Tolerance studies and Dispersion Free Steering for FCC-ee

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On behalf of the FCC-ee Lattice Design team

Acknowledgements to
Andreas Doblhammer, Bernhard Holzer,
Bastian Haerer, Katsunobu Oide,
Jorg Wenninger.

Outline

- FCC-ee beam parameters – Saw-tooth effect
- Emittance tuning for electron machines
- Lattice errors and challenges for the tolerance study
- Status Review Meeting & Recommendations
- BPMs errors
- Dispersion Free Steering for FCC-ee
- Summary

Related Talks at FCC Week

This study relies on

- FCC-ee Lattice design option: **Katsunobu Oide**
- Lattice Design & Chromaticity correction W-function matching in the Arcs: **Bastian Haerer**
- IR design and local chromaticity correction at the IP: **Anton Bogomyagkov**
- Tapering : **Andreas Doblhammer (Poster)**

FCC-ee Beam Parameters

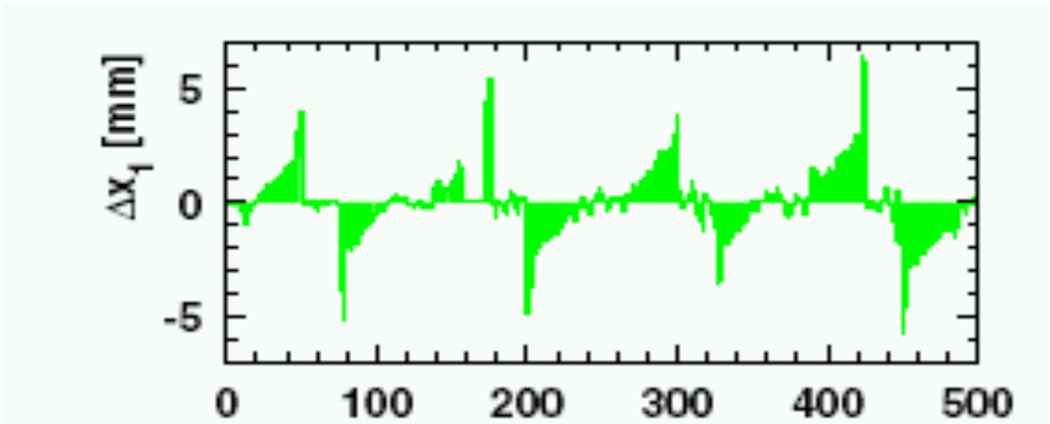
	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
Beam current [mA]	1450	152	30	6.6
Bunches / beam	91500	5260	780	81
Bunch population [10^{11}]	0.33	0.6	0.8	1.7
Transverse emittance ε - Horizontal [nm] - Vertical [nm]	 0.09 0.001	 0.26 0.001	 0.61 0.0012	 1.3 0.0025
Momentum comp. [10^{-5}]	0.7	0.7	0.7	0.7
Betatron function at IP β* - Horizontal [mm] - Vertical [mm]	 1000 2	 1000 2	 1000 2	 1000 2
Energy loss / turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	0.2	0.8	3	10

- Coupling ratio **V.emit/H.emit ~ 2/1000** and 1/1000

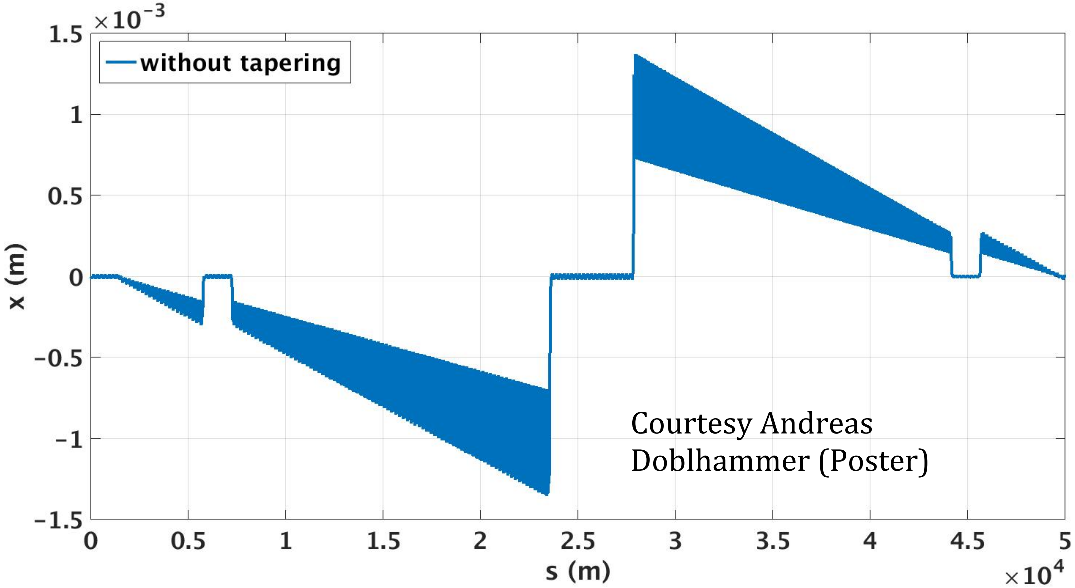
Light source emittance type

$$P = \frac{cC_\gamma \beta^3 E^4}{2\pi R\rho} \longrightarrow P_{175}/P_{45} \approx 200$$

Saw-tooth Effect



- LEP time
- Saw-tooth =+/-5mm



Courtesy Andreas Doblhammer (Poster)

- 175 GeV, 2 RF sections
- Large chromaticity
  Q'x = -573.6506369
  Q'y = -852.4978106
- Sextupoles 100 times stronger
- Tapering needed to keep the beam as centered as possible
- More details Andreas's poster

Emittance tuning for electron machine

- <u>Horizontal emittance</u>

$$\epsilon_x = \frac{C_g}{J_x}\gamma^2\theta^3 F \qquad F_{FODO} = \frac{1}{2\sin\psi}\frac{5+3\cos\psi}{1-\cos\psi}\frac{L}{l_B}$$

L: cell length
l_B: dipole length
ψ: phase advance/cell

- <u>Vertical emittance</u>

$$\epsilon_y = \left(\frac{dp}{p}\right)^2 (\gamma D^2 + 2\alpha D D' + \beta D'^2)$$

Alignment errors, rolls angle and coupling spoil the vertical emittance and compromise the coupling of 1/1000 (2/1000)
-> <u>Coupling and Dy should be under control.</u>

Lattice errors and challenges for the tolerance study

- **Quadrupoles off-set**: dipolar kick *

$$B_x = k(y + \Delta y) = ky + \underline{k\Delta y}$$

Constant term

Vertical dipole -> vertical dispersion

- **Sextupoles off-set** *

$$B_x = kx(y + \Delta y) = kxy + \underline{kx\Delta y}$$

$$B_y = k(x^2 - (y + \Delta y)^2) = \mathrm{k}(x^2\text{-}y^2) - 2\underline{ky\Delta y} - \underline{(\Delta y^2)}$$

Skew quad (coupling) + vertical dipole

- **Quadrupole roll:** skew quad, coupling of the planes
- **Dipole roll:** vertical dipole

Source emittance growth

* SY Lee "Accelerator Physics", Javier Barcelona Presentation

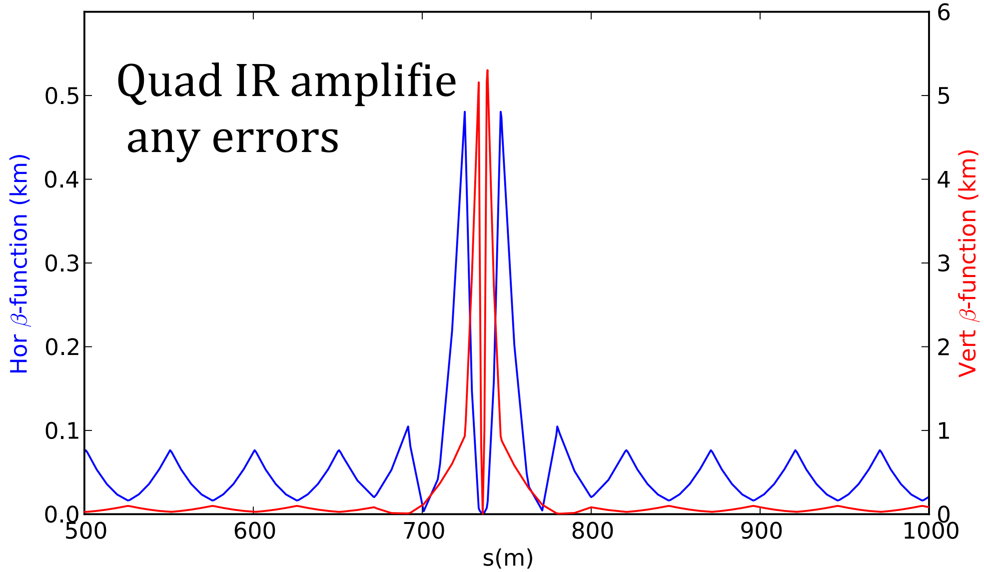
Lattice errors and challenges for the tolerance study

Why is it critical for FCC-ee?

Closed Orbit Distortion (COD)
due to a kick (or misaligned quadrupole)

$$y_{co}(s) = \theta_0 G(s, s_0)$$

$$G_0 = \frac{\boxed{\sqrt{\beta_0 \beta(s)}}}{2\sin(\pi\mu)} \cos(\pi\mu - |\psi(s_0) - \psi(s)|)$$

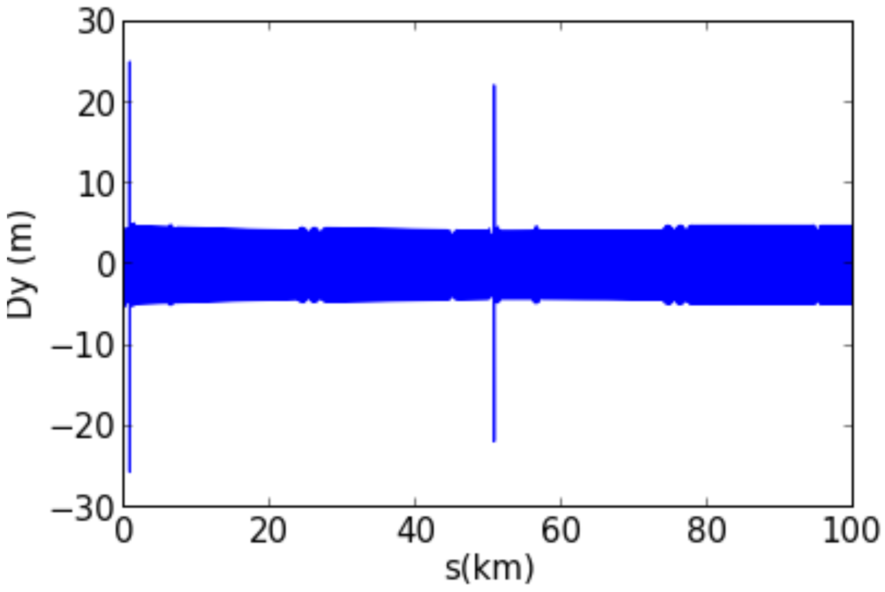


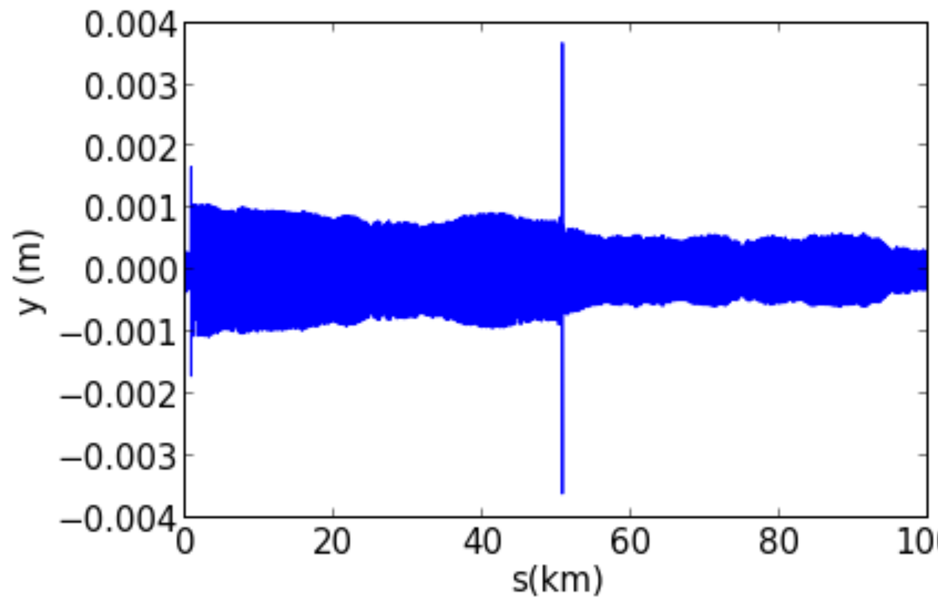
Dispersion response
kick (or misaligned quadrupole)

$$\Delta D_i^l = K_i L_i \Delta u_i \frac{\sqrt{\beta_l \beta_i}}{\sin(\pi Q)} \cos(|\mu_l - \mu_i| - \pi Q)\theta_j$$

Lattice errors and challenges for the tolerance study

- 2 microm RMS vertically misaligned quadrupoles, no sextupole
- 175GeV





To keep the vertical emittance within the requirement , Vert. Dispersion ~1mm

Lattice errors and challenges for the tolerance study

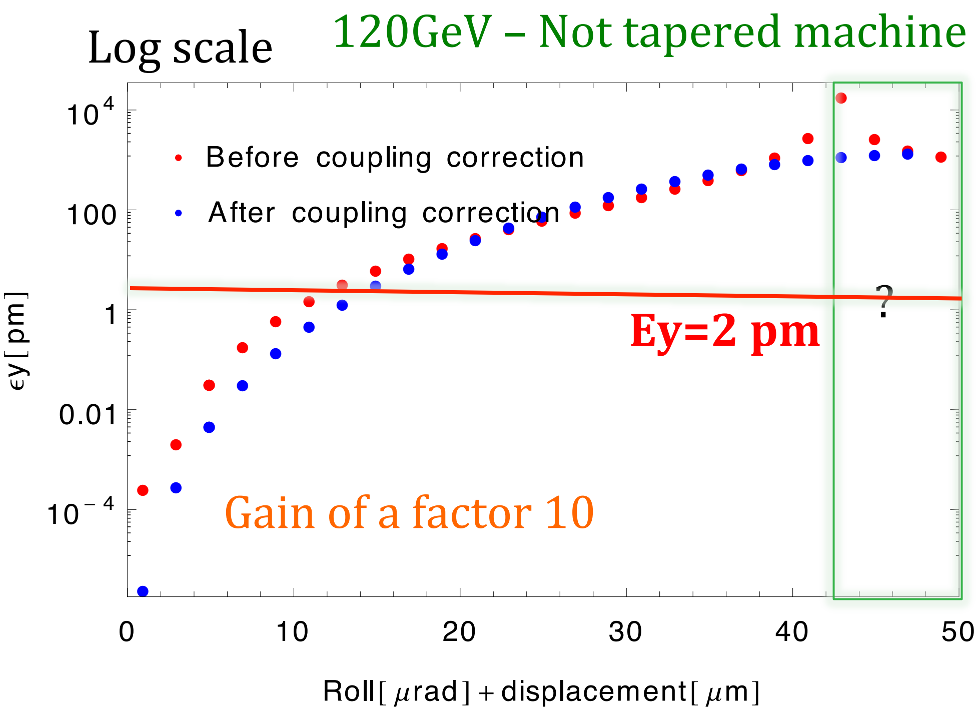
Beam Physics Challenges

- FCC-ee is a collider with beam parameters of a Light Source (flat beam, extreme low vertical emittance)-> **Hor~nm, Vert. pm!!**
- **How to conserve 2pm Vert. Emittance with spurious dispersion**
- How to keep coupling ratio **Ey/Ex of 1/1000 or 2/1000** with strong sextupole field (x100 in k2 larger than LEP)?
- How to keep the vertical dispersion **to 1mm RMS**

Algorithm & Methodology Challenges

- **Getting powerful algorithms of lattice correction** (orbit-dispersion matrix response, and coupling correction) inspired from light source experience (LOCO) and LHC or other colliders
- Computation time ~L^4
- Apply adapt them to 100km collider with a emittance ratio of 1 or 2/1000
- **MADX itself is not sufficient and limited**

Rolls & Displacements errors on quadrupoles



- 12-folds lattice
- Coupling correction from the non-diagonal element+vert. dispersion
- Vertical dispersion RMS ~50mm (1/2m at the IP)

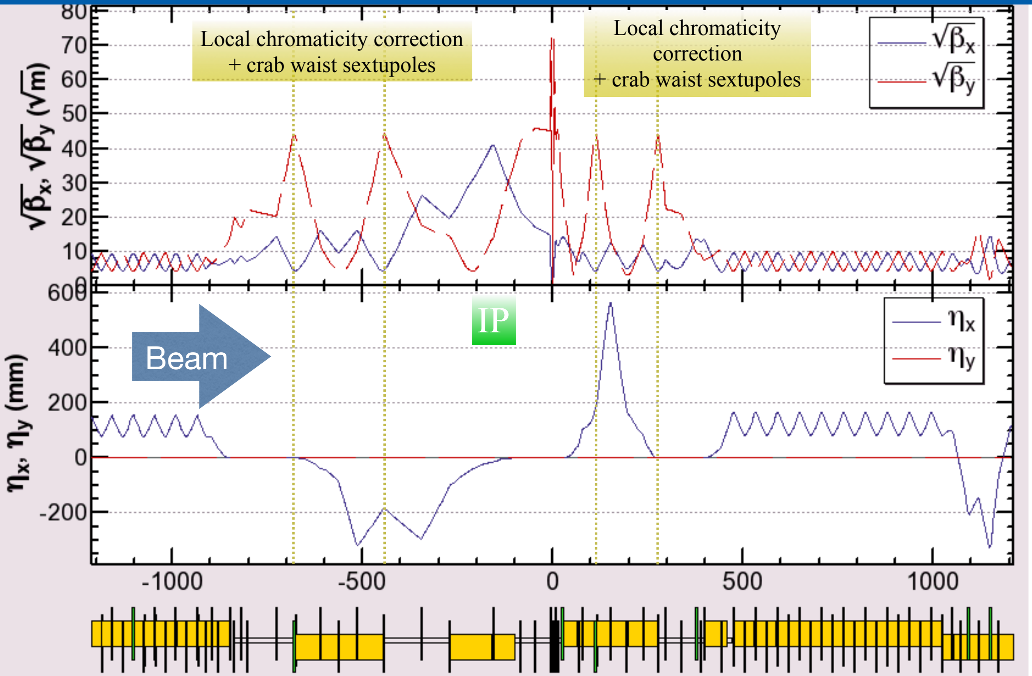
Recommendations by the review committee:

1 - More iterations should be apply for coupling

2 - BPMs errors should be taken into account

3 - For LEP operation experience: max effort to keep the vertical dispersion as low as possible

Racetrack Layout



Racetrack follows official design

K. Oide lattice option (K.Oide 's talk)

2 IPs

$\beta^*_{x/y} = 1$ m / 2 mm.

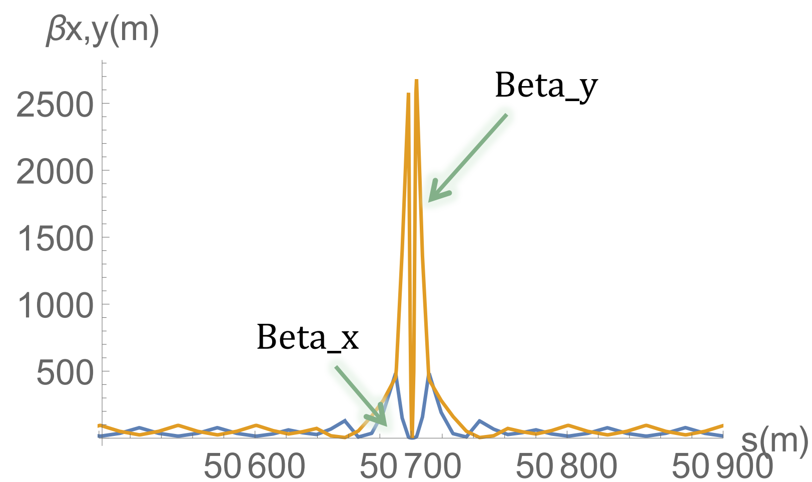
B. Haerer lattice option (See his talk)

2 Ips

$\beta^*_{x/y} = 1$ m / 2 mm.

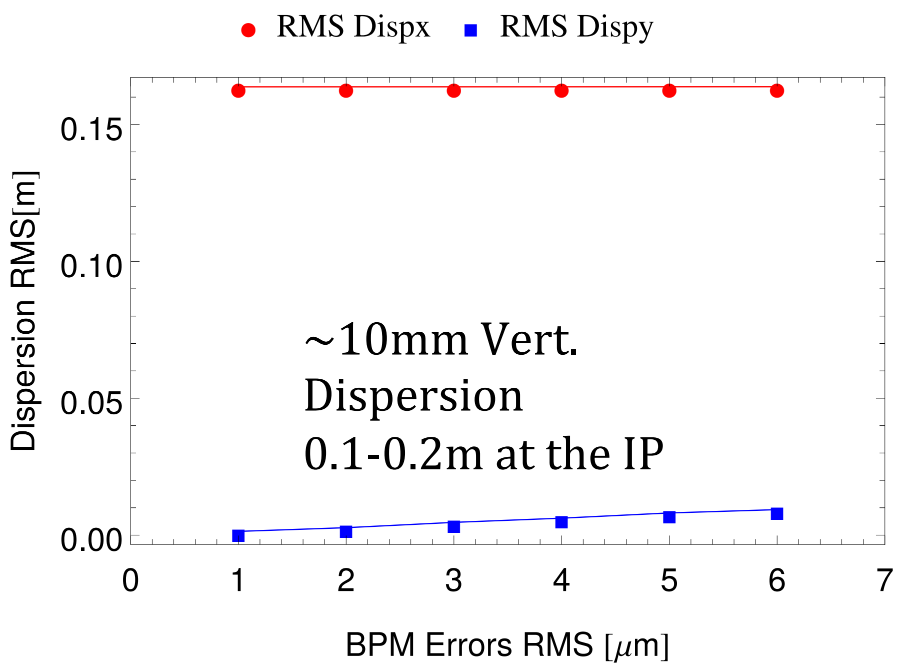
No local chromaticity correction

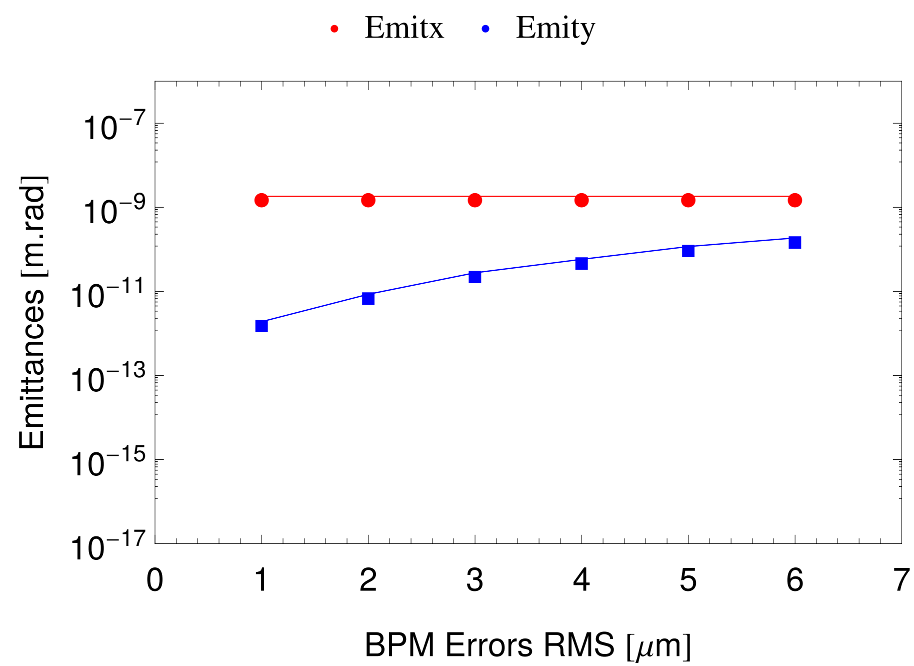
Will be combined with A. Bogomyagkov's IR in the future



BPM Error Tolerance

- Racetrack type lattice , 175GeV, 2RF, fully tapered
- Very low tolerance, emittance growth driven by vertical dispersion.
- Preferable to correct the vert Disp. via a DISPERSION FREE STEERING (DFS) rather than by a orbit correction





Dispersion Free Steering: Principle

- Build a matrix for vertical orbit (u) & dispersion (Du) response under a corrector kick (al)

$$\begin{pmatrix} (1-\alpha)\vec{u} \\ \alpha \vec{D}_u \end{pmatrix} + \begin{pmatrix} (1-\alpha)\mathbf{A} \\ \alpha \mathbf{B} \end{pmatrix} \vec{\theta} = 0$$

Response build with 1micro.rad

- Orbit response $$A_{i,j} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi Q_y)} \cos(|\mu_i - \mu_j| - \pi Q_y)$$

- Dispersion response

$$\begin{aligned} B_{ij} \;=\; & \{\sum_{l}^{quad} \frac{K_l L_l \beta_l}{4\sin(\pi Q)^2} \cos(|\mu_i - \mu_l| - \pi Q)\cos(|\mu_l - \mu_j| - \pi Q) \\ & - \sum_{m}^{sext} \frac{K_{2,m} D_{x,m} L_m \beta_m}{4\sin(\pi Q)^2} \cos(|\mu_i - \mu_m| - \pi Q)\cos(|\mu_m - \mu_j| - \pi Q) \\ & - \frac{\cos(|\mu_i - \mu_j| - \pi Q)}{\sin(\pi Q)}\} \sqrt{\beta_l \beta_j} \end{aligned}$$

"Dispersion Free Steering for YASP and dispersion for TI8", J. Wenninger, LHC-Performance-Note-005.

DFS optimization with singular value decomposition

- Without SVD, the correction does not work – mandatory step.
- SVD principle

$$\mathbf{T} = \mathbf{U}\mathbf{W}\mathbf{V}^{\mathbf{t}} = \mathbf{U}\begin{pmatrix} w_1 & 0 & \cdots & 0 \\ 0 & w_2 & & \\ \cdots & & \cdots & 0 \\ 0 & \cdots & 0 & w_M \end{pmatrix}\mathbf{V}^{\mathbf{t}},$$

- W is a diagonal matrix with w_i are the singular values.
- Establish a cutoff to eliminate the singular value to optimize the correction –
  Compromise between noise in the correction and efficiency
  More singular value -> more local correction, more noise
  Less singular value-> global correction, IP

DFS optimization with singular value decomposition

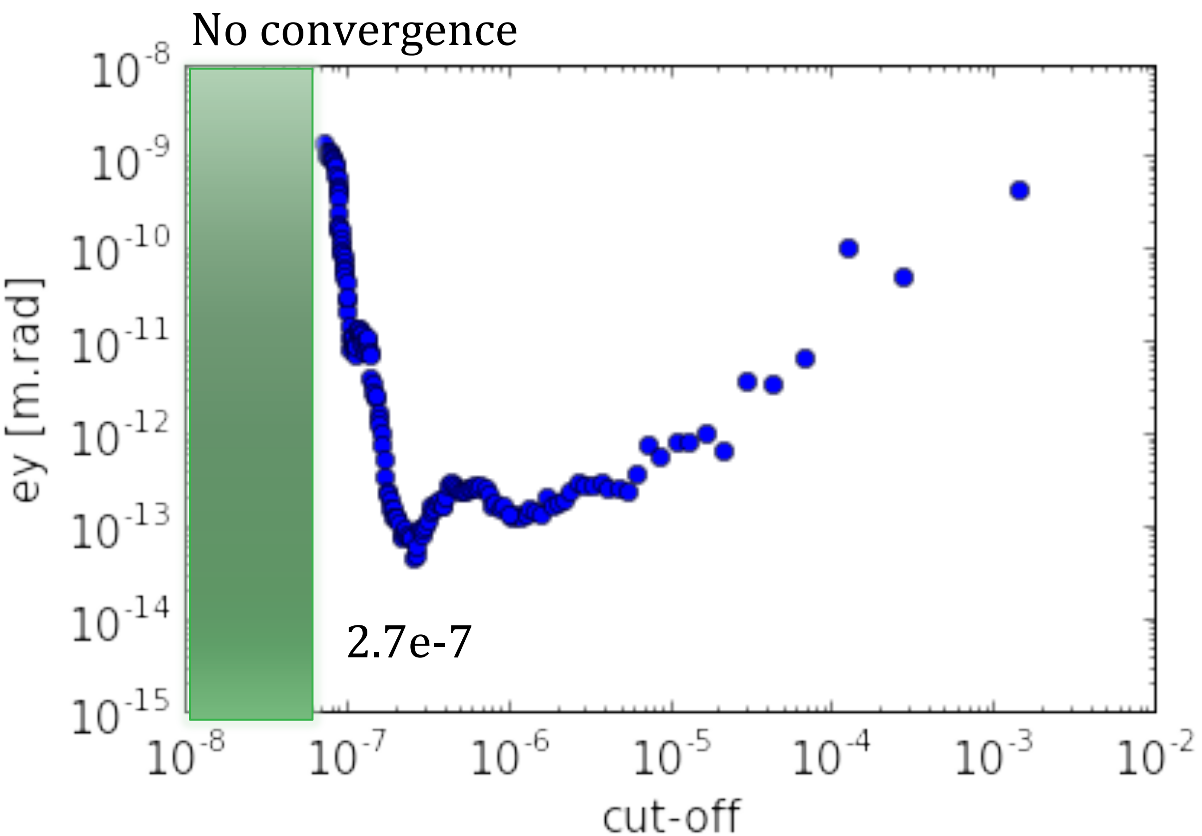
First approach with small misalignments

Matrix Size (2006,2006)

- Scan in number of singular values considered
- 2 microm vertically misaligned quads
- Pure vertical dispersion correction (0 weight on the orbit)
- 20 iterations of DFS
- Chromaticity correction is applied (Bastian’s scheme)
- Tapering, which includes a re-matching optics
- Computation of the emittance.

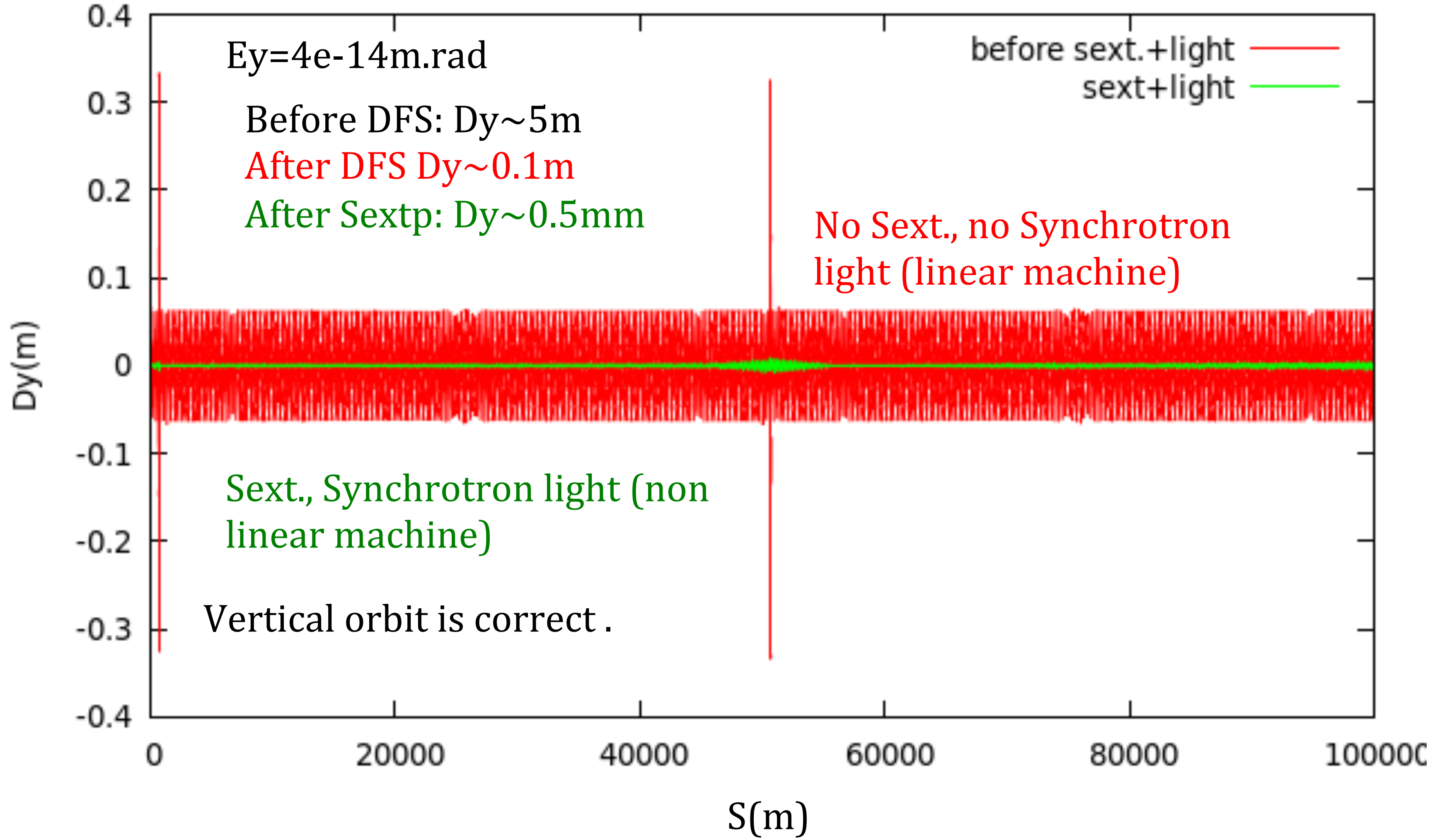
DFS optimization with singular value decomposition

DFS, chromaticity correction+W function optimization
(See Bastian Haerer's talk)



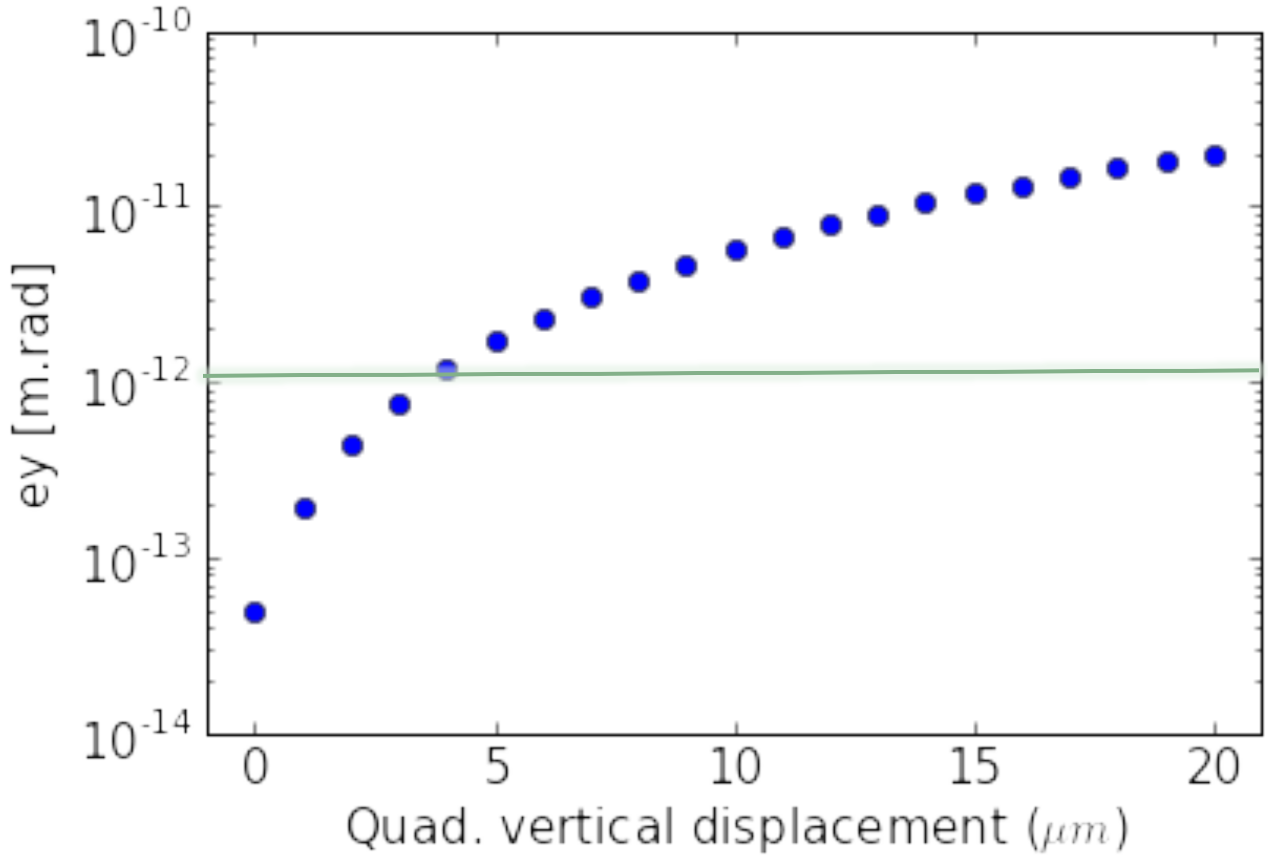
Cut-off:
smallest considered singular value/largest singular value

DFS optimization with singular value decomposition

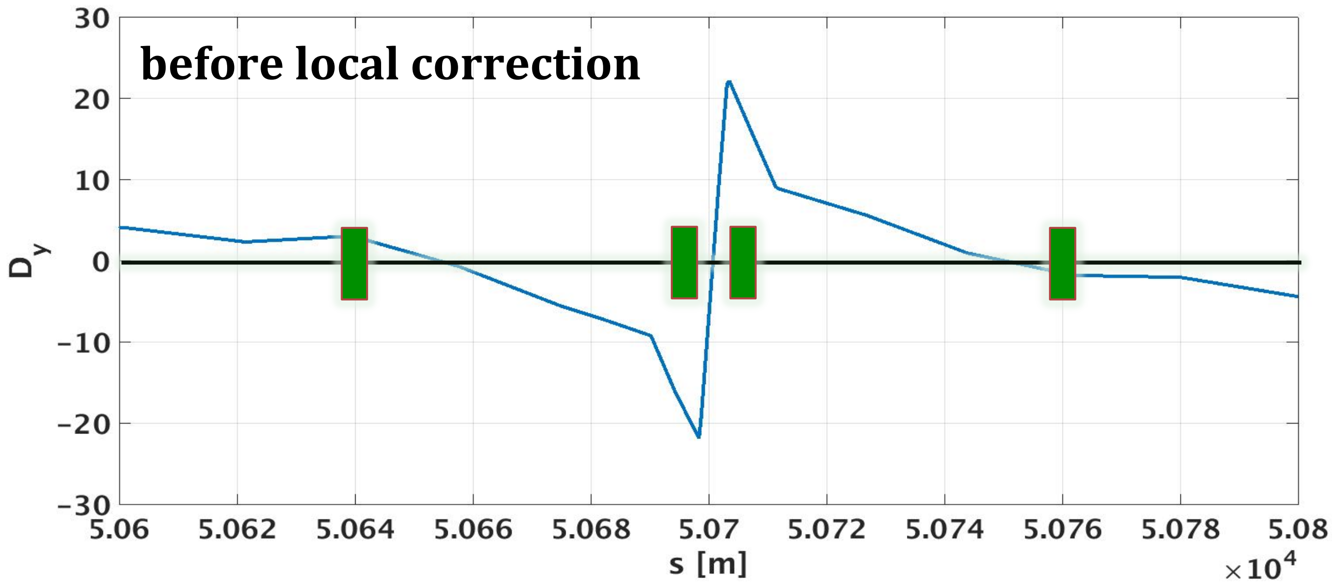


DFS optimization with singular value decomposition

According to the SEED, 4-6microm



Local Dispersion Correction at the IP



- Clear indications show that the IRs has to be treated separately from the arcs.
- Vert. Dispersion excursion is driving Ey to high value.
- Using a local bump at the IP, correct locally the Vert. Dispersion

  From 2% emittance ratio (Ey/Ex) -> 0.5% emittance ratio
- **Next step: should be fully integrated to the correction algorithm**

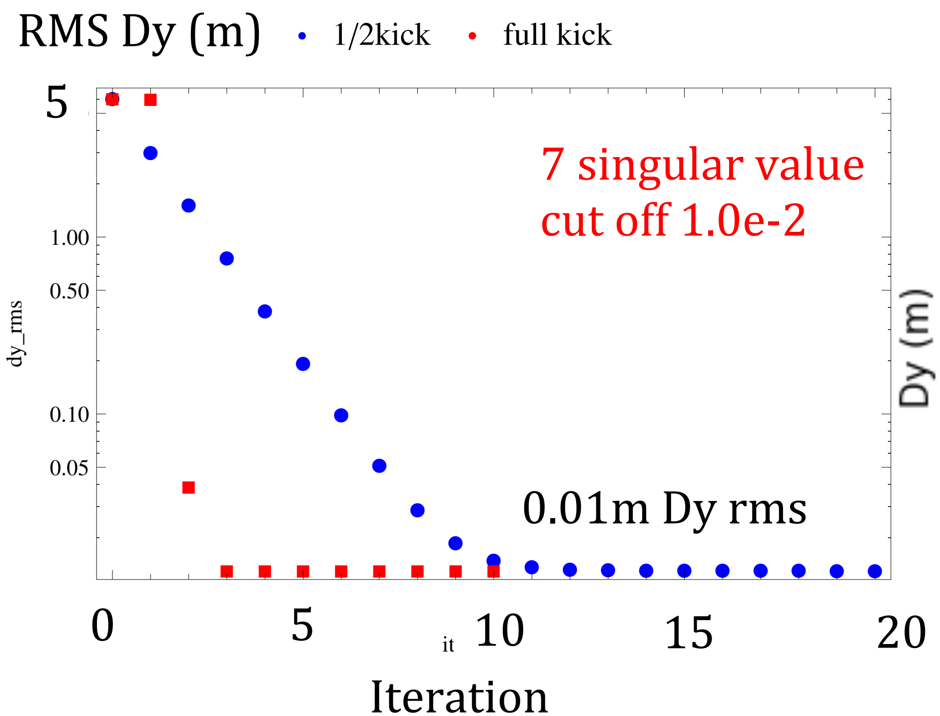
Summary

- **Lattice errors huge impact on Dy & Ey, due to the beta-function from the IRs, very sensitive**
- **Developing lattice correction methods, adapting them to 100km machine is still on going**
- To overcome BPM errors, a Dispersion Free Steering has been implemented.
- …. still needs quite some optimizations (DFS directly with sextupoles)
- Next step: what do we gain by treating IP & Arcs ?
- Coupling correction is another very challenging next step.
- Alignment techniques from Light sources should be considered.

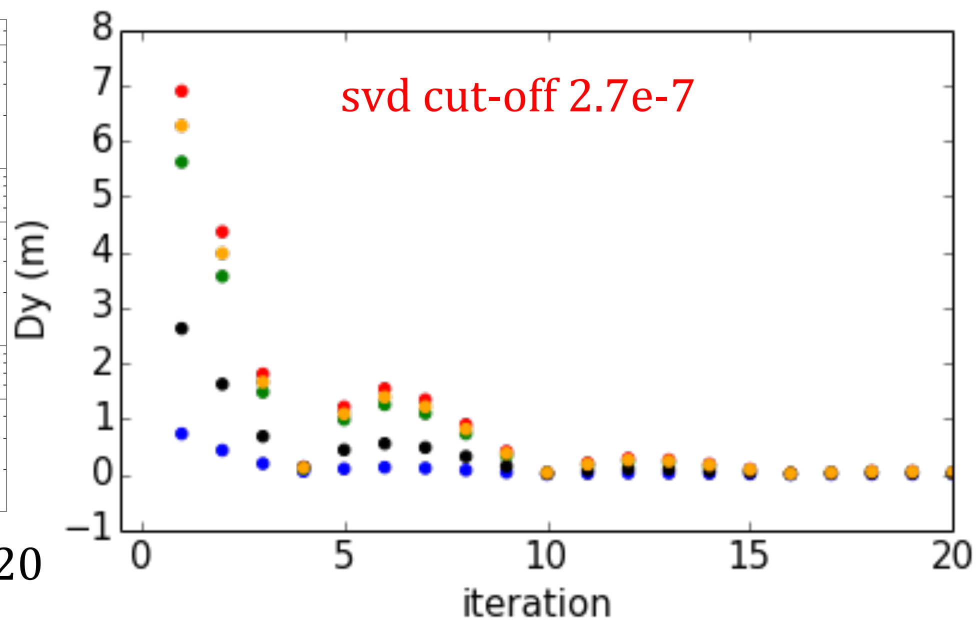
Thank you for your attention!

DFS optimization with singular value decomposition

- Vertical Dispersion Convergence (No sextupole, no SR)



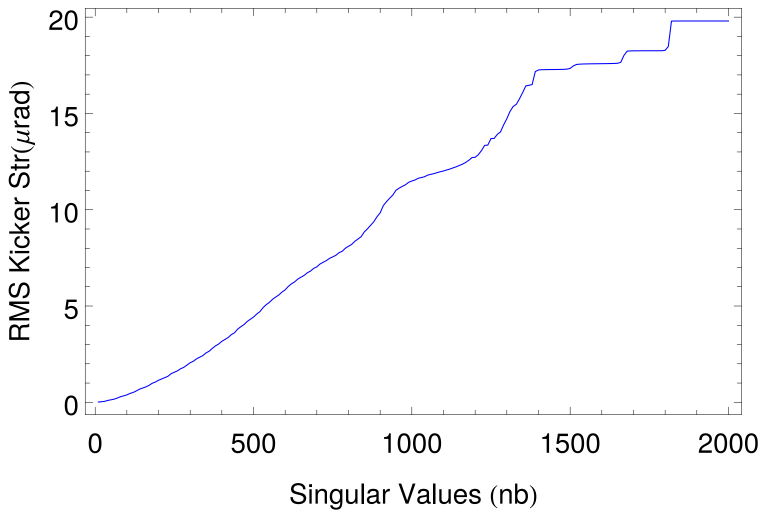
Repeatable on 50 seeds..

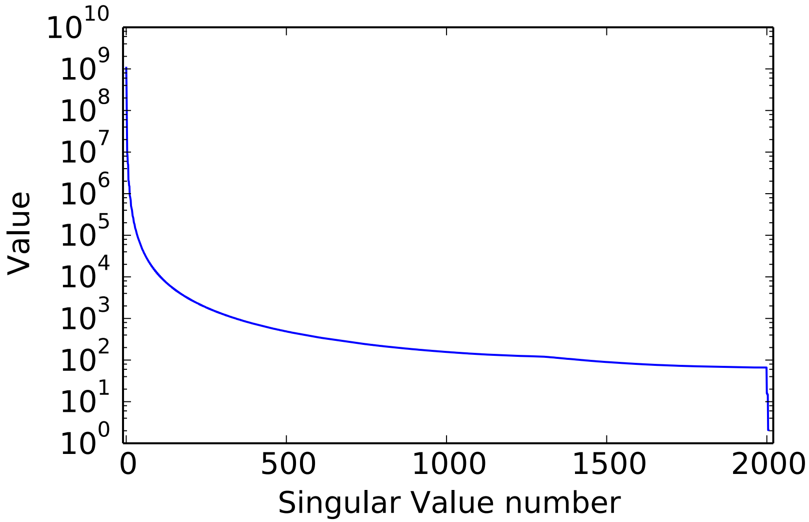


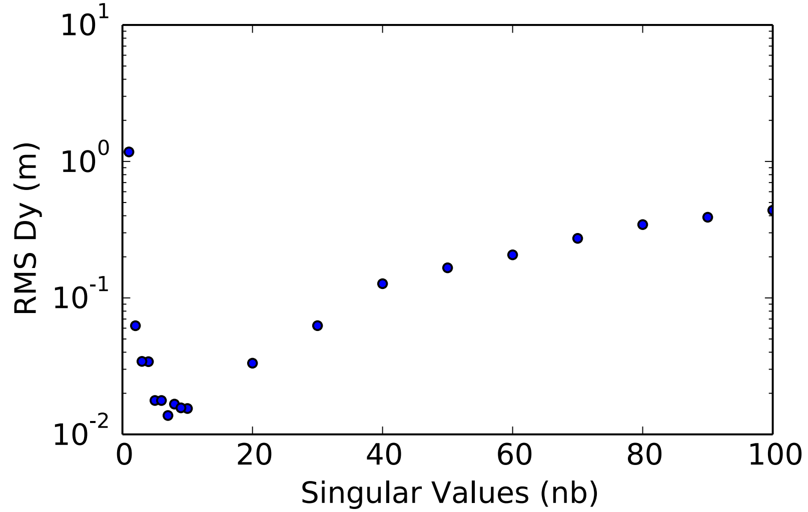
After sextupoles:
Ey~1e-10m.rad

After sextupoles:
Ey~2e-13m.rad

SVD no sextupoles

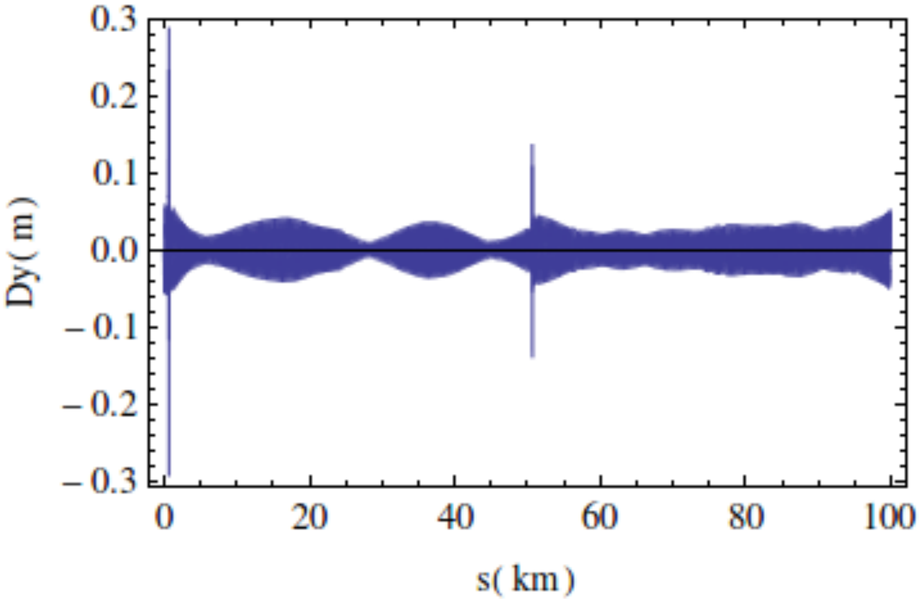


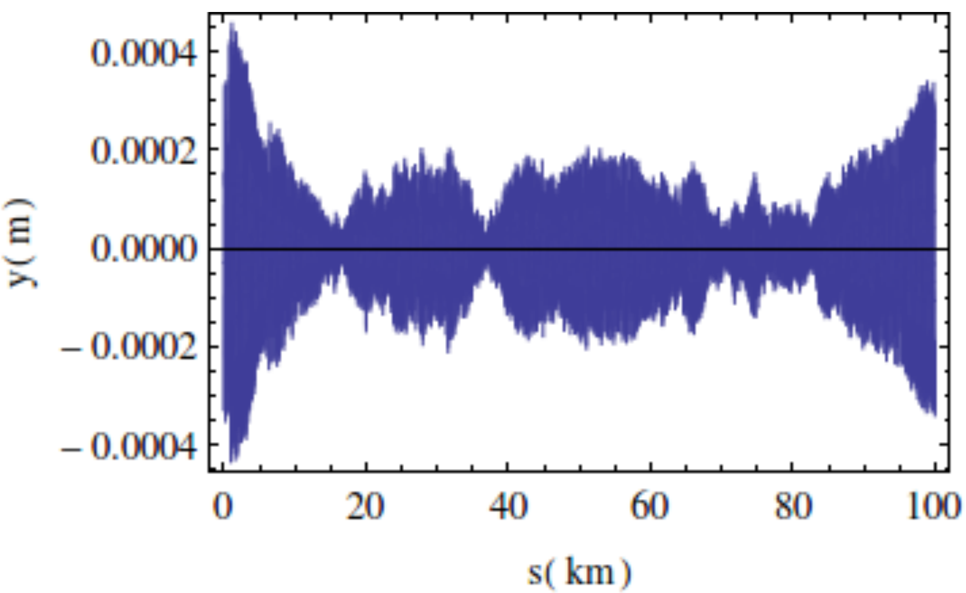




Keep the 7th largest singular values
Sv_max/sv~1.0e-3

DFS applied to a misaligned lattice



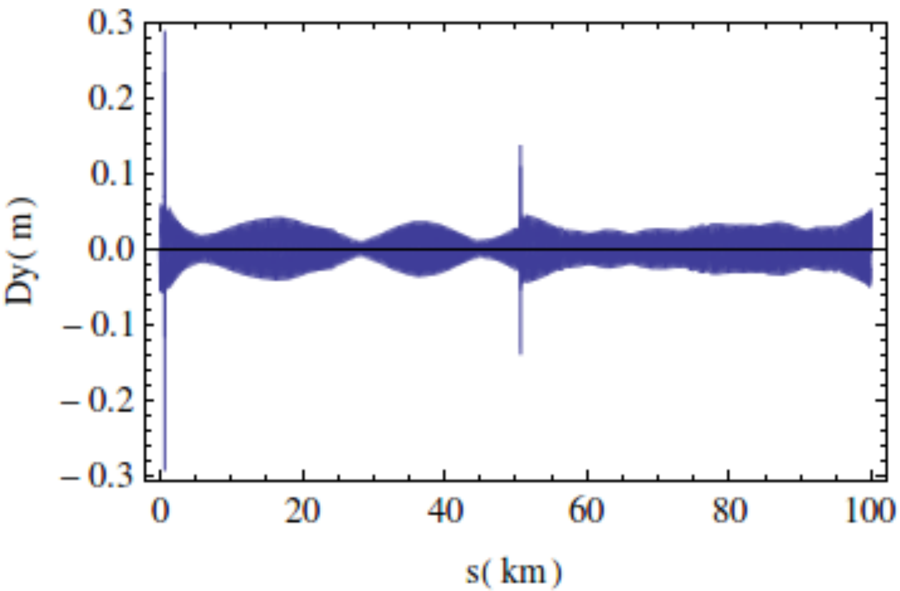


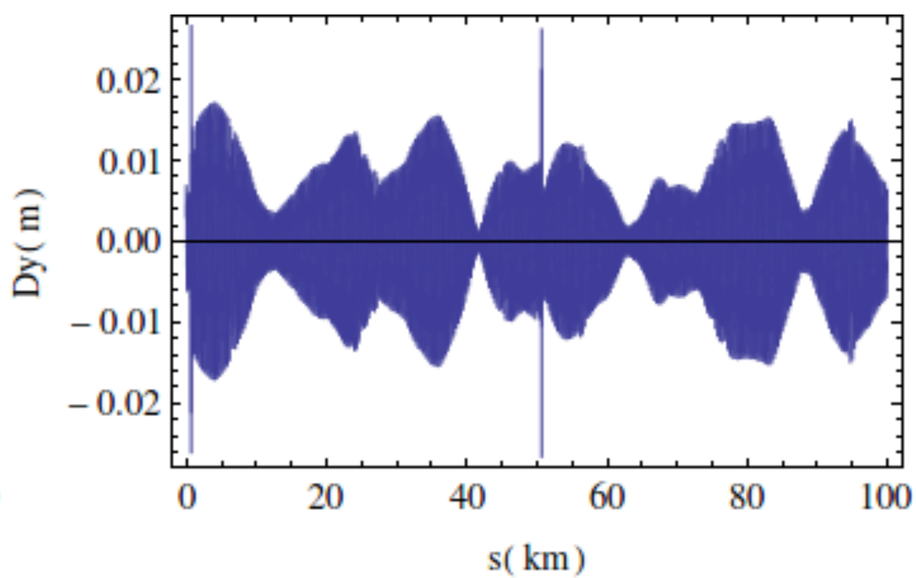
Emittance ratio~2%

Dispersion at the IP drive the emittance to large value

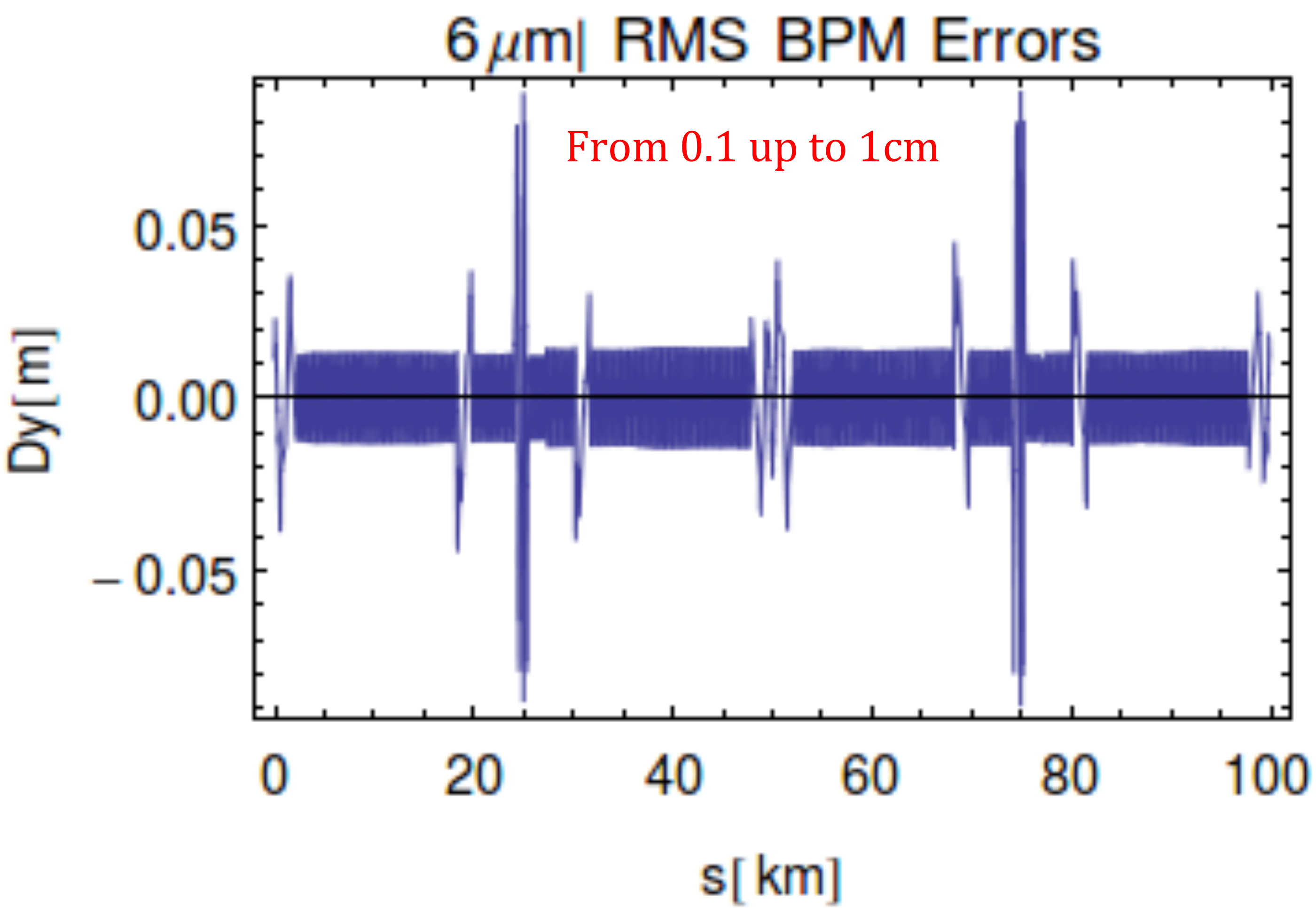
Local Dispersion Correction

- … extremely efficient:
  it brings the vertical dispersion at the same order of magnitude as the arcs.
- **2%-> 0.5%** in emittance ratio.
- DFS extra iterations do not change the kicker strengths in the IRs





Motivations



Dispersion Free Steering: Motivations

- Dispersion Free Steering (used in LEP):
  simultaneous correction of the dispersion and of the orbit with orbit correctors.
- Method to minimize the vertical emittance at LEP
- For Vert. Disper, BPM errors do not matter.
- No DFS in MADX (only MAD8)
  YASP (J. Wenninger)

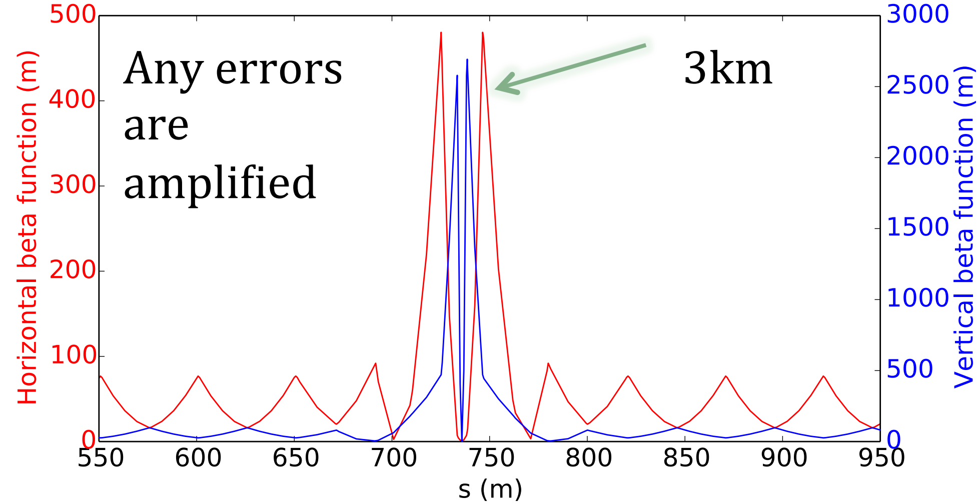
$$\varepsilon_y \simeq \varepsilon_{y0} + \kappa\varepsilon_x + rE^2(D_y^{\mathrm{rms}})^2,$$

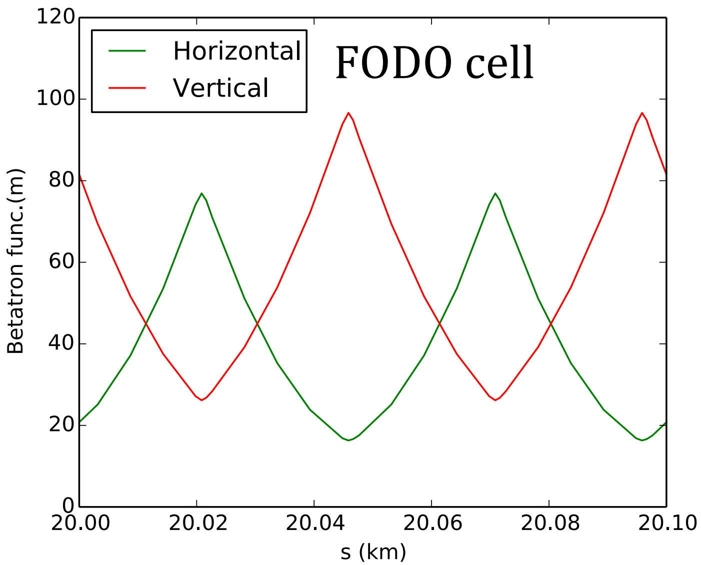
Status Review Meeting & Recommendations Oct 2015

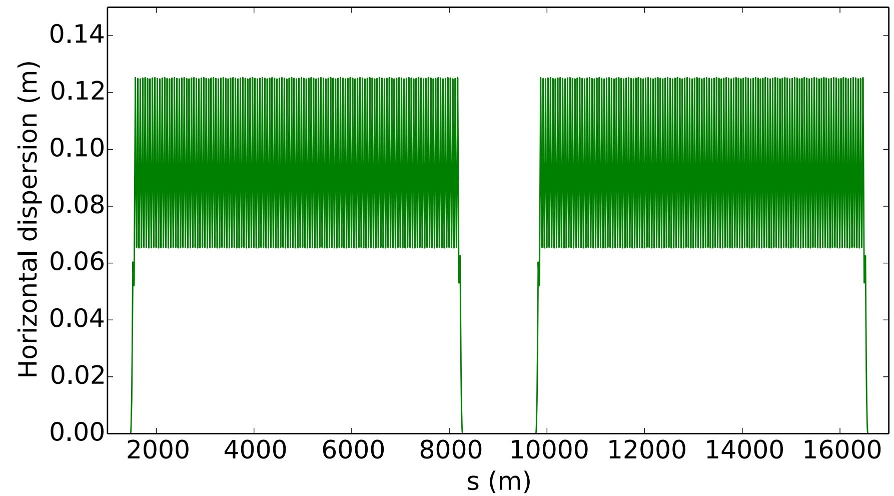
- 120 GeV
- 1m/2mm beta*, 2 Ips
- RF spread around the ring

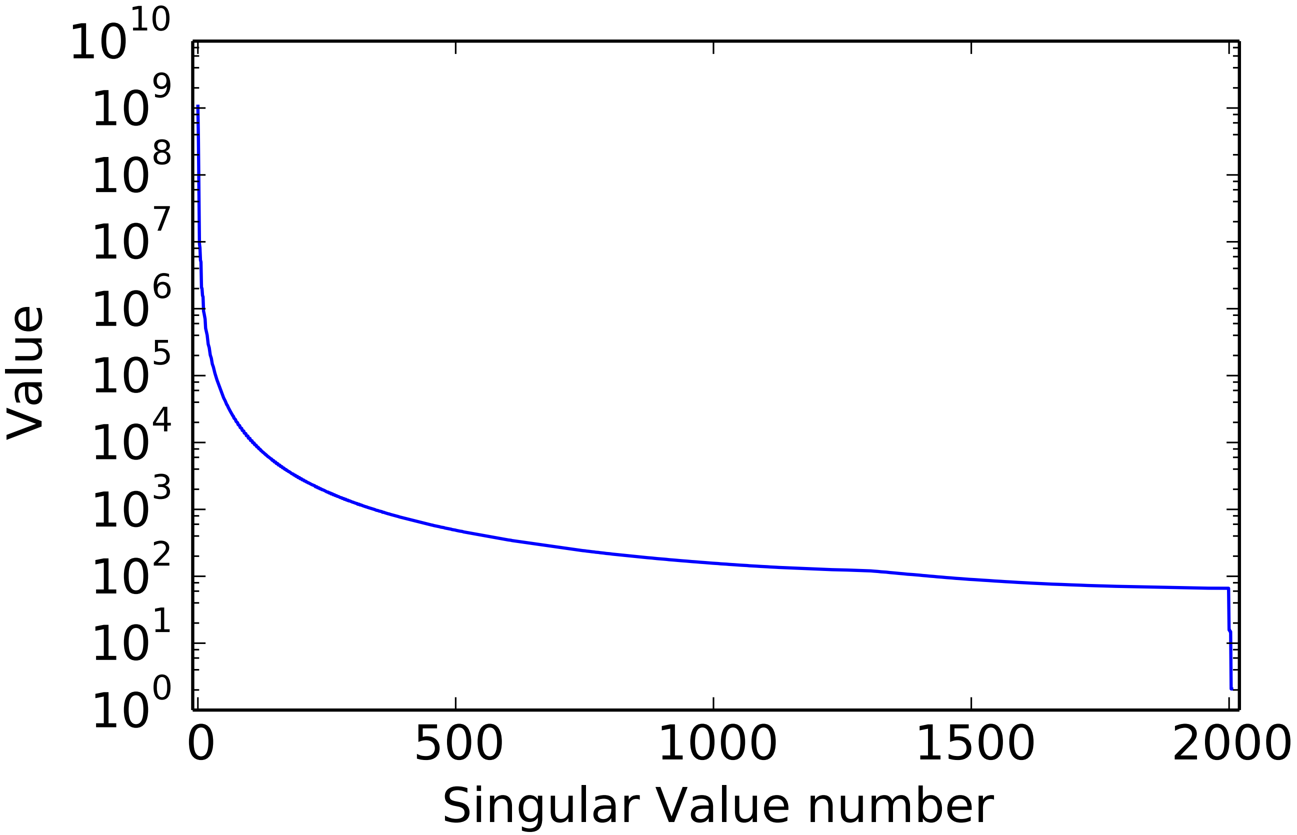
- Qx=419.08/ Qy=333.14
- Q'x = -573.6506369
- **Q'y = -852.4978106**

Interaction Region (no crab waist)









10^{10}
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2000
Singular Value number