beam based alignments in both horizontal and vertical planes using the orbit response matrix .The positions and angles are set at the IDs with local bumps at those locations. The orbit so obtained is set as the golden orbit for combined orbit and dispersion correction in horizontal plane. The horizontal dispersion is corrected using this procedure with a SVD algorithm in a few iterations till the required tolerance limits are reached. In this case all the available BPMs (217 out of 226) are used with 173 horizontal correctors. The slow corrector magnets embedded in the dipole magnets in the DBA section are not used for horizontal dispersion correction for some specific reasons.

The spurious vertical dispersion is reduced to certain values due to vertical orbit correction and the combined orbit and vertical dispersion correction is not required. As mentioned earlier the dispersion is critical at two damping wiggler sections on west/north and at the IDs. So, it is not so important to worry about the spurious vertical dispersion at other FODO octants. Importance is given to minimise the distortions at insertion sections. As a result, the vertical dispersion is corrected using a selected number of 44 BPMs and 12 skew quadrupoles using a SVD algorithm in global correction scheme. The measured dispersion values obtained after a dispersion correction with ORMDRM in few iterations.

One can observe that the theoretical and measured horizontal dispersion values are almost matching and within our tolerable limits. Looking into the difference of dispersion values plot one can see that the rms of this plot is ~5mm which is quite small.

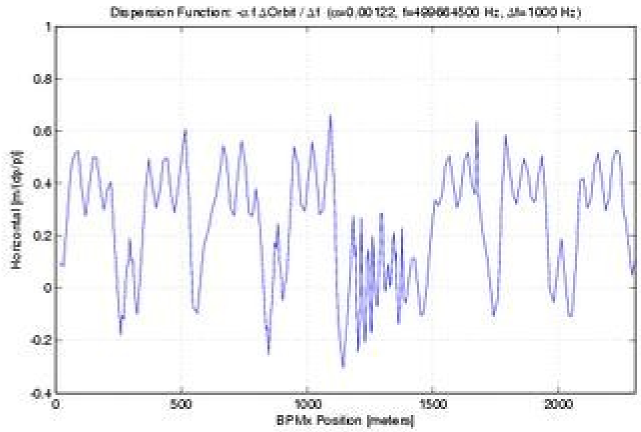


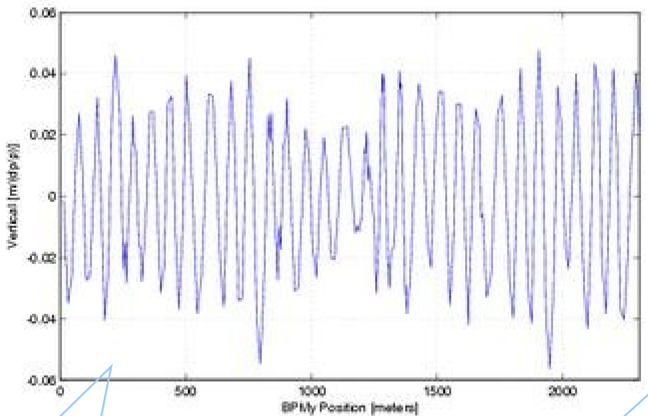


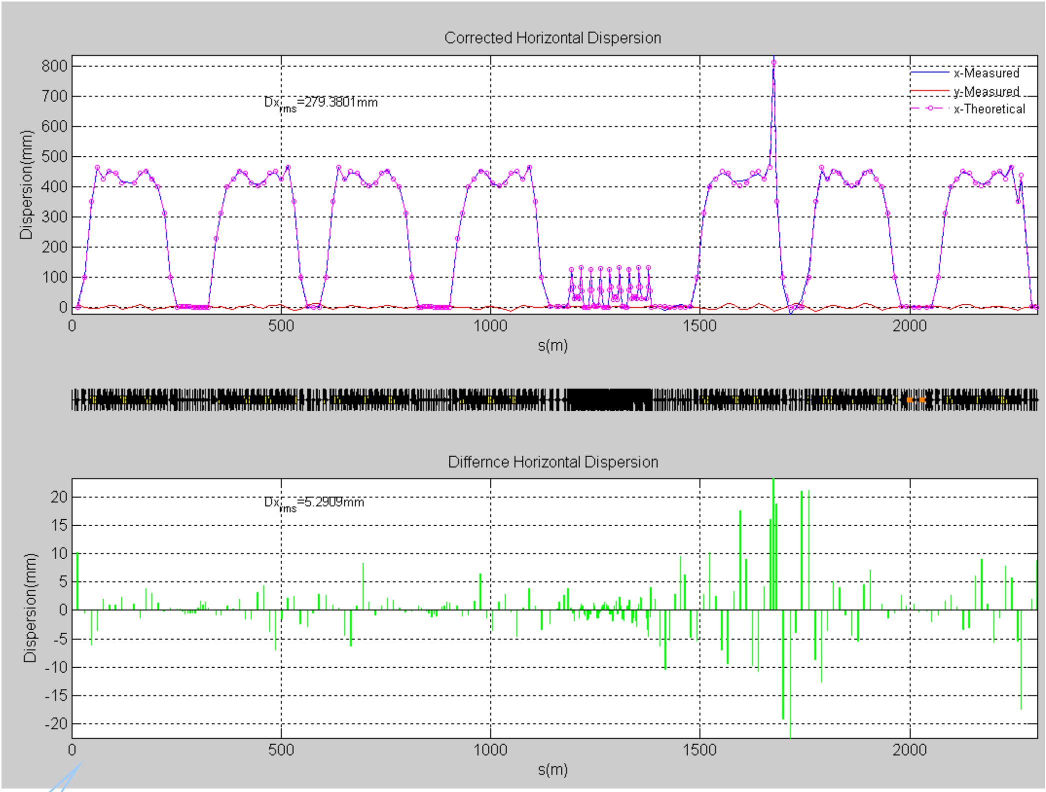
The Theoretical Horizontal (black) and vertical dispersion (red) as determined by MADx program.

The Theoretical Horizontal (blue) and vertical dispersion (red) at monitor locations as determined by MATLAB MiddleLayer program.

Online Measurements, Corrections and Results







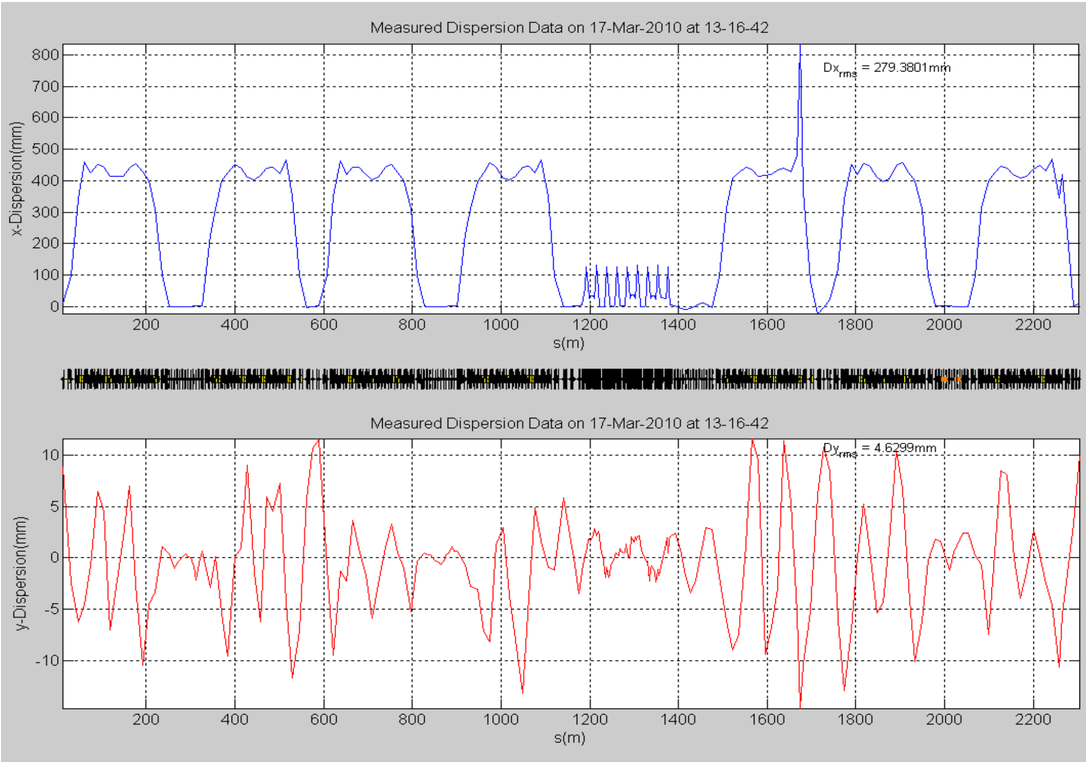
Before
Dispersion Correction

After
Dispersion Correction

(a) The horizontal dispersion measured (blue) and theoretical (magenta) are plotted along with measured vertical dispersion (red) for PETRA III for comparison.

(b) Shows the difference horizontal dispersion between the theoretical and the measured data.

Online Measurements, Corrections and Results



Theoretical

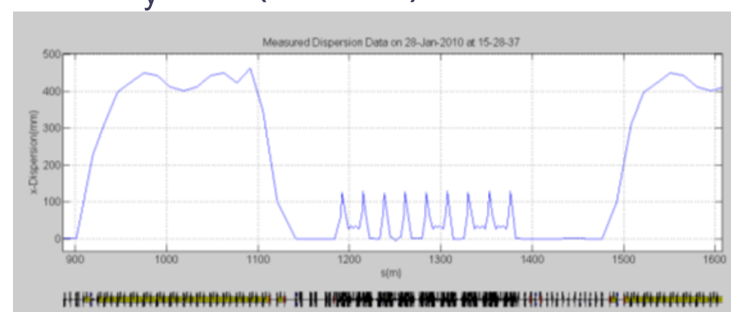
Maximum D_x : 822mm

D_x rms(226BPMs): 274mm

Measured

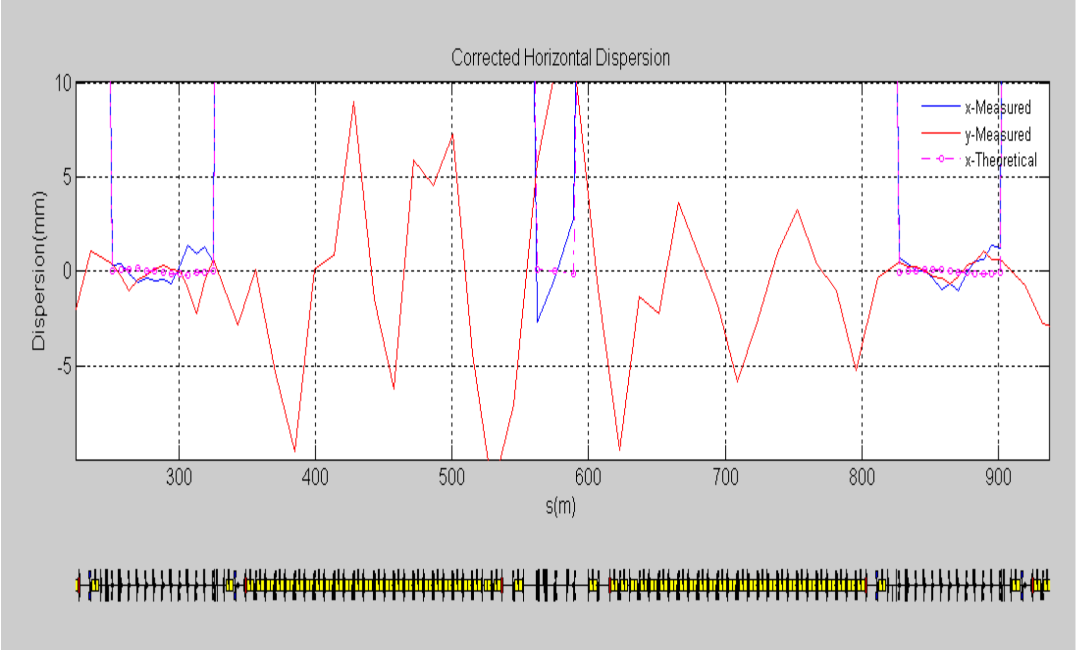
D_x rms(217BPMs): 279mm

D_y rms(217BPMs): 4.6mm



(a) The measured horizontal dispersion (blue) and
(b) the measured vertical dispersion (red) are plotted as a function of position to visualise at the damping wiggler west/north and DBA sections.

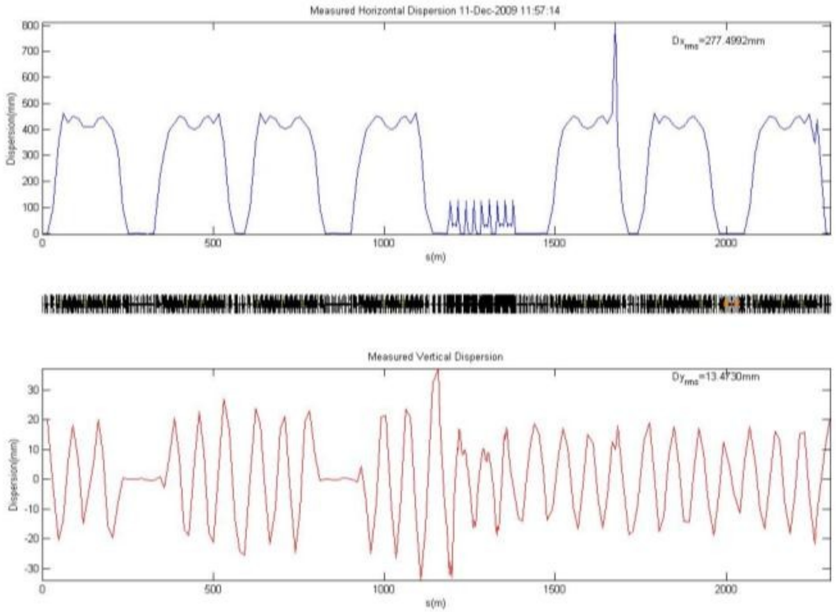
Online Measurements, Corrections and Results



The measured horizontal dispersion (blue) and vertical dispersion (red) are zoomed up at the damping wiggler sections in west/north to show that they are within ±5mm.

As the damping wiggler sections are crucial, the dispersion plot is zoomed at high lighted in sections west/north to so that the corrected values are within our tolerance limits of present correction scheme. We vary ±1.5kHz RF frequency that corresponds to $\Delta P/P$ = 5‰ at 6GeV. So 10mm dispersion will give rise to a 50µm orbit shift. With out fast orbit feedback system the stability of orbit is observed to be ~30µm. So looking to the measured dispersion data at these damping wiggler sections a resolution ±5mm is tolerable.

Online Measurements, Corrections and Results



Local Bump Method
(simulation)

Zonal Dispersion Distribution Panel

	rms HorDisp(mm)	rms VerDisp(mm)
Allover	279.38	4.63
in use	13.12	1.01
DW West	0.70	0.78
DW North	0.75	0.51
New Octant	63.30	1.49
Old Octant	321.24	5.29

Summary

For PETRA III, the scheme to correct the spurious vertical dispersion using a set of 12 skew quadrupoles is implemented. Keeping the betatron coupling coefficient low (as the required skew quadrupole strengths are low $K_{1s\ max}$= ~0.011m^{-2}), it is shown that the vertical dispersion is corrected to millimetre level at the two damping wiggler sections and in the DBA sections with insertion devices.

As the lowest emittance light source in the world, this goal is achieved with proper correction of horizontal dispersion using combined orbit and dispersion correction scheme in the achromats side by side in the dispersion free long straight sections incorporating 80m of damping wigglers. The results so achieved are satisfactory and limited to currently used measurement accuracies.