Update on the CLIC DR design

- Linear and nonlinear beam dynamics

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CERN

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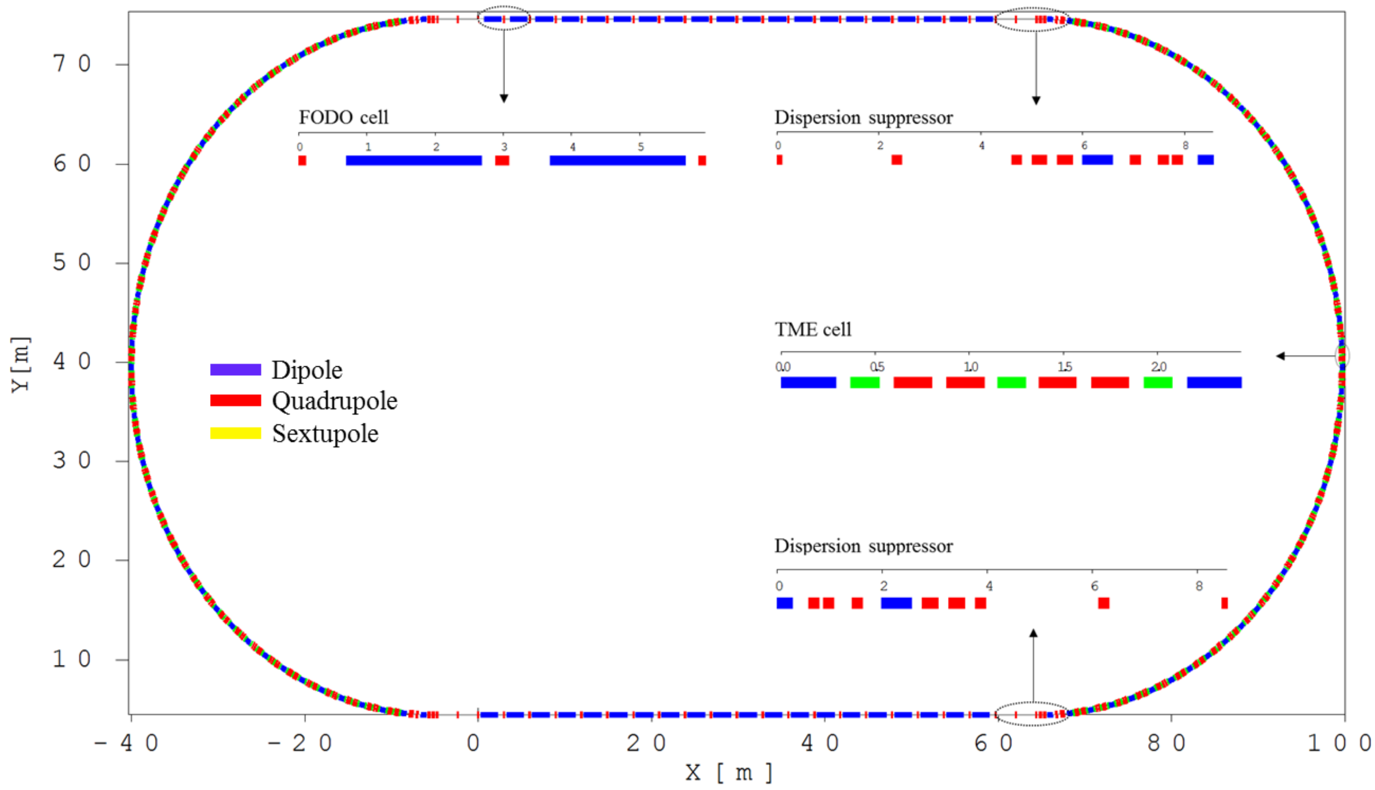
Outline

- CLIC DR new design
  - Longitudinal variable bend and superconducting wiggler
  - Trapezium field profile dipole
  - Optics and parameters

- Nonlinear dynamics
  - Chromaticity correction and tune sensitivity with energy
  - Phase space and dynamic aperture
  - Lost particles
  - FMA
  - Multipole error

- Vertical emittance tuning algorithm - to bring the vertical emittance to design value (ε_y<1 pm rad including IBS effect) under the misaligned lattice
  - Effects of misalignments – Theory
  - Distribution of correctors
  - Tuning algorithm
  - Tolerances
  - Vertical emittance

General layout of CLIC damping ring (DR)

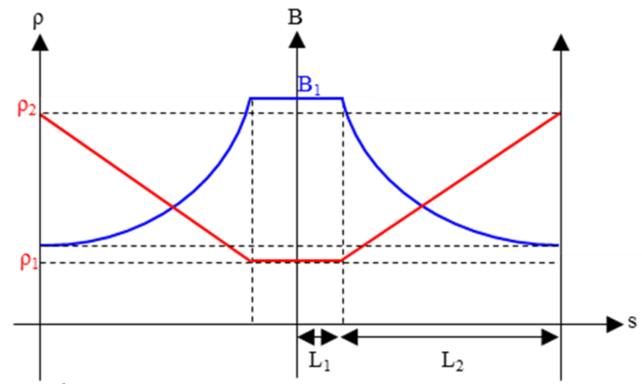


- The DRs' layout has a racetrack shape (two arcs and two long straight sections)
- The arcs are composed of theoretical minimum emittance (TME) cell with longitudinally variable bends and the straight sections are based on FODO cell filled with high field super conducting damping wigglers.
- Each arc/straight section includes of 42 TME/10 FODO cells and there are totally 90 dipoles and 40 superconducting wiggler magnets in the whole DR.
- There are four matching sections grouped in two types to match the optics of straight section to the optics of arc section and vice versa.

Longitudinal variable bend

- The longitudinally variable dipole, whose magnetic field varies along their length, can provide lower horizontal emittances than a uniform dipole of the same bending angle.
- For this propose, the maximum magnetic field of a variable bend should be applied at its center and decreases towards the two exit edges of the dipole.
- Several longitudinal field profile of dipoles and corresponding DR parameters have been studied.

The results revealed that damping ring based on trapezium field profile dipole provides better conditions in view of beam emittance, number of dipole and ring circumference, etc. and therefore I mainly focus on DR based Trapezium dipole.

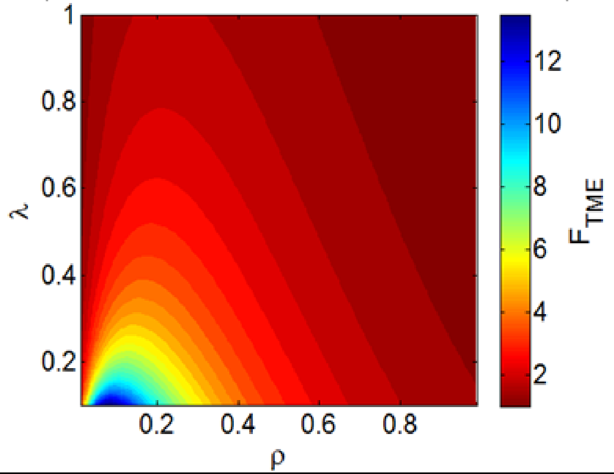


- Defining λ and ρ as $\lambda = L_1/L_2$ and $\rho = \rho_1/\rho_2$ and assuming L as the half length of dipole ;

$$\begin{cases} L_1 = \dfrac{\lambda L}{\lambda + 1} \\ L_2 = \dfrac{L}{\lambda + 1} \end{cases}$$

$$\begin{cases} \rho_1 \ (0 < s < L_1) \\ \rho_1 \left[1 + \dfrac{\lambda + 1}{L}\left(\dfrac{1-\rho}{\rho}\right)\left(s - \dfrac{\lambda L}{\lambda + 1}\right)\right] \ (L_1 < s < L_1 + L_2) \end{cases}$$

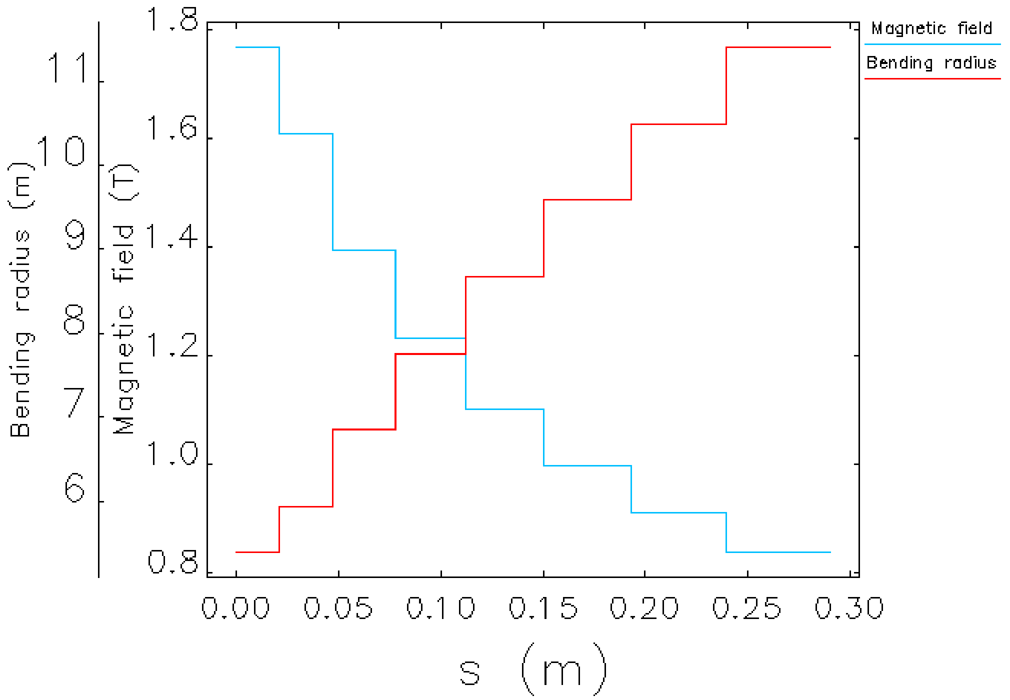
$$\begin{cases} B_1 \ (0 < s < L_1) \\ B_1 \left[1 + \dfrac{\lambda + 1}{L}\left(\dfrac{1-\rho}{\rho}\right)\left(s - \dfrac{\lambda L}{\lambda + 1}\right)\right]^{-1} \ (L_1 < s < L_1 + L_2) \end{cases}$$



S. Papadopoulou, F. Antoniou and Y. Papaphilippou
Emittance reduction with variable bending magnet strengths: Analytical optics considerations, preprint (2017).

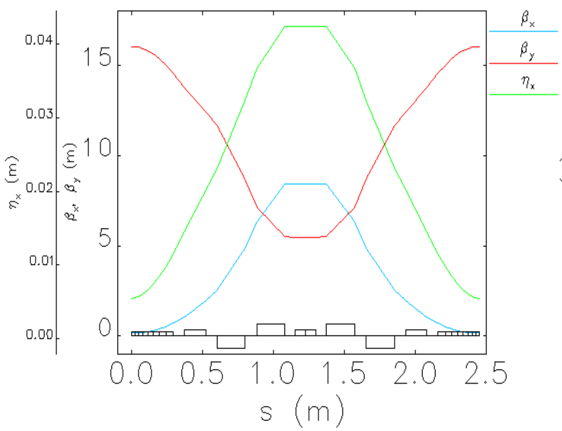
Trapezium field profile dipole

- The dipole total length is set to L = 58 cm as the optimized value.
- Each trapezium field profile dipole bends the beam 4 Degrees.
- Trapezium dipole has small gradient for beam focusing.
- The highest field section with length of about 4.2 cm provides magnetic field of 1.76 T.

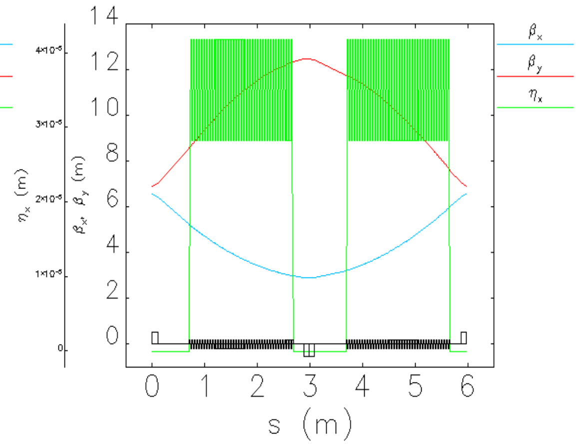


Parameters	Highest field section	Lowest field section
Length (cm)	4.1825	5.0550
Field (T)	1.7666	0.8366
Radius (m)	5.4000	11.4028
Def. angle (Deg.)	0.4438	0.2540
K (m^{-2})	-1.1000	-1.1000
Gradient (T/m)	-10.4937	-10.4937

Optical functions and parameters

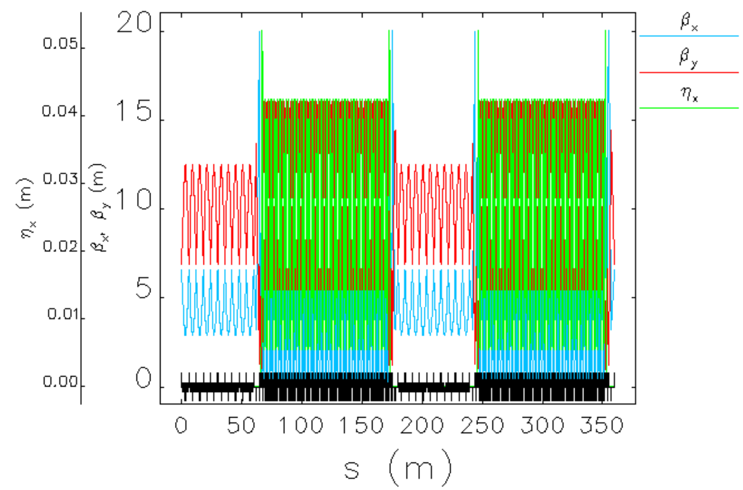


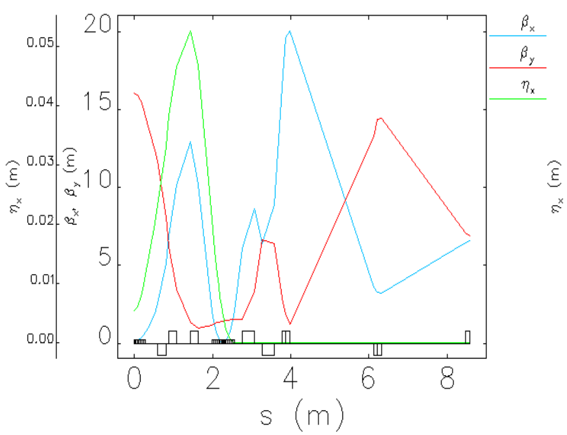
TME cell;
Length= 2.45 m
$\psi_x/2\pi$= 0.442
$\psi_y/2\pi$= 0.042



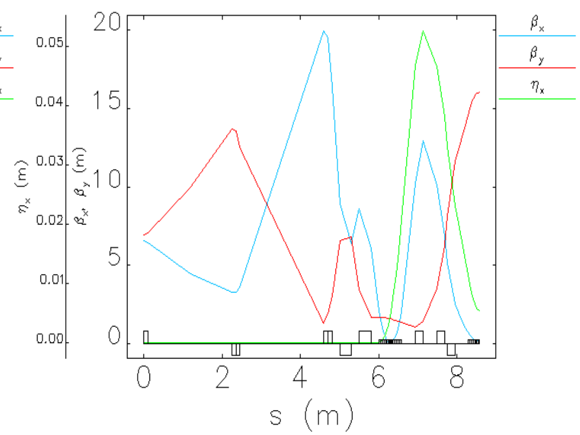
FODO cell;
Length= 5.969
$\psi_x/2\pi$= 0.238
$\psi_y/2\pi$= 0.096
Wiggler (l=2 m, B=3.5 T, λ=49 mm)

Parameters	Value
Energy (GeV)	2.860
Circumference (m)	359.440
Hor./Ver. tune	45.2895/8.3133
Natural emittance (pm.rad)	75.8924
Natural chromaticity	-128.789/-61.832
1st order mom. com. factor	1.2478E-4
Energy spread	1.2745E-3
Energy loss per turn (MeV)	5.721
Damping time (ms/ms/ms)	1.179/1.199/0.604





Dispersion suppressor;
Length=8.57
$\psi_x/2\pi$= 0.851
$\psi_y/2\pi$=0.726

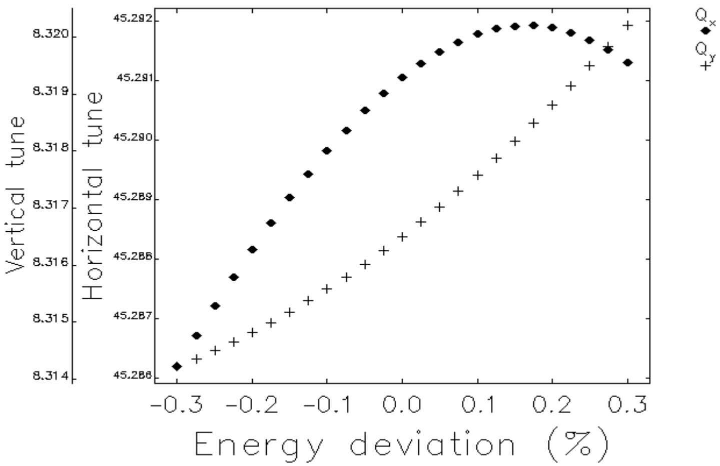


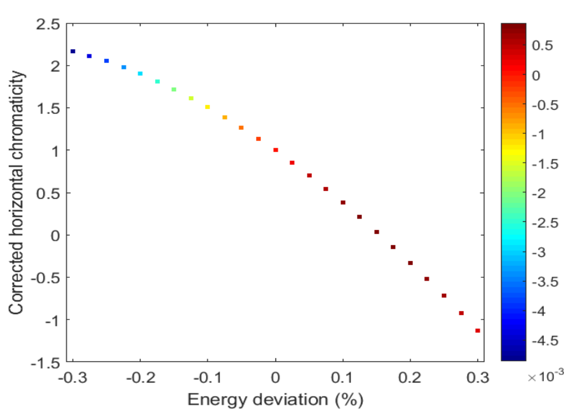
Dispersion suppressor;
Length= 8.56
$\psi_x/2\pi$= 0.851
$\psi_y/2\pi$= 0.709

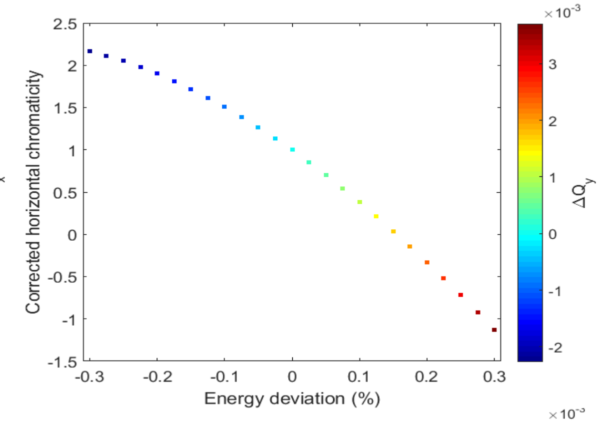
Chromaticity correction-Tune shift with energy

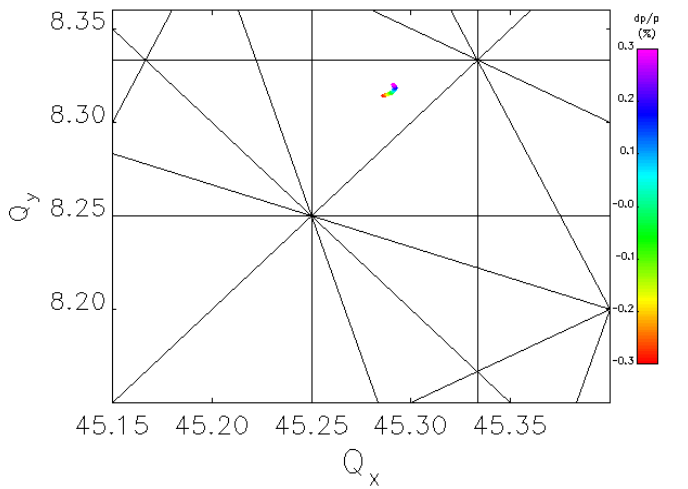
- Two families of sextupole magnets both with the same length of 15 cm in the TME cell are considered to correct the natural chromaticity of ring to +1.

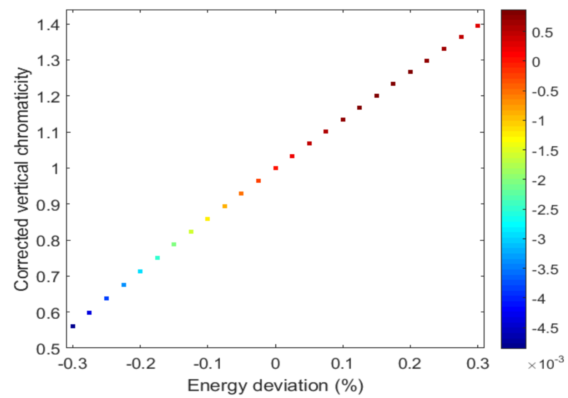
Parameters	SD	SF
Length [cm]	15	
Pole radius [mm]	15	
Sextupole strength [m^{-2}]	-362.6698	416.5494
B" (T/m^{-2})	-3459.7589	3973.7531
Pole tip field (T) [R=15 mm]	0.3892	0.44705

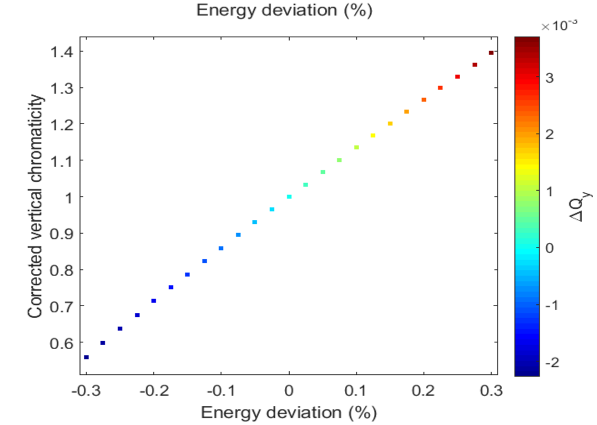












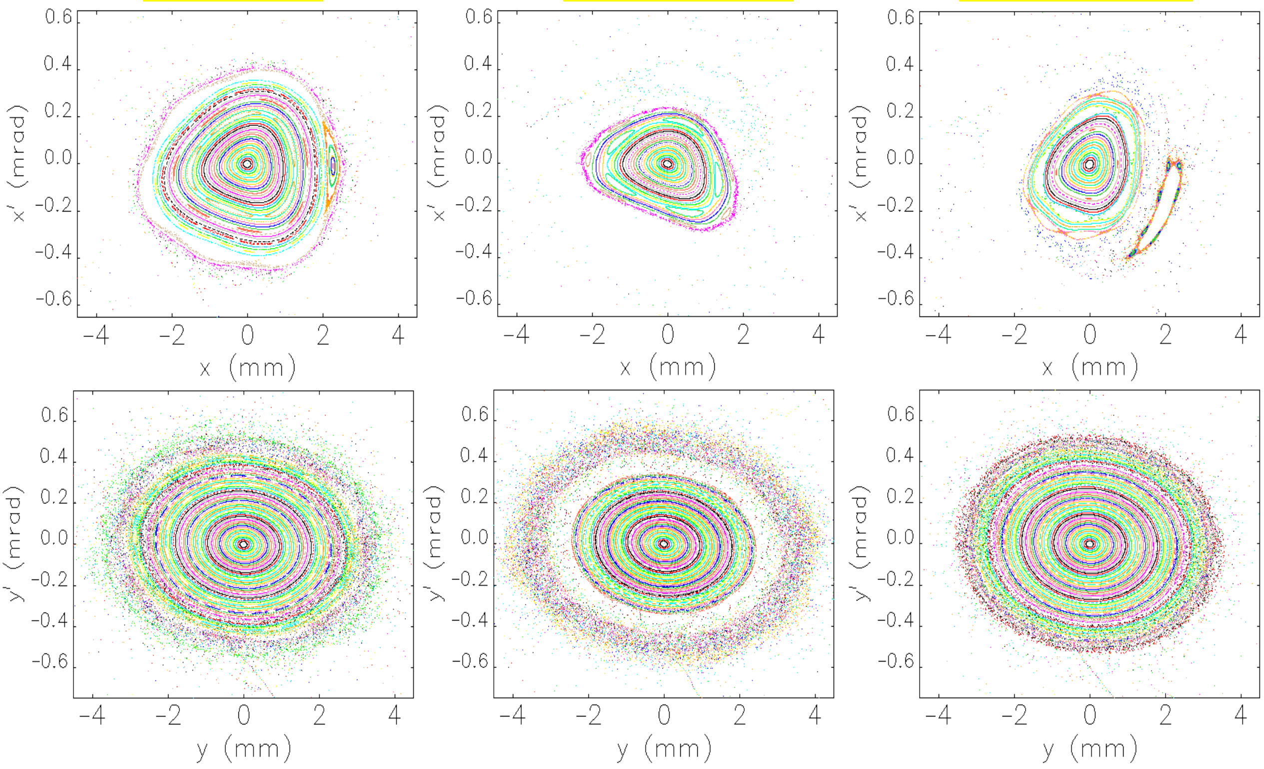
Phase space & DA

DA: Physical transverse stable space for the particles after a given number of turns (2000 here)

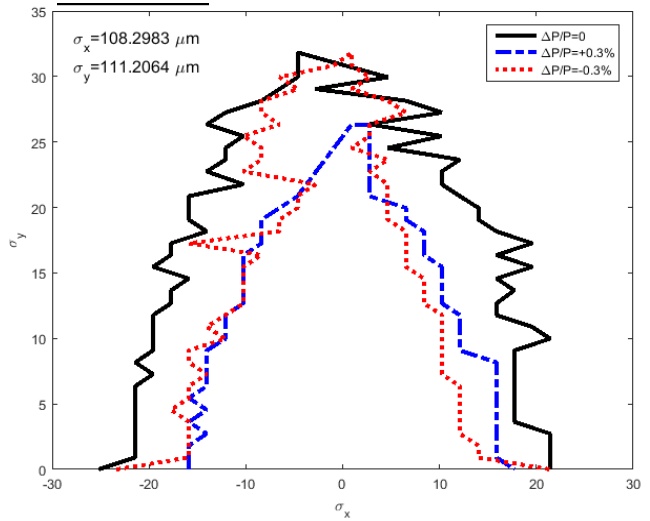
The injected beam normalized emittance and energy spread;

- For electron DR: ε_{xn}=10 μm and ε_{yn}=10 μm, δ=0.3%
- For positron DR: ε_{xn}=65 μm and ε_{yn}=10 μm, δ=0.3%

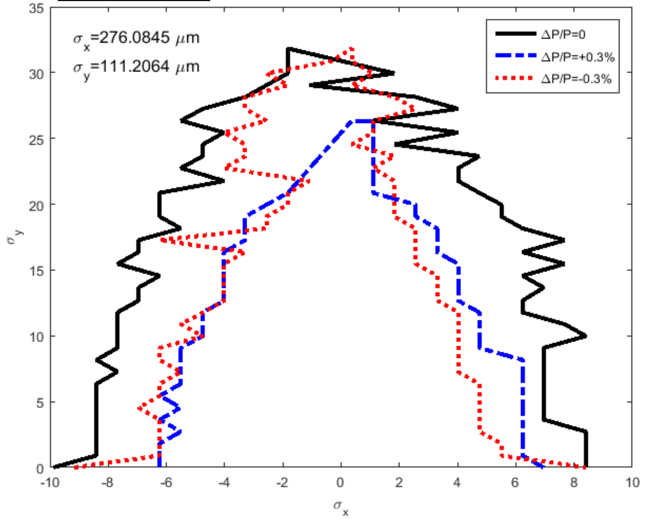
ΔP/P=0 | ΔP/P=0.3% | ΔP/P=-0.3%



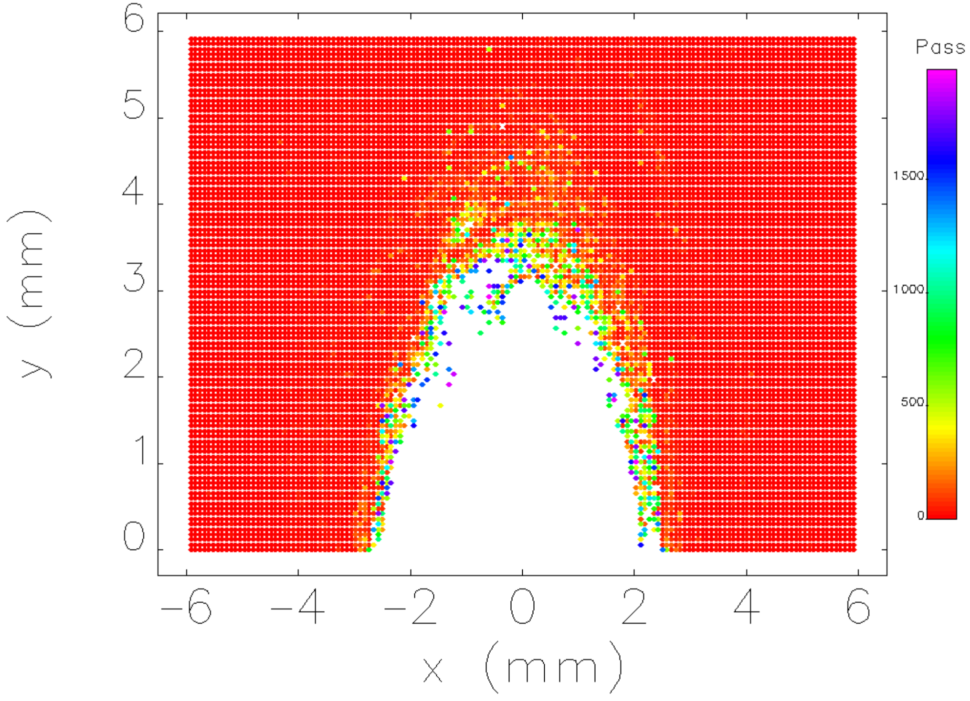
Electron DR

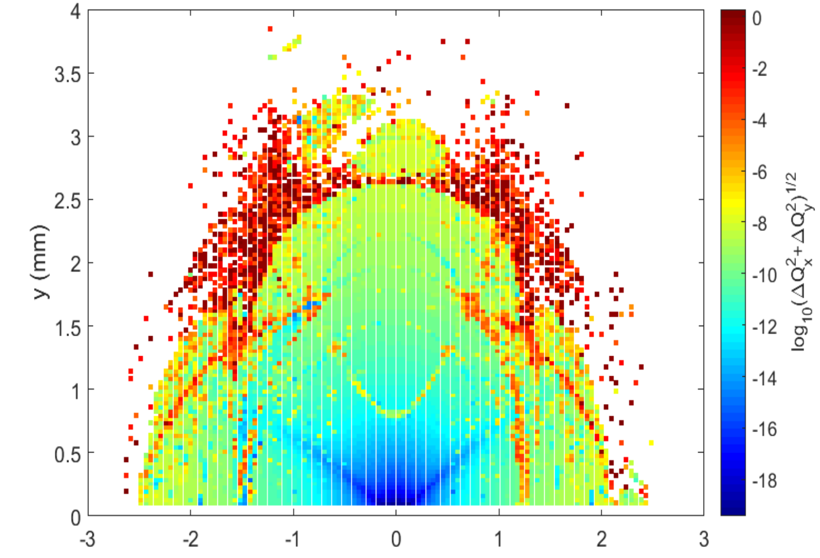


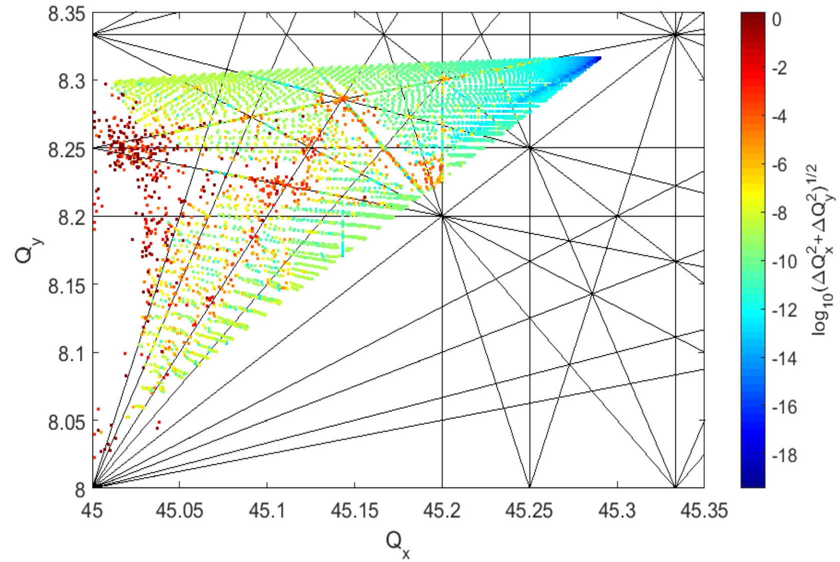
Positron DR



Lost particles & FMA





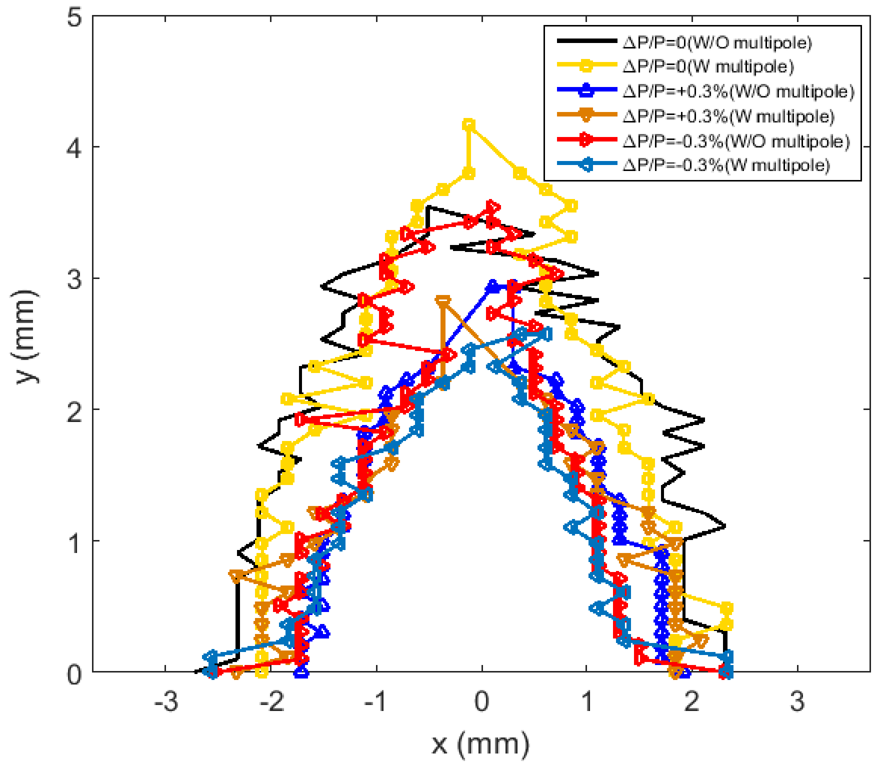


The on energy particles will be survived between -2.6 mm to +2 mm in horizontal and ±3 mm in vertical plane after passing 2000 turns.

Multipole errors

	Order	Multipole	Systematic	Random
Dipole, B_n/B_1 @ 10 mm	2	Quadrupole	$1.00*10^{-4}$	$1.00*10^{-3}$
	3	Sextupole	$1.50*10^{-4}$	$1.00*10^{-3}$
	4	8-pole	0.00	$1.00*10^{-3}$
	5	10-pole	$5.00*10^{-5}$	$1.00*10^{-3}$
	6	12-pole	0.00	$1.00*10^{-3}$
	7	14-pole	$5.00*10^{-4}$	$1.00*10^{-3}$
	8	16-pole	0.00	$1.00*10^{-3}$
Quadrupole, B_n/B_2 @ 10 mm	3	Sextupole	0.00	$1.00*10^{-3}$
	4	8-pole	0.00	$1.00*10^{-3}$
	5	10-pole	0.00	$1.00*10^{-3}$
	6	12-pole	$1.00*10^{-6}$	$1.00*10^{-3}$
	7	14-pole	0.00	$1.00*10^{-3}$
	8	16-pole	0.00	$1.00*10^{-3}$
	9	18-pole	0.00	$1.00*10^{-3}$
	10	20-pole	$1.00*10^{-7}$	$1.00*10^{-3}$
	11	22-pole	0.00	$1.00*10^{-3}$
	12	24-pole	0.00	$1.00*10^{-3}$
	13	26-pole	0.00	$1.00*10^{-3}$
	14	28-pole	$1.00*10^{-8}$	$1.00*10^{-3}$
	15	30-pole	0.00	$1.00*10^{-3}$
	16	32-pole	0.00	$1.00*10^{-3}$
	17	34-pole	0.00	$1.00*10^{-3}$
	18	36-pole	$1.00*10^{-8}$	$1.00*10^{-3}$
Sextupole, B_n/B_3 @ 10 mm	4	8-pole	0.00	$1.00*10^{-3}$
	5	10-pole	0.00	$1.00*10^{-3}$
	6	12-pole	0.00	$1.00*10^{-3}$
	7	14-pole	0.00	$1.00*10^{-3}$
	8	16-pole	0.00	$1.00*10^{-3}$
	9	18-pole	$1.00*10^{-6}$	$1.00*10^{-3}$
	15	30-pole	$1.00*10^{-7}$	$1.00*10^{-3}$
	21	42-pole	$1.00*10^{-6}$	$1.00*10^{-3}$
	26	54-pole	$5.00*10^{-7}$	$1.00*10^{-3}$
	33	66-pole	$1.00*10^{-7}$	$1.00*10^{-3}$
	39	78-pole	$5.00*10^{-8}$	$1.00*10^{-3}$
	45	90-pole	$1.00*10^{-8}$	$1.00*10^{-3}$

$$B_n = \sum_{n=1}^{\infty} \frac{\left(\frac{\partial^{n-1} B}{\partial x^{n-1}}\right)}{(n-1)!} x^{n-1}$$



Vertical emittance & alignment errors

- In practice, the vertical emittance for a circular machine is dominated by two factors;
  - residual vertical dispersion (This is caused by the coupling between longitudinal and vertical motion)
  - betatron coupling (This is caused by the coupling between horizontal and vertical motion)
- Magnet alignment errors are the dominant sources of vertical emittance in particular:
  - tilts of the dipoles around the beam axis;
  - vertical alignment errors of the quadrupoles;
  - tilts of the quadrupoles around the beam axis;
  - vertical alignment errors of the sextupoles.

Misalignments of magnets

Combined Dipole

$$\begin{pmatrix}B_x\\B_y\end{pmatrix}=\begin{pmatrix}ky\\B+kx\end{pmatrix}\rightarrow\begin{pmatrix}B_x\\B_y\end{pmatrix}=\begin{pmatrix}\cos\vartheta & -\sin\vartheta\\ \sin\vartheta & \cos\vartheta\end{pmatrix}\begin{pmatrix}k(y+\Delta y)\\B+k(x+\Delta x)\end{pmatrix}=\begin{pmatrix}ky\cos\vartheta+k(\Delta y\cos\vartheta-\Delta x\sin\vartheta)-B\sin\vartheta-kx\sin\vartheta\\(B+kx)\cos\vartheta+k(\Delta y\sin\vartheta+\Delta x\cos\vartheta)+ky\sin\vartheta\end{pmatrix}$$

Ignoring Δxsinθ, Δysinθ ⇒

$$\begin{cases}B_x=ky\cos\vartheta+k(\Delta y\cos\vartheta)-B\sin\vartheta-kx\sin\vartheta\\B_y=(B+kx)\cos\vartheta-k(\Delta x\cos\vartheta)+ky\sin\vartheta\end{cases}$$

Combined horizontal dipole generated by Δx, θ

Vertical dipole generated by Δy, θ

Skew quadrupole generated by θ

Quadrupole

$$\begin{pmatrix}B_x\\B_y\end{pmatrix}=\begin{pmatrix}ky\\kx\end{pmatrix}\rightarrow\begin{pmatrix}B_x\\B_y\end{pmatrix}=\begin{pmatrix}\cos\vartheta & -\sin\vartheta\\ \sin\vartheta & \cos\vartheta\end{pmatrix}\begin{pmatrix}k(y+\Delta y)\\k(x+\Delta x)\end{pmatrix}=\begin{pmatrix}ky\cos\vartheta+k(\Delta y\cos\vartheta-\Delta x\sin\vartheta)-kx\sin\vartheta\\kx\cos\vartheta+k(\Delta y\sin\vartheta+\Delta x\cos\vartheta)+ky\sin\vartheta\end{pmatrix}$$

Ignoring Δxsinθ, Δysinθ ⇒

$$\begin{cases}B_x=ky\cos\vartheta+k\Delta y\cos\vartheta-kx\sin\vartheta\\B_y=kx\cos\vartheta+k\Delta x\cos\vartheta+ky\sin\vartheta\end{cases}$$

Orth. quadrupole generated by θ

Hor/ver dipole generated by Δx/Δy

Skew quadrupole generated by θ

Sextupole

$$\begin{pmatrix}B_x\\B_y\end{pmatrix}=\begin{pmatrix}kxy\\\frac{k}{2}(x^2-y^2)\end{pmatrix}\rightarrow\begin{pmatrix}B_x\\B_y\end{pmatrix}=\begin{pmatrix}\cos\vartheta & -\sin\vartheta\\ \sin\vartheta & \cos\vartheta\end{pmatrix}\begin{pmatrix}k(x+\Delta x)(y+\Delta y)\\\frac{k}{2}((x+\Delta x)^2-(y+\Delta y)^2)\end{pmatrix}$$

$$\begin{pmatrix}B_x\\B_y\end{pmatrix}=\begin{pmatrix}kxy\cos\vartheta+ky(\Delta y\sin\vartheta+\Delta x\cos\vartheta)+kx(\Delta y\cos\vartheta-\Delta x\sin\vartheta)-\frac{k}{2}(x^2-y^2)\sin\vartheta\\\frac{k}{2}(x^2-y^2)\cos\vartheta+kx(\Delta y\sin\vartheta+\Delta x\cos\vartheta)+ky(\Delta x\sin\vartheta-\Delta y\cos\vartheta)+kxy\sin\vartheta\end{pmatrix}$$

Ignoring Δxsinθ, Δysinθ, ΔxΔy, Δx^2, Δy^2 ⇒

$$\begin{cases}B_x=kxy\cos\vartheta+ky\Delta x\cos\vartheta+kx\Delta y\cos\vartheta-\frac{k}{2}(x^2-y^2)\sin\vartheta\\B_y=\frac{k}{2}(x^2-y^2)\cos\vartheta+kx\Delta x\cos\vartheta-ky\Delta y\cos\vartheta+kxy\sin\vartheta\end{cases}$$

Orth. sextupole generated by θ

Orth. quadrupole generated by Δx

Skew quadrupole generated by Δy

Skew sextupole generated by θ

Correctors installed

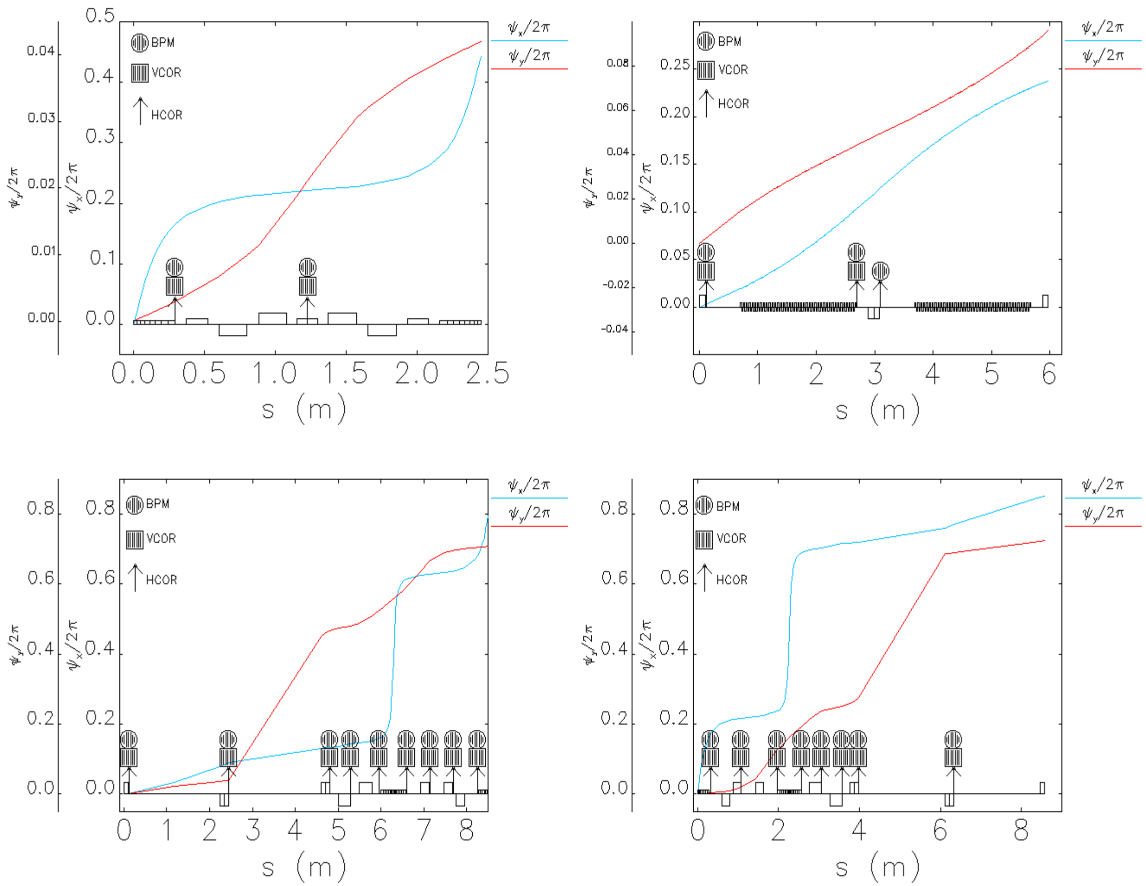
- 242 vertical; (84 per arc, 8 per DS-I, 9 per DS-II, 20 per LSS)
- 262 horizontal; (84 per arc, 8 per DS-I, 9 per DS-II, 30 per LSS)

Monitors installed

- 262 BPM; (84 per arc, 8 per DS-I, 9 per DS-II, 30 per LSS)

Skew quads

- 2 sextupole families in the arcs
- Skew quads installed as windings in the sextupoles.



Correction method – response matrix

Variation of the orbit and the vertical dispersion at the BPM resulting from the corrector kick or skew strength can be written in matrix formalism;

$$\begin{bmatrix} \Delta U_1 \\ \Delta U_2 \\ \Delta U_3 \\ . \\ . \\ . \\ \Delta U_n \end{bmatrix} = R_{n.m} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ . \\ . \\ . \\ V_m \end{bmatrix}$$

This is the response of the orbit and the vertical dispersion measured at BPMs due to a unit change in the strength of correctors and skew quads. "n" is the number of BPMs and "m" indicates number of correctors or skew quads.

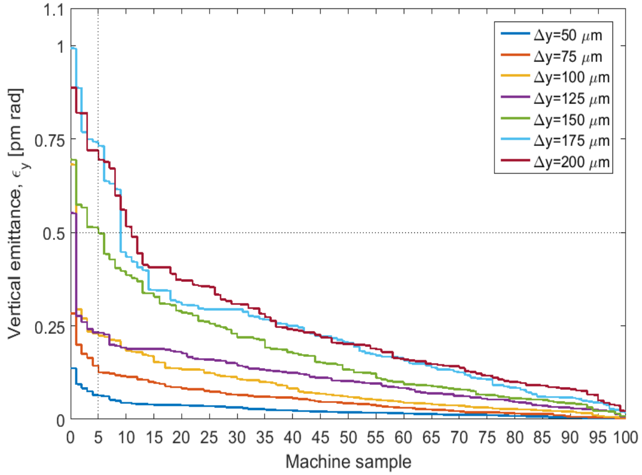
Feed alignment error

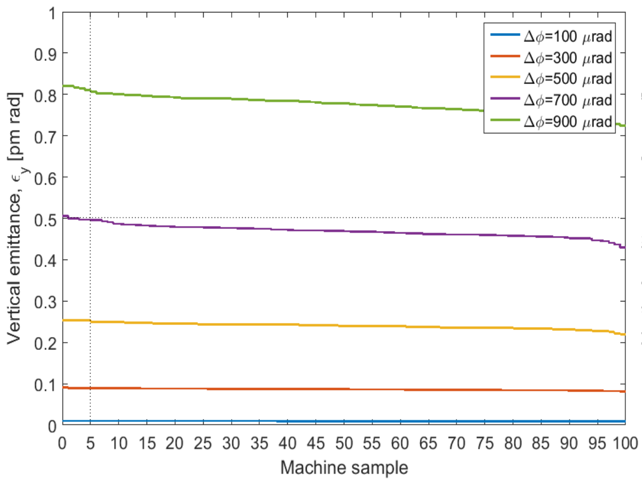
$$U_{Meas.} + R.V = 0$$

$$V = R^{-1}(-U_{Meas.})$$

Vertical offset and roll- Accumulated histograms

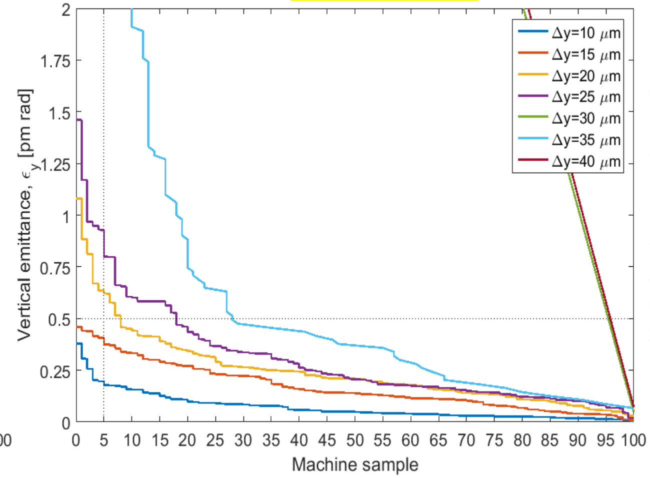
Dipole

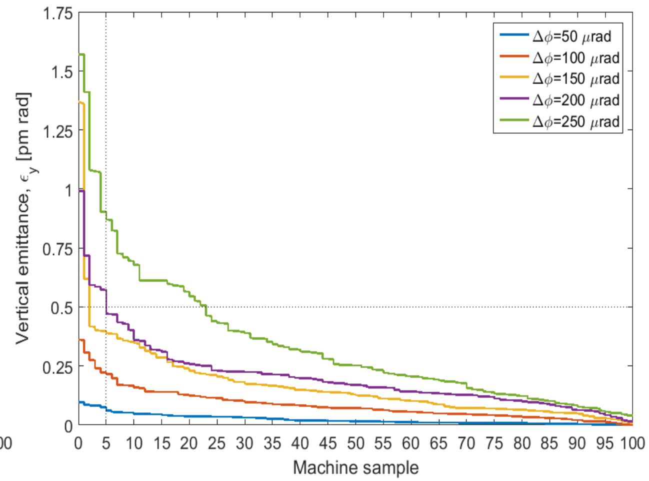




- For the case of Δy=150 μm, ϵ_y is larger than 0.5 pm only for 5 machine samples.
- Dipole roll up to 0.7 mrad is tolerable.

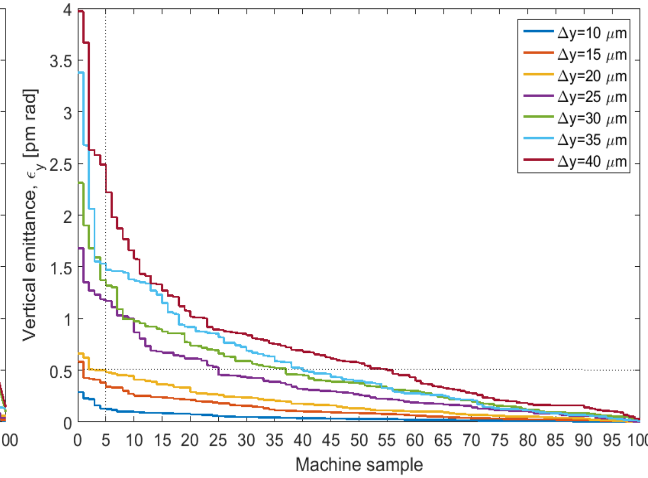
Quadrupole

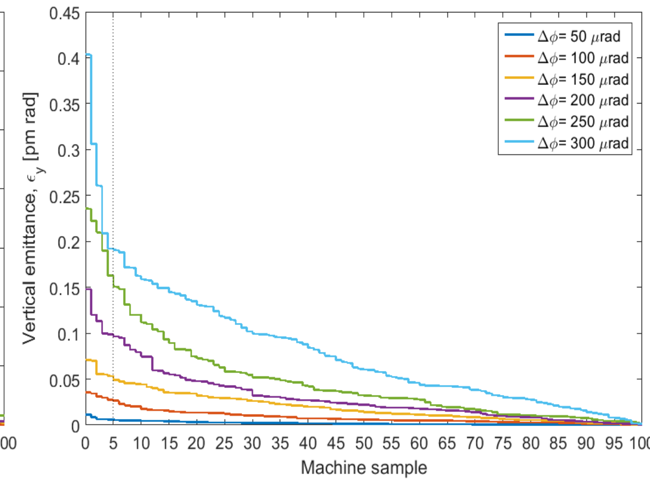




- ϵ_y is very sensitive to misalignment of quads and to be in goal ϵ_y region, vertical offset of them must be kept in ±15 μm range.
- ±100 μrad corresponding to ϵ_y < 0.5 pm for 100 machine samples can be achievable with present day alignment techniques.

Sextupole

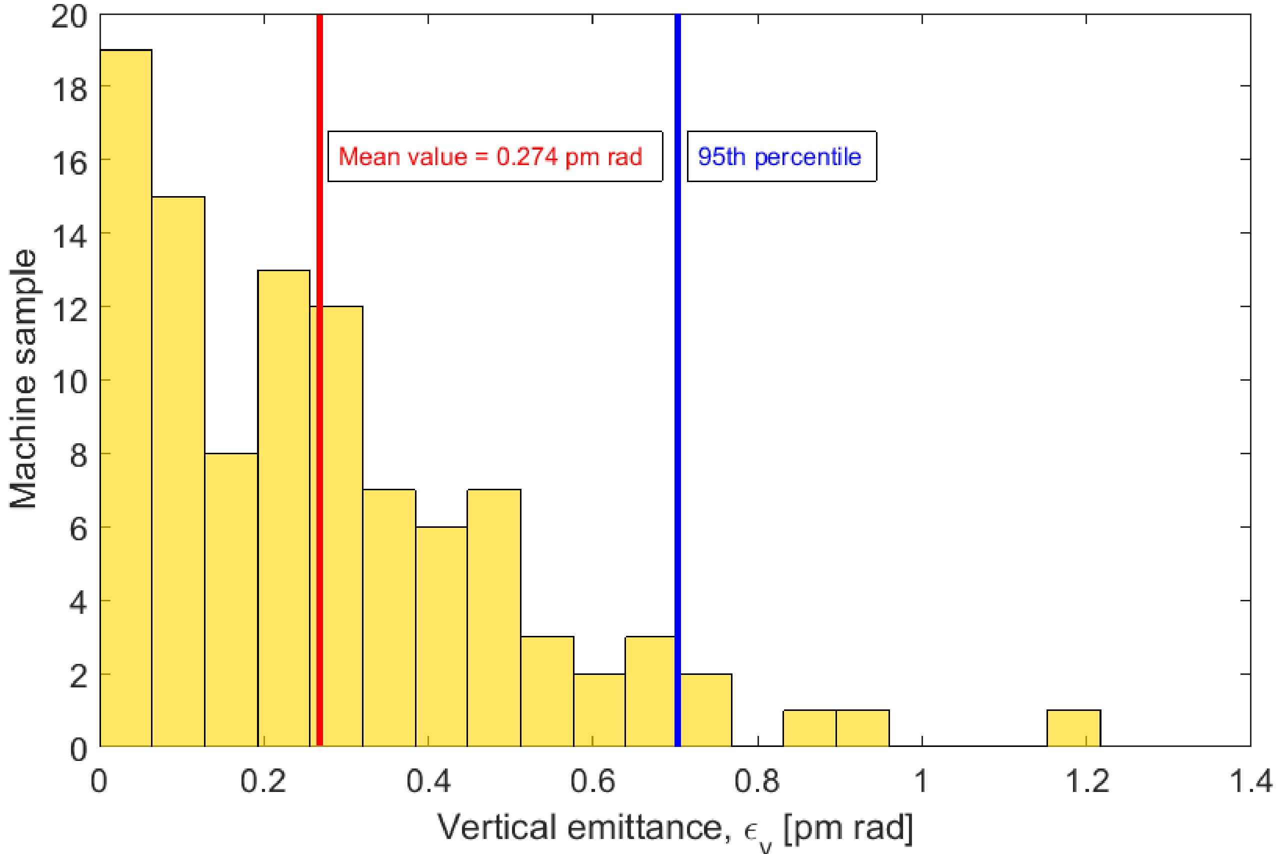




- ϵ_y is very sensitive to misalignment of sexts. For 100 machine samples ϵ_y < 1 pm rad due to sext. vertical offset up to 20 μm.
- Up to 300 μrad, ϵ_y is in the goal region for the 100 machine samples.

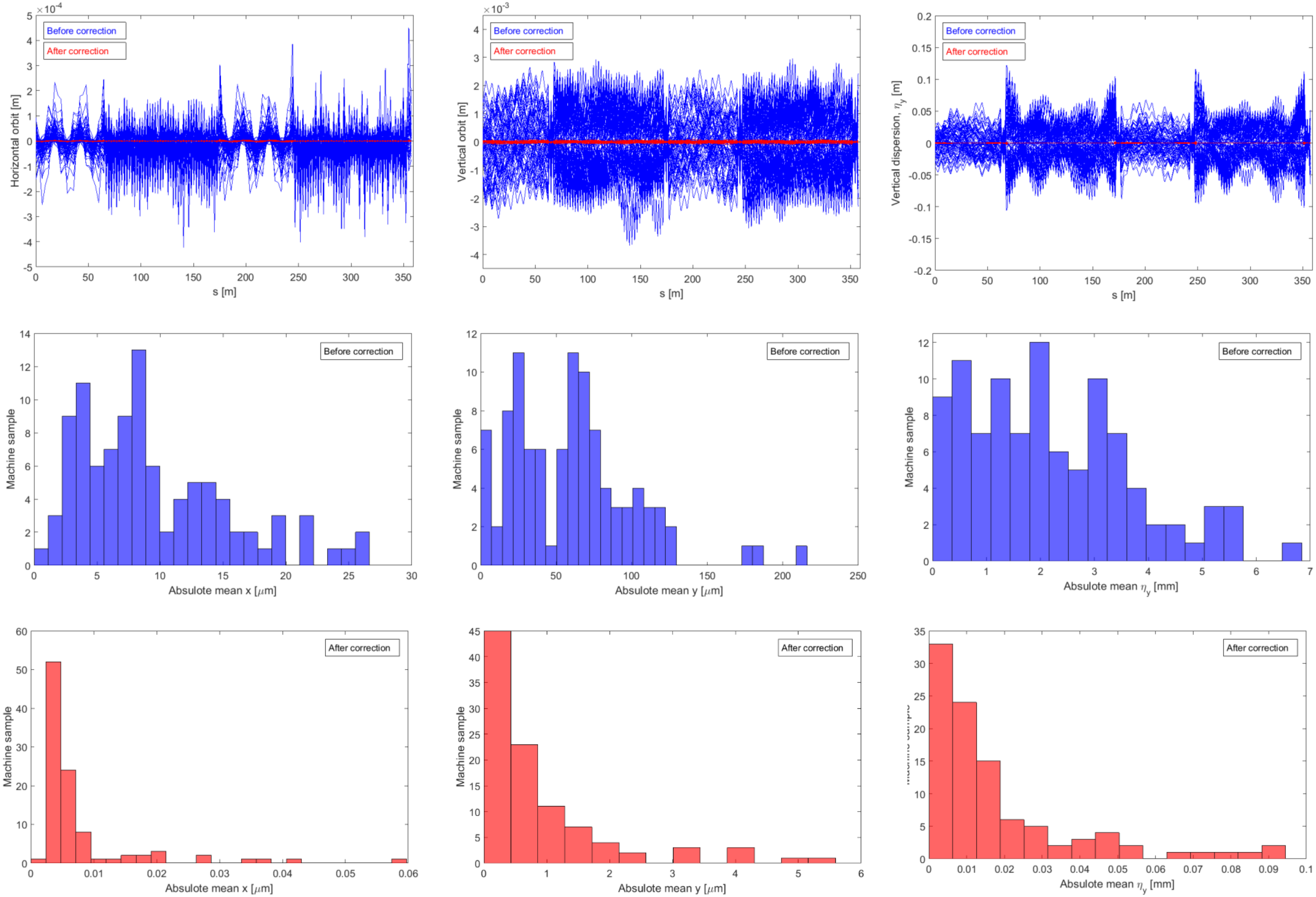
Vertical emittance

Error	Unit	Value
Dipole/quadrupole/sextupole/BPM vertical misalignment	µm	35/20/20/50
Dipole/quadrupole/sextupole roll	µrad	80/50/50
BPM roll	µrad	50
BPM noise	nm	200

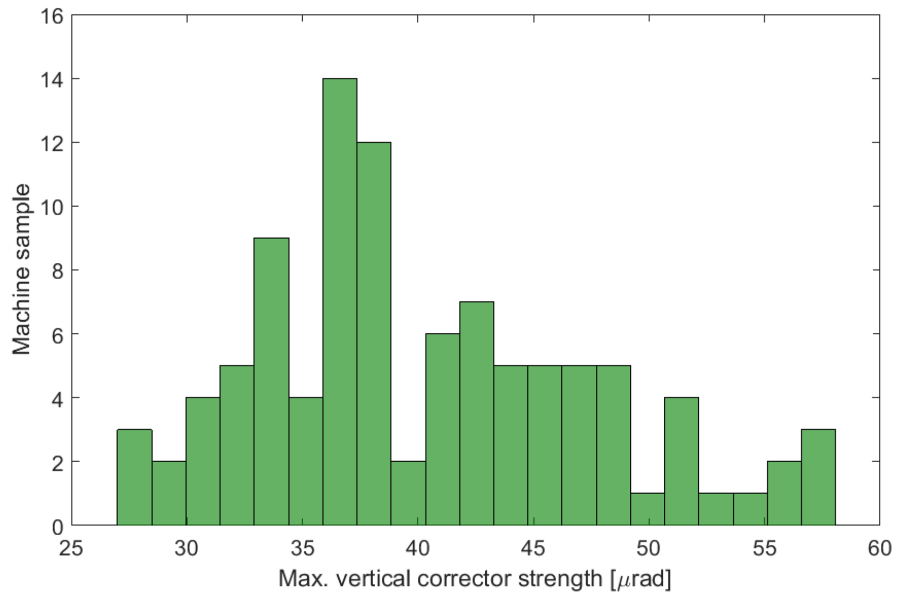


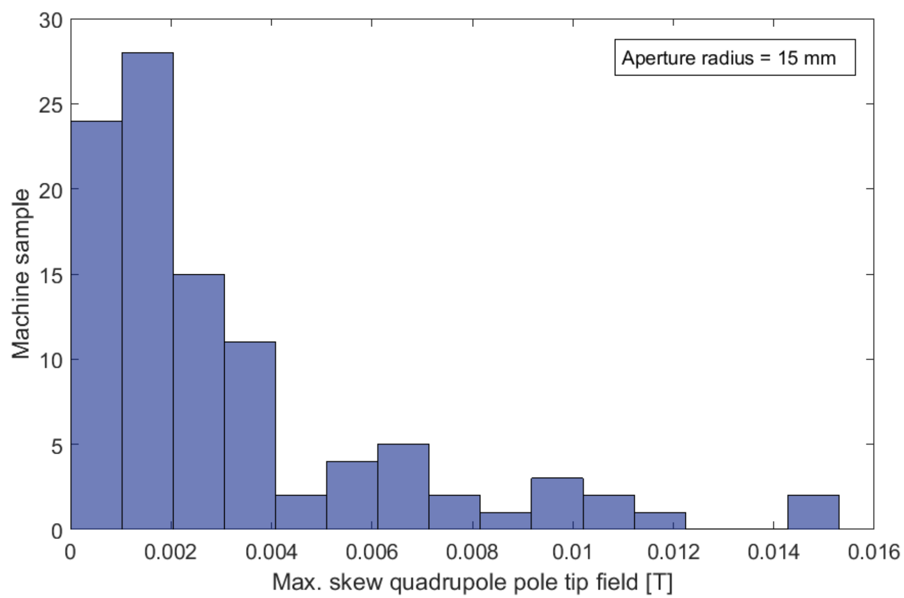
For 95% of machine samples,
vertical emittance is below than 0.7 pm rad.

Closed orbit & vertical dispersion

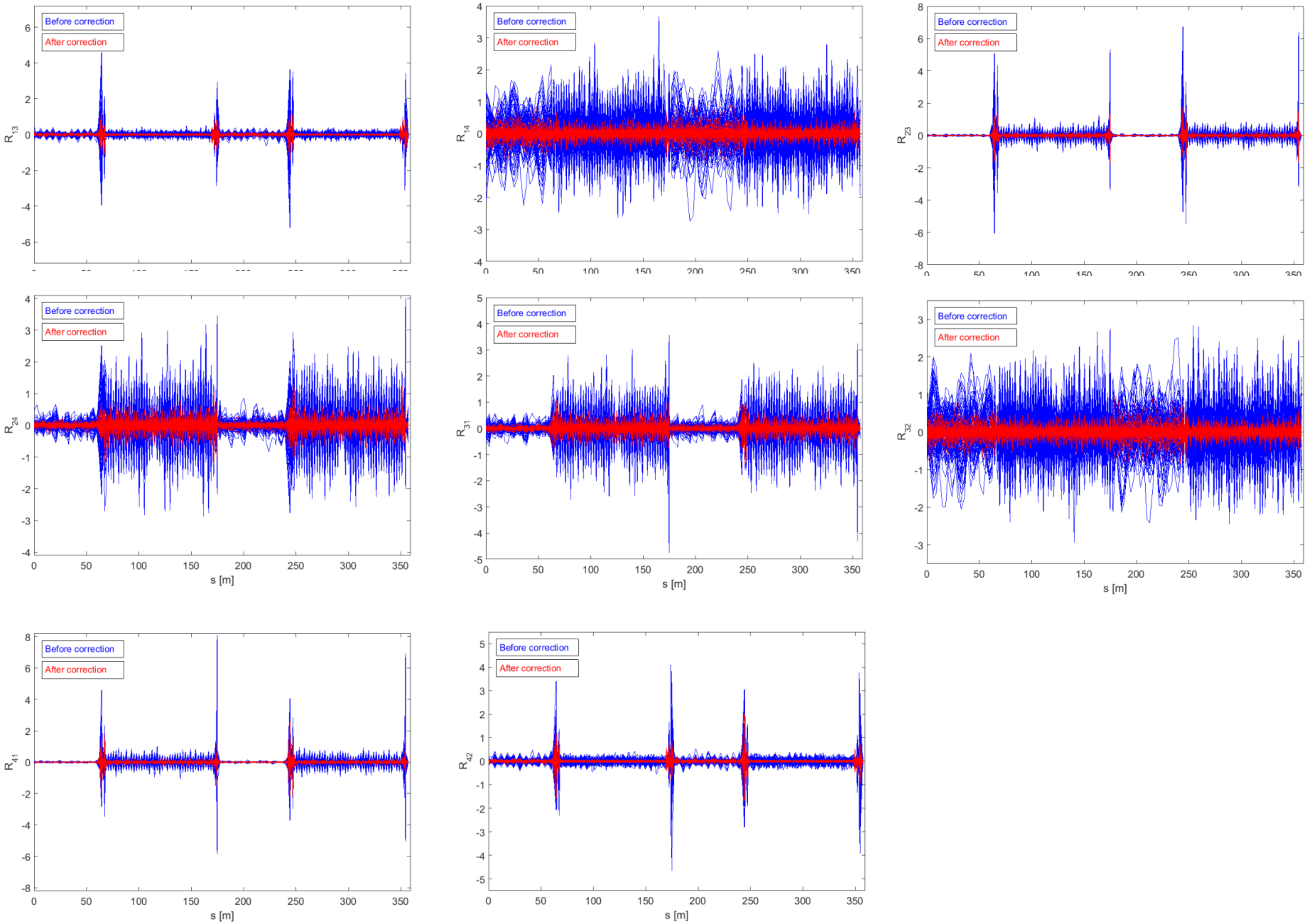


Corrector's strength



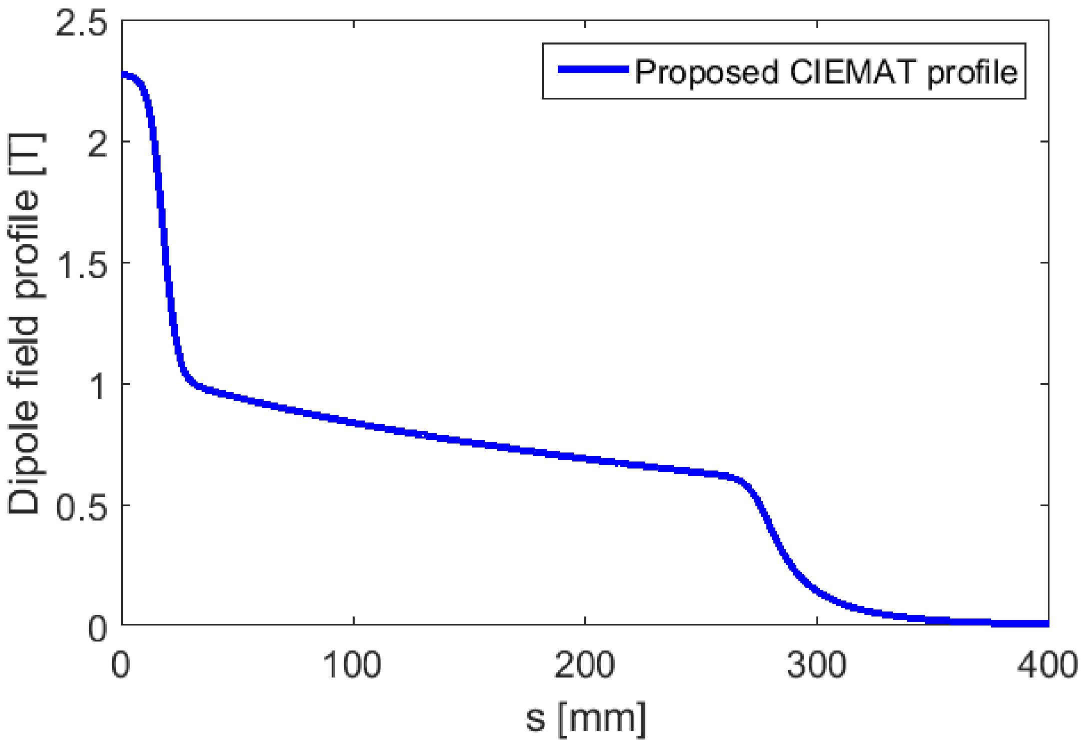


Coupling coefficients



CIEMAT variable bend new proposal

- The dipole is fully designed by CIEMAT.
- This dipole field is between the step and trapezium profiles.
- The magnetic field of 2.3 T is reached at the center of dipole.
- Efforts have been done to apply this profile for the CLIC damping ring in MADX.



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Thank you
for your
attention!