Low ε tuning and Non-linear dynamics for CLIC DR

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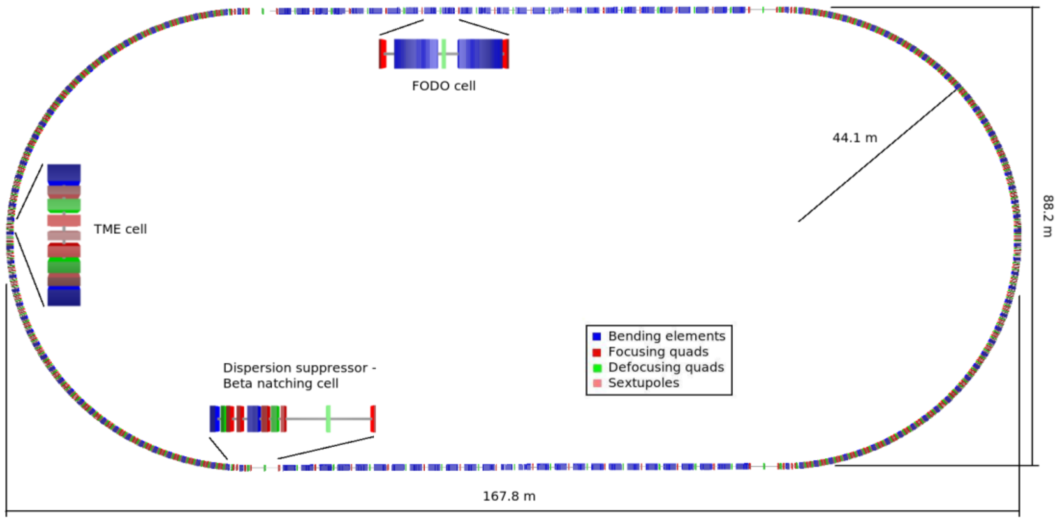
GOAL:

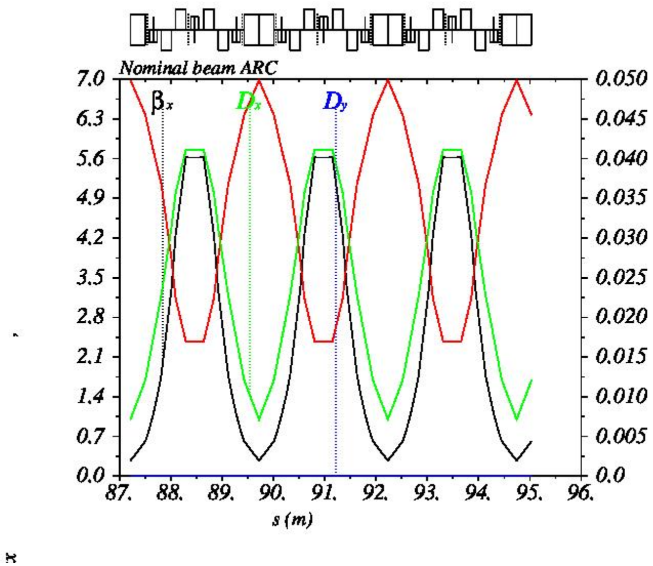
- Define a tuning procedure to bring the vertical emittance to the design value ($\varepsilon_y < 1\, pm \cdot rad$ to allow for IBS growth) under a misaligned lattice.
- Identify the alignment tolerances.
- Study non-linear behaviour of the lattice.

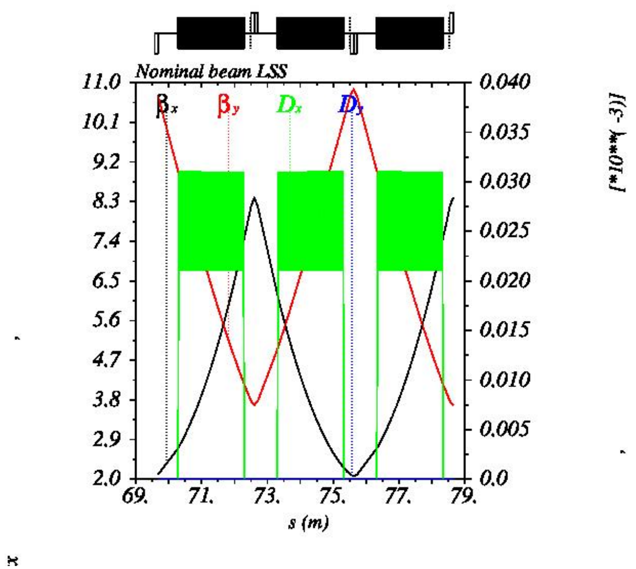
<u>OUTLINE</u>:

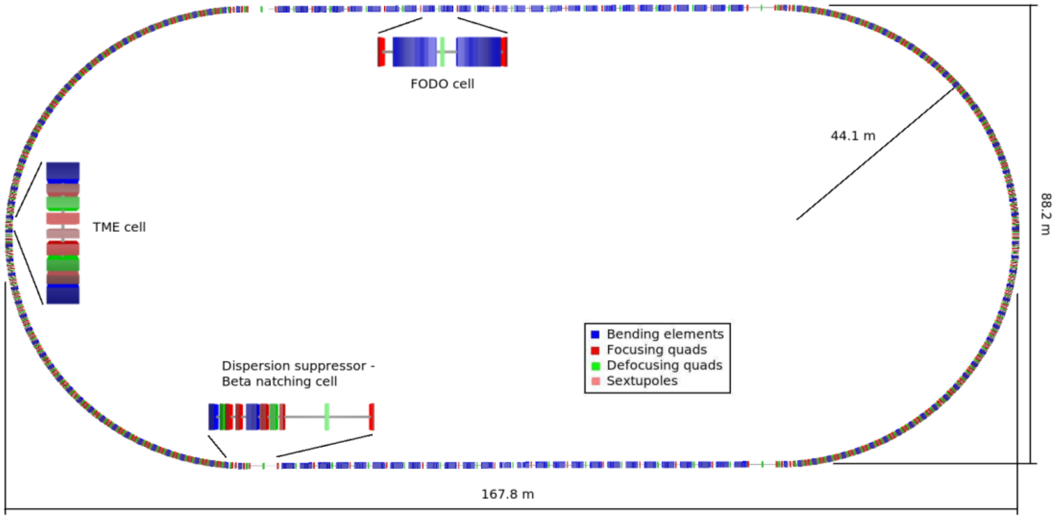
- Low Emittance tuning
  - Effect of misalignments
  - Closed orbit correction
  - Coupling and dispersion correction
- Adding BPM resolution
- Tolerances
- Dynamic aperture
  - Impact of Synchrotron Radiation in DA
- Frequency Maps



Parameter	Symbol	Value
Energy	E [GeV]	2.86
Circumference	C [m]	427.5
Bunch population	$N_b[10^9]$	4.1
Hor. Norm. Emittance	$\varepsilon_{x,n}$[nm·rad]	456
Ver. Norm. Emittance	$\varepsilon_{y,n}$[nm·rad]	4.8
Horizontal Tune	Q_x	48.34
Vertical Tune	Q_y	16.39







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- 100 TME arc cells
  - Small defocusing gradient dipoles
- LSS
  - 52 SC damping wigglers
- DS and beta matching cells
- Steady-state emittance dominated by IBS due to high bunch charge and small size in 3 dimensions

- Quads powered individually.
- Correctors installed:
  - 320 vertical:
    - 141 per arc, 3 per Dispersion Suppressor, 13 per LSS
  - 312 horizontal:
    - 141 per arc, 1 per Dispersion Suppressor, 13 per LSS
- Monitors installed:
  - 358 vertical&horizontal:
    - 141 per arc, 6 per Dispersion Suppressor, 26 per LSS
- 2 sextupole families in the arcs.
- Skew quads installed as windings in the sextupoles.

Low emittance tuning simulations

- Nominal lattice with PDR beam ← $\varepsilon_y = 316\, pm \cdot rad$
- Equilibrium emittance ← $\varepsilon_y = 10^{-37} m \cdot rad$ (zero current)
- Feed misalignments
- H&V CO correction
- Coupling and Dispersion correction
- RF Matching
- Chromaticity correction
- Measure equilibrium emittance

Tuning algorithm (H&V CO correction, Coupling and Dispersion correction, RF Matching, Chromaticity correction)

Simulations done in MADX

Low emittance tuning simulations

- Nominal lattice with PDR beam ← $\varepsilon_y = 316\ pm \cdot rad$
- Equilibrium emittance ← $\varepsilon_y = 10^{-37} m \cdot rad$ (zero current)
- **<u>Feed misalignments</u>**
- H&V CO correction
- Coupling and Dispersion correction
- RF Matching
- Chromaticity correction
- Measure equilibrium emittance

(H&V CO correction, Coupling and Dispersion correction, RF Matching, Chromaticity correction: **Tuning algorithm**)

Simulations done in MADX

- **Quadrupole vertical off-set (QV)**

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

ortogonal quad + constant term (vertical dipole)

- **Quadrupole roll (QR)**

$$\begin{pmatrix} B_x \\ B_y \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} ky \\ kx \end{pmatrix} = \begin{pmatrix} ky\cos\theta - \underline{kx\sin}\theta \\ kx\cos\theta + \underline{ky\sin}\theta \end{pmatrix}$$

ortogonal quad + skew quadrupole

- **Dipole roll (DR)**

$$\begin{pmatrix} B_x \\ B_y \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 0 \\ B \end{pmatrix} = \begin{pmatrix} -\underline{B\sin}\theta \\ B\cos\theta \end{pmatrix}$$

horizontal dipole + vertical dipole

- **Sextupole vertical off-set (SV)**

$$B_x = kx(y+\Delta y) = kxy + \underline{kx\Delta y}$$
$$B_y = k(x^2 - (y+\Delta y)^2) = k(x^2 - y^2) - 2\underline{ky\Delta y} - (\Delta y^2)$$

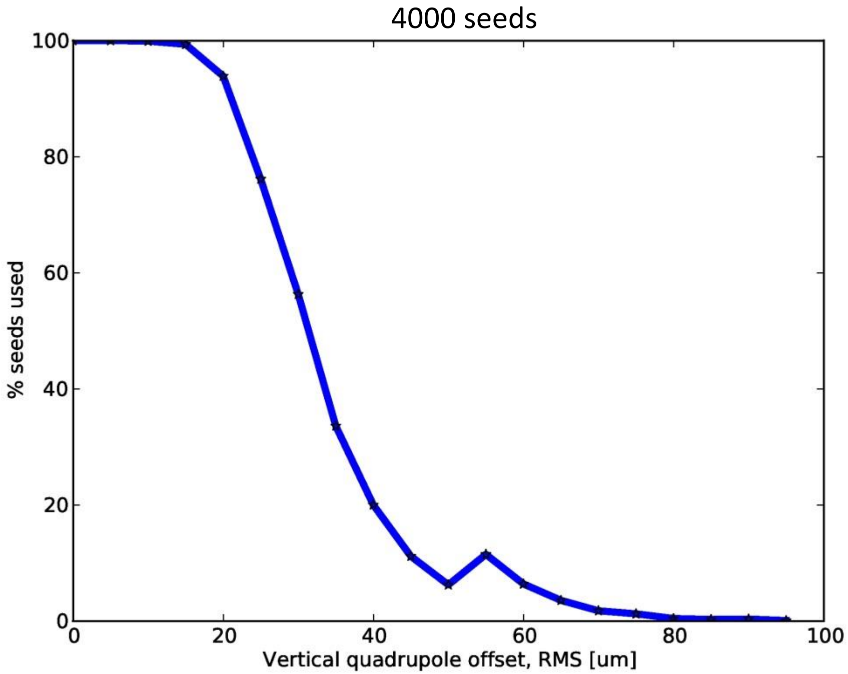
ortogonal sextupole + skew quadrupole

Mainly emittance grows through:

Betatron coupling
: Directly generated and vertical non-zero closed orbit [through sexts]

Vertical dispersion
: Directly generated and vertical non-zero closed orbit [through quads]

- Apply gaussian distributions truncated at 2.5 sigma.
- Lattice too sensible to ARC quadrupole offsets (LSS quads offsets have no influence on sensibility)
- MADX Twiss calculation fails after applying misalignments.



- **For quadrupole misalignments divide the error** in 7 parts **and apply them gradually**, correcting *x* and *y* CO each step.

Low emittance tuning simulations

- Nominal lattice with PDR beam ← $\varepsilon_y = 316\ pm \cdot rad$
- Equilibrium emittance ← $\varepsilon_y = 10^{-37} m \cdot rad$ (zero current)
- Feed misalignments
- **H&V CO correction**
- Coupling and Dispersion correction
- RF Matching
- Chromaticity correction
- Measure equilibrium emittance

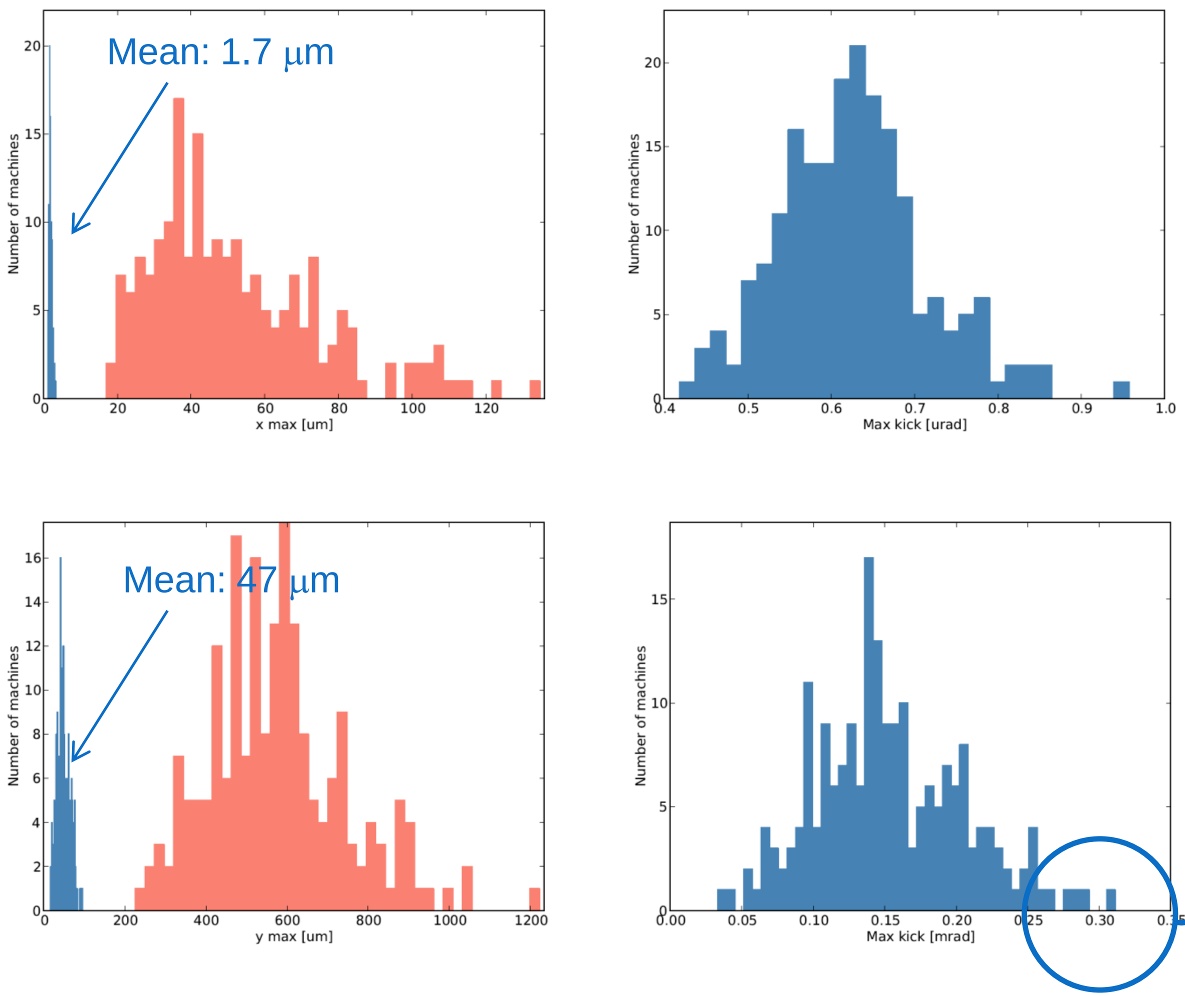
(H&V CO correction, Coupling and Dispersion correction, RF Matching, Chromaticity correction:) **Tuning algorithm**

Simulations done in MADX

Max CO **Max kick**

x

y



- 200 seeds
- 45 μm for QV
- 345 μrad for QR
- 450 μrad for DR
- 195 μm for SV
- MADX SVD algorithm
- ~350 correctors/plane (15cm long)
- ~300 BPMs

Max kick = 0.02T

Low emittance tuning simulations

- Nominal lattice with PDR beam ← $\varepsilon_y = 316\, pm \cdot rad$
- Equilibrium emittance ← $\varepsilon_y = 10^{-37} m \cdot rad$ (zero current)
- Feed misalignments
- H&V CO correction
- **<u>Coupling and Dispersion correction</u>**
- RF Matching
- Chromaticity correction
- Measure equilibrium emittance

(H&V CO correction, Coupling and Dispersion correction, RF Matching, Chromaticity correction:) **Tuning algorithm**

Simulations done in MADX

Coupling and Dispersion correction – Tuning algorithm

- **Previously**, the correction canceled dispersion and x-y coupling term of the one turn transfer matrix.
    - x-y coupling term was taken directly from MADX, not realistic.
    - To introduce BPM resolution had to simulate the whole transfer matrix measurement.
- **Now**, build response matrix relating skew strengths with:
    - Dispersion at each BPM (D)
    - Change in vertical position at each BPM when beam is horizontally excited by a specific kicker (C).

$$\begin{pmatrix} & & \Delta\eta_y \\ w & \cdot & \Delta y \end{pmatrix} = \begin{pmatrix} & & D \\ w & \cdot & C \end{pmatrix} (k_{skew})$$

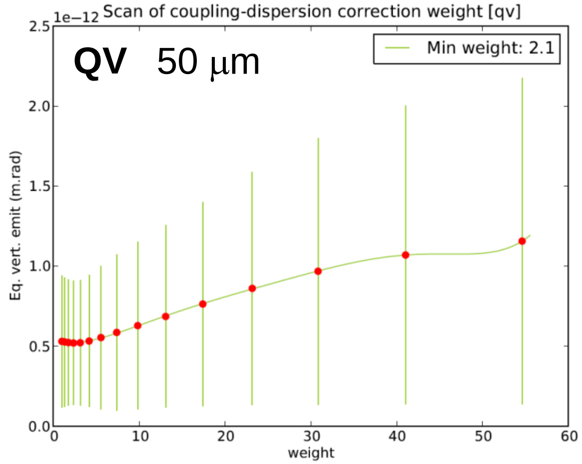
- Pseudoinvert the response matrix to calculate the skew corrections to be applied from the BPM readings.
- If BPM resolution is present:
    - Apply directly to C matrix.
    - Experimentally dispersion is measured as $D_y = \frac{\Delta y}{\Delta(\frac{\Delta E}{E})}$ then $\sigma_{D_y} = f(\frac{\Delta E}{E})$

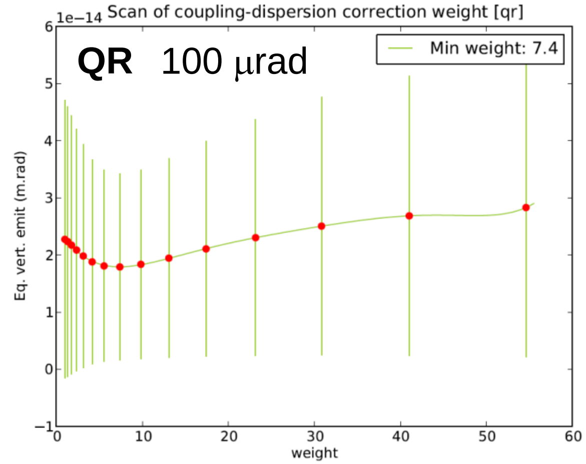
Assume an energy scan equal ±8 times the beam energy spread (as in ATF DR): 16e-3

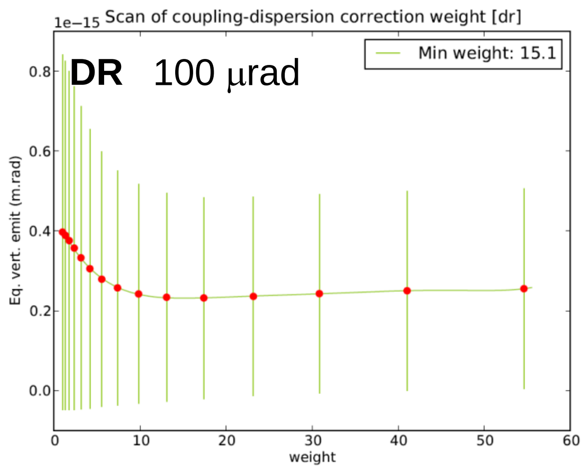
Coupling and Dispersion correction – Tuning algorithm

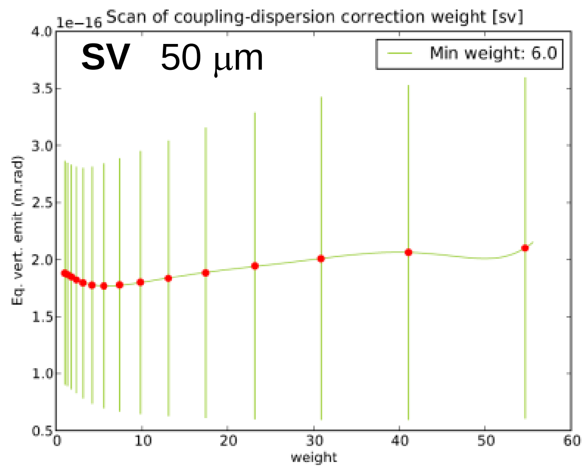
Scan of the algorithm weight

$$\begin{pmatrix} & & \Delta\eta_y \\ w & \cdot & \Delta y \end{pmatrix} = \begin{pmatrix} & & D \\ w & \cdot & C \end{pmatrix} (k_{skew})$$









- 25 seeds per weight value

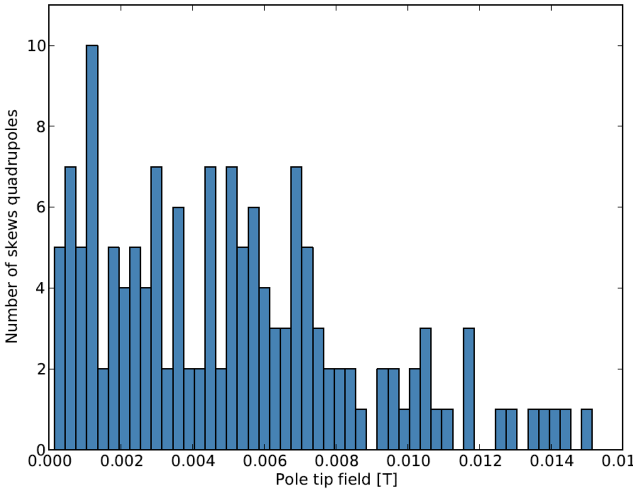
Chosen *w* = 2.1

because lattice most sensible to QV

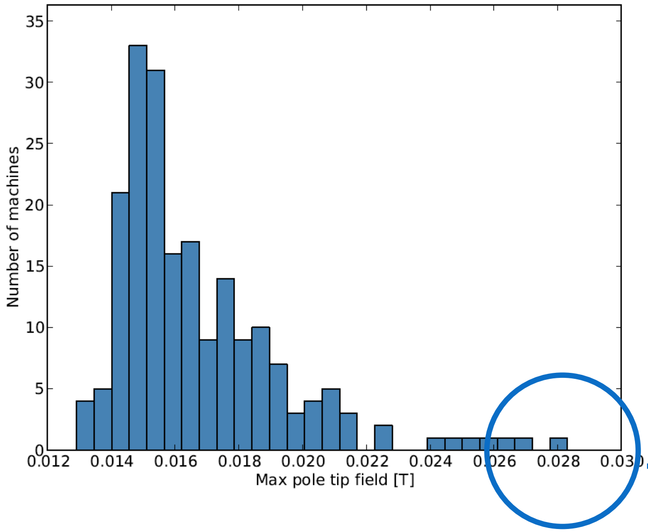
Scan of the algorithm weight

$$\begin{pmatrix} & \Delta\eta_y \\ w \cdot & \Delta y \end{pmatrix} = \begin{pmatrix} & D \\ w \cdot & C \end{pmatrix} (k_{skew})$$

1 seed distribution



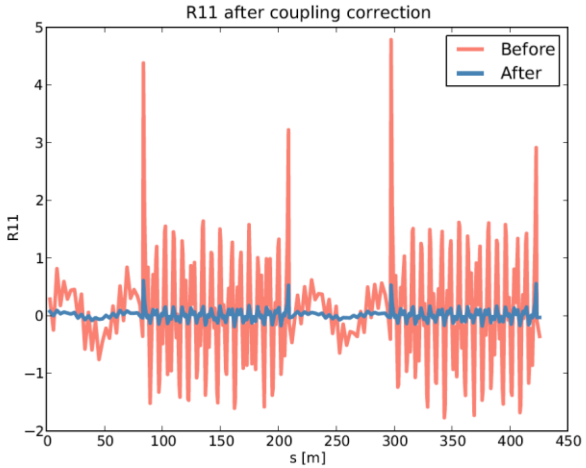
Max skew strenght over 200 seeds

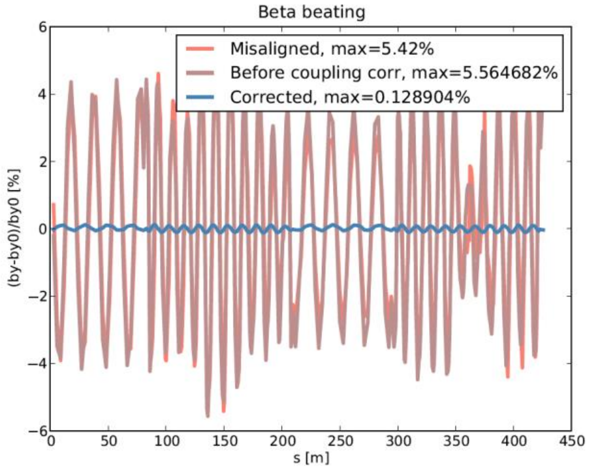


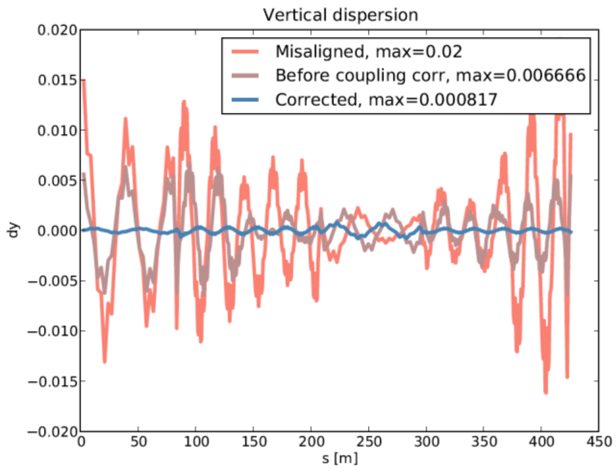
- 45 μm for QV
- 345 μrad for QR
- 450 μrad for DR
- 195 μm for SV

Max pole tip field = 0.03 T (for a 20mm aperture)

Coupling and Dispersion correction – Tuning algorithm







Example of correction

1 seed

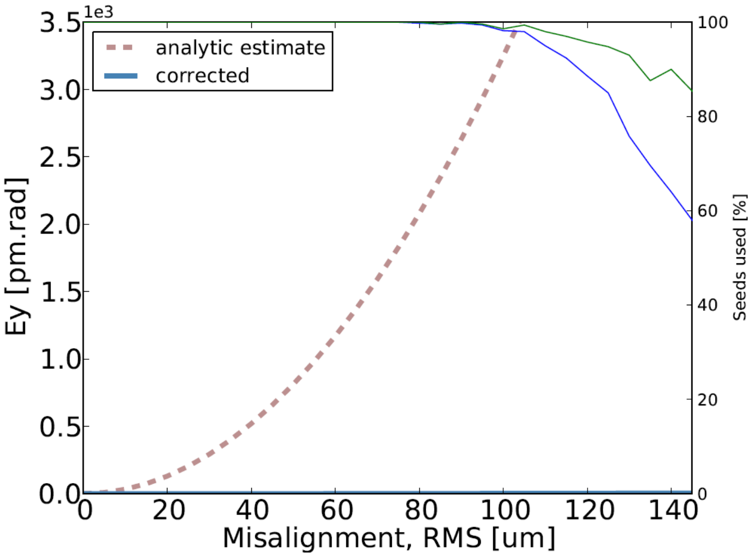
QV(rms) = 45 μm
QR(rms) = 345 μrad
DR(rms) = 495 μrad
SV(rms) = 195 μm

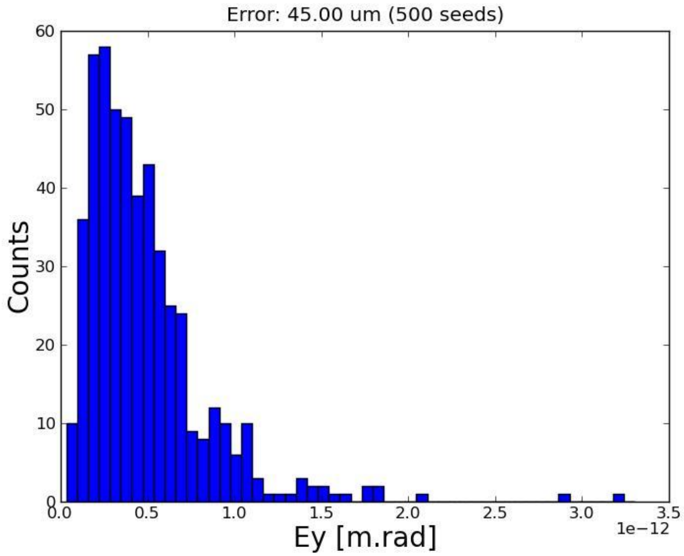
(tolerance values, next slides)

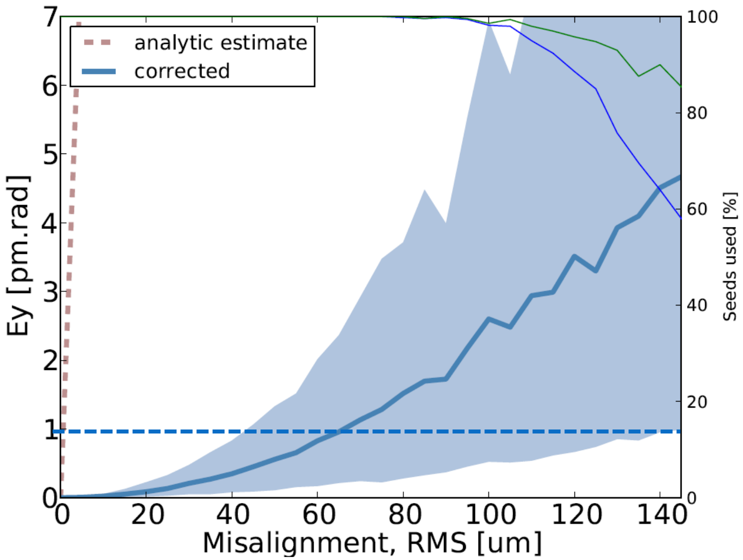
Low emittance tuning simulations

- Nominal lattice with PDR beam
- Equilibrium emittance
- Feed misalignments
- H&V CO correcion
- Coupling and Dispersion correction
- **RF Matching** ← 1 RF cavity situated just after a LSS
- **Chromaticity correction** ← Two sextupole families in TME cells, LMDIF algorithm
- **Measure equilibrium emittance** ← Target → $\varepsilon_y < 1\ pm \cdot rad$

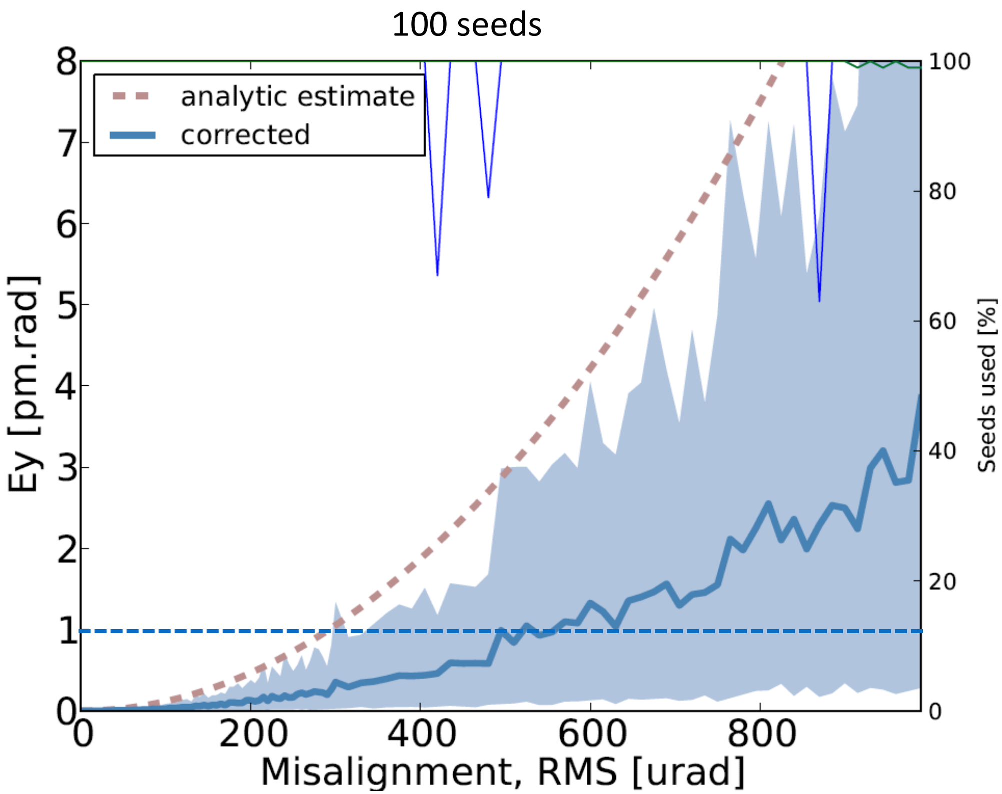
500 seeds

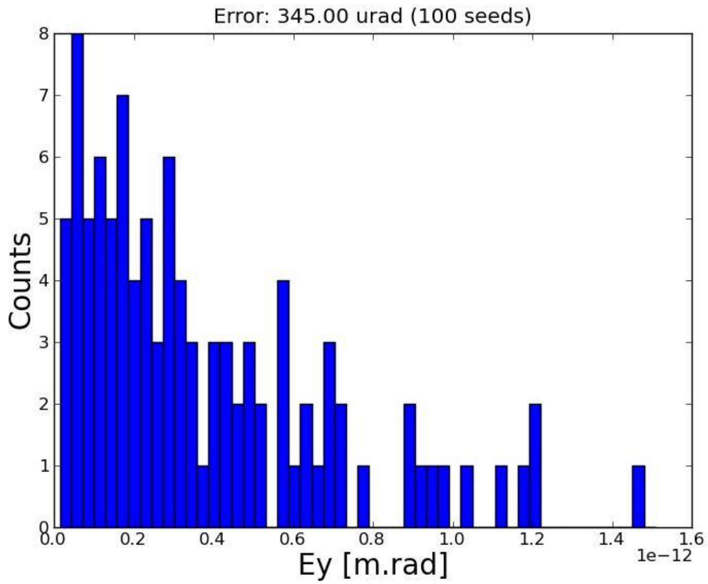




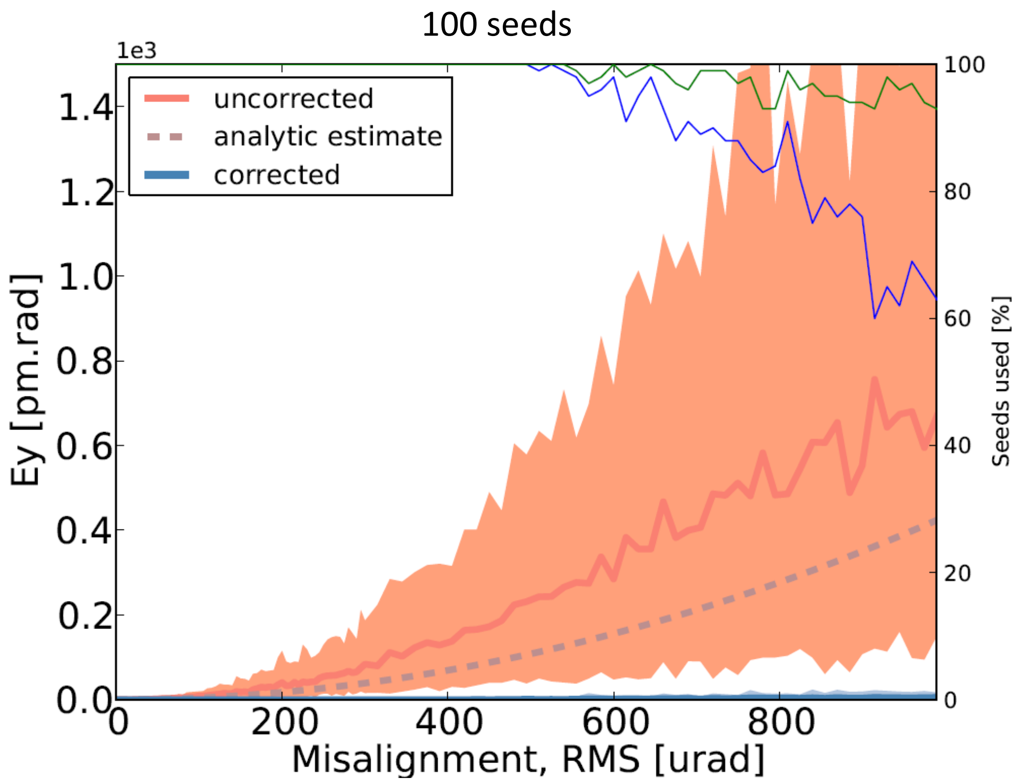


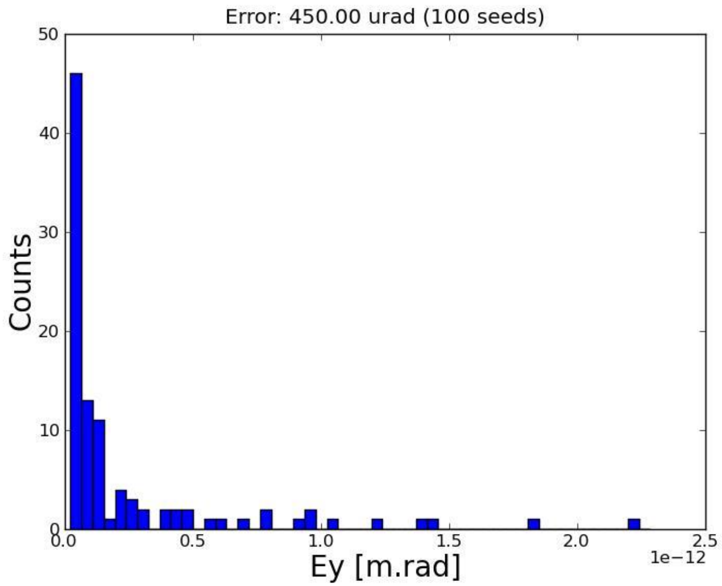
$$\Delta Y_{RMS}(95\%\ \varepsilon_y < 1pm \cdot rad) = 45\mu m$$



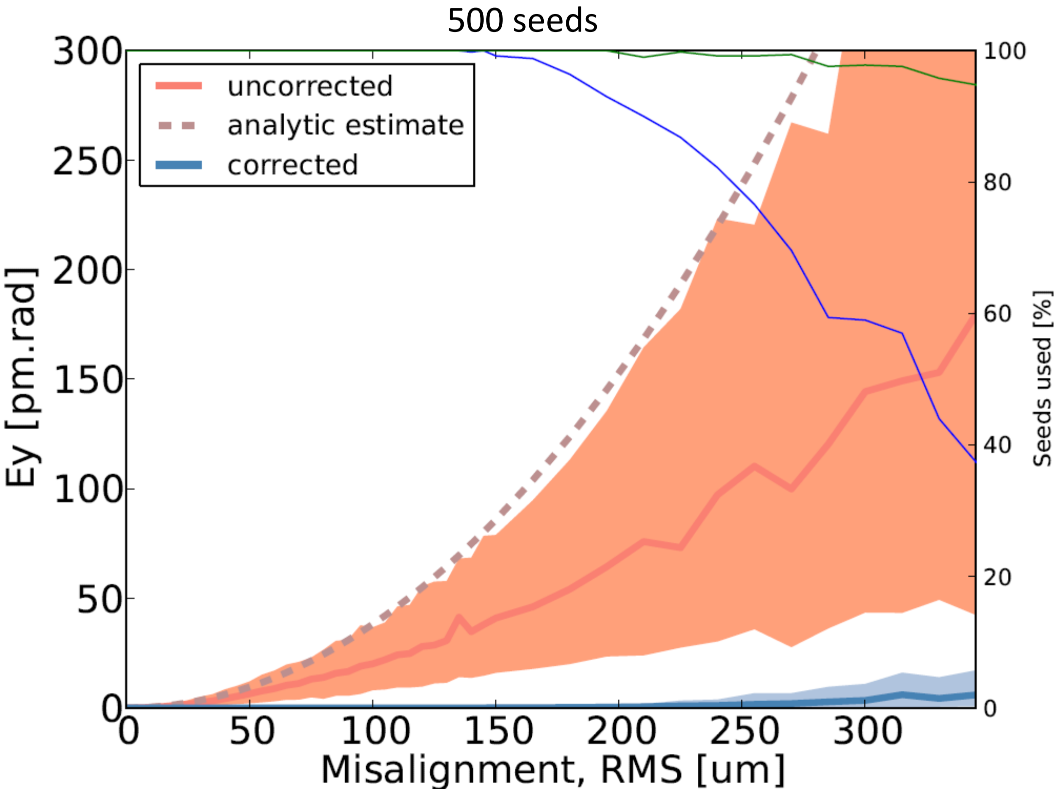


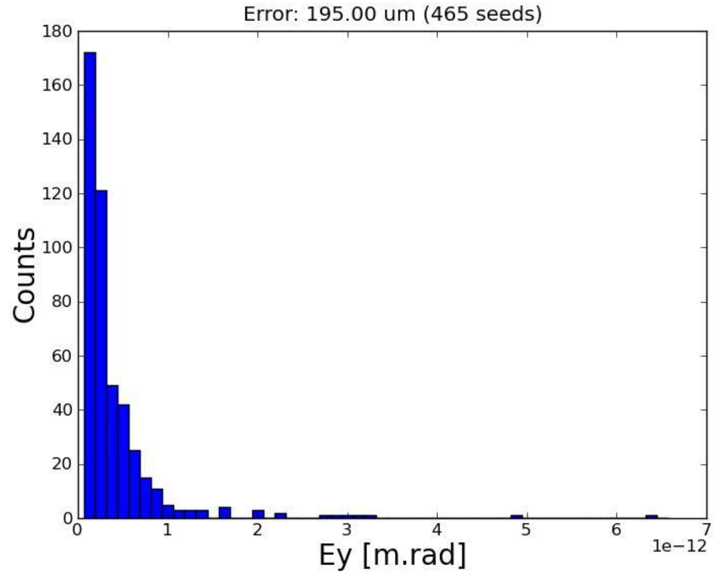
$$\Delta\theta_{RMS}(95\% \ \varepsilon_y < 1pm \cdot rad) = 345\mu rad$$



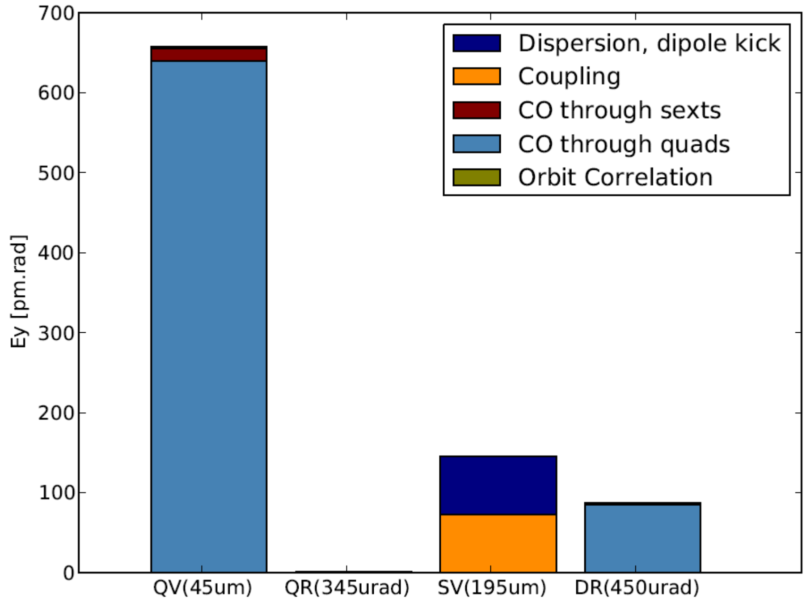


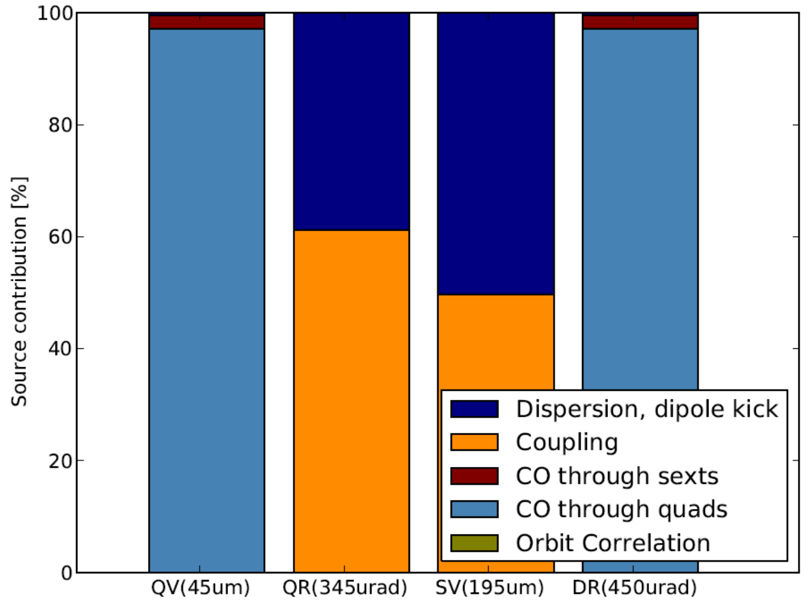
$$\Delta\theta_{RMS}(95\%\ \varepsilon_y < 1pm \cdot rad) = 450\mu rad$$





$$\Delta Y_{RMS}\left(95\%\ \varepsilon_y < 1pm \cdot rad\right) = 195\mu m$$

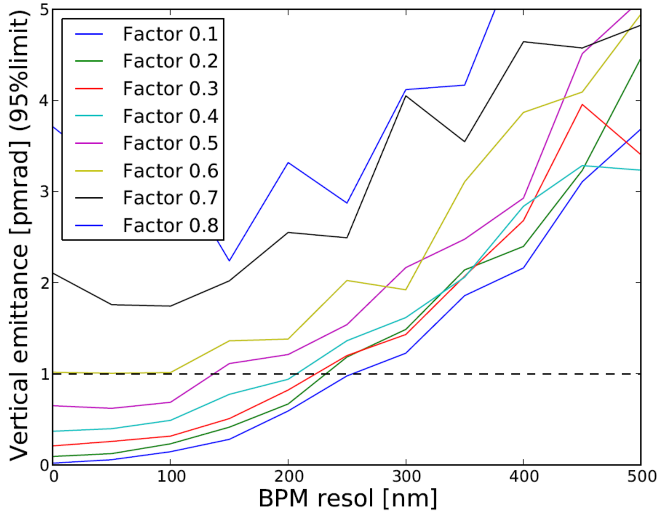


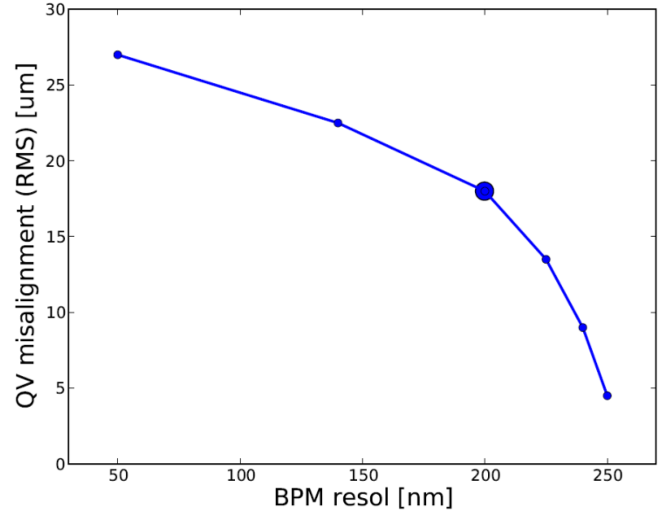


Contribution of different emittance growth sources, for RMS $45\mu m$ (QV), $345\ \mu rad$ (QR), $195\mu m$ (SV), $450\ \mu rad$ (DR).

Following SLAC-PUB-4937 [T. Raubenheimer]

Adding BPM resolution

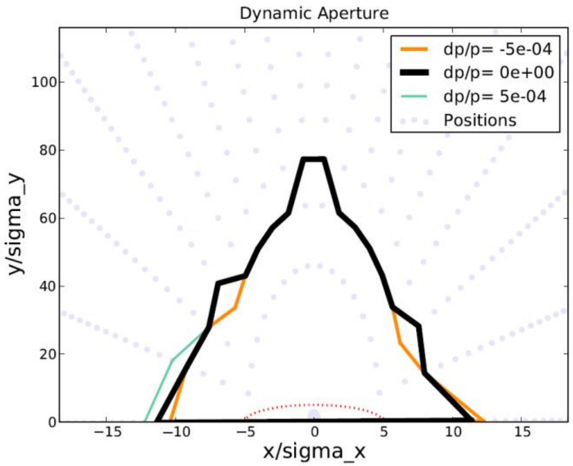




- Feed all misalignments together at found tolerances multipled by a factor.
- Scan this factor from 0 to 1 (for 200 seeds) and calculate the tolerance to BPM resolution as previously
- Choose a compromise between BPM resolution and QV misaligment (the tightest one)

Tolerances $(95\%\ \varepsilon_y < 1pm \cdot rad)$		
Quadrupole Vertical Offset	18	µm
Quadrupole Roll	138	µrad
Dipole Roll	180	µrad
Sextupole Vertical Offset	78	µm
BPM resolution	200	nm

- Dynamic aperture: Region of the transverse space where tracked particles survive a given number of turns (1056 here).

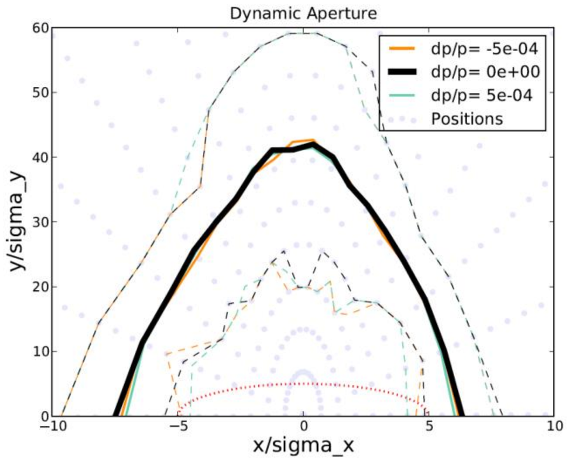


No error

DA:
10 σ_x
80 σ_y

At injection:

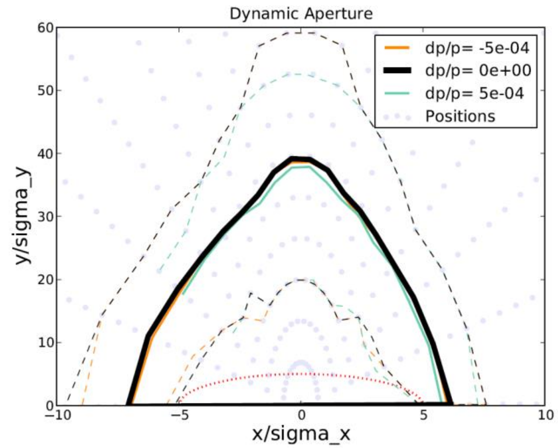
$$\sigma_x = 330\mu m$$
$$\sigma_y = 34\mu m$$



200 seeds

QV(rms) = 18 μm
QR(rms) = 138 μrad
DR(rms) = 180 μrad
SV(rms) = 78 μm
No BPM resolution

DA (95% of lattices):
>5 σ_x
>40 σ_y



200 seeds

QV(rms) = 18 μm
QR(rms) = 138 μrad
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SV(rms) = 78 μm
BPM resolution = 200nm

DA (95% of lattices):
>5 σ_x
>40 σ_y

Typically in a DR, radiation effects are slow compared to revolution frequency.

In CLIC DR:

Revolution period $T_0 = 1.4\ \mu s$
Horizontal damping time $\tau = 2\ ms$
} One damping time is 1400 turns

Simplified simulations:

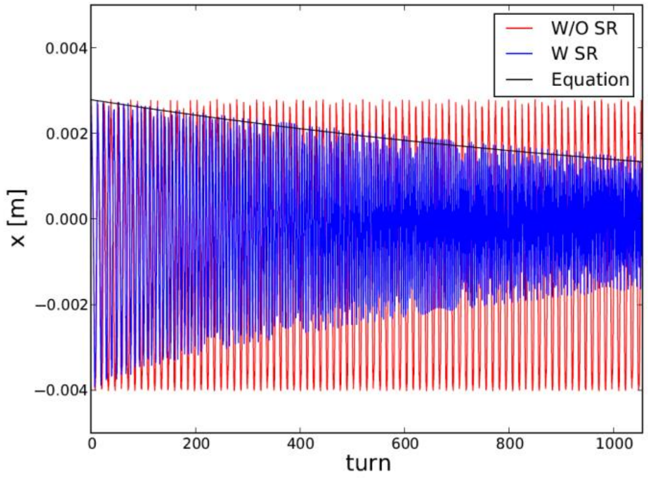
To avoid going into MADX tracking code:

Perform 1-turn tracking using exit coordinates as an input of next 1-turn tracking.

$$\varepsilon(t) = \varepsilon_0 e^{-2^{t}/\tau}$$

$$x \propto \sqrt{\varepsilon} \rightarrow \frac{x_2}{x_1} \sim \sqrt{e^{-2^{T_0}/\tau}} = 0.999303$$

Multiply position and angle by a damping factor at the end of each whole turn.



Since MADX needs to reload the tracking environment, the simulations become extremely slow and takes near a factor 1056 (number of turns) in running time. Lower the factor by taking the non SR DA and tracking from it.

Impact of Synchrotron Radiation in DA

Typically in a DR, radiation effects are slow compared to revolution frequency.

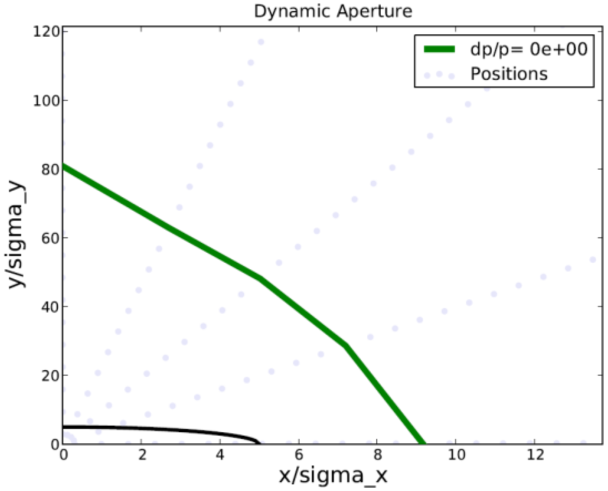
In CLIC DR:

Revolution period $T_0 = 1.4\ \mu s$
Horizontal damping time $\tau = 2\ ms$

One damping time is 1400 turns

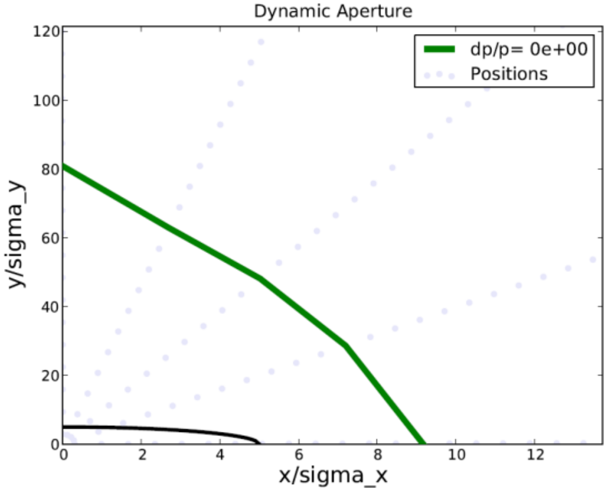
Simplified simulations:

No SR



Couple of hours runtime

SR



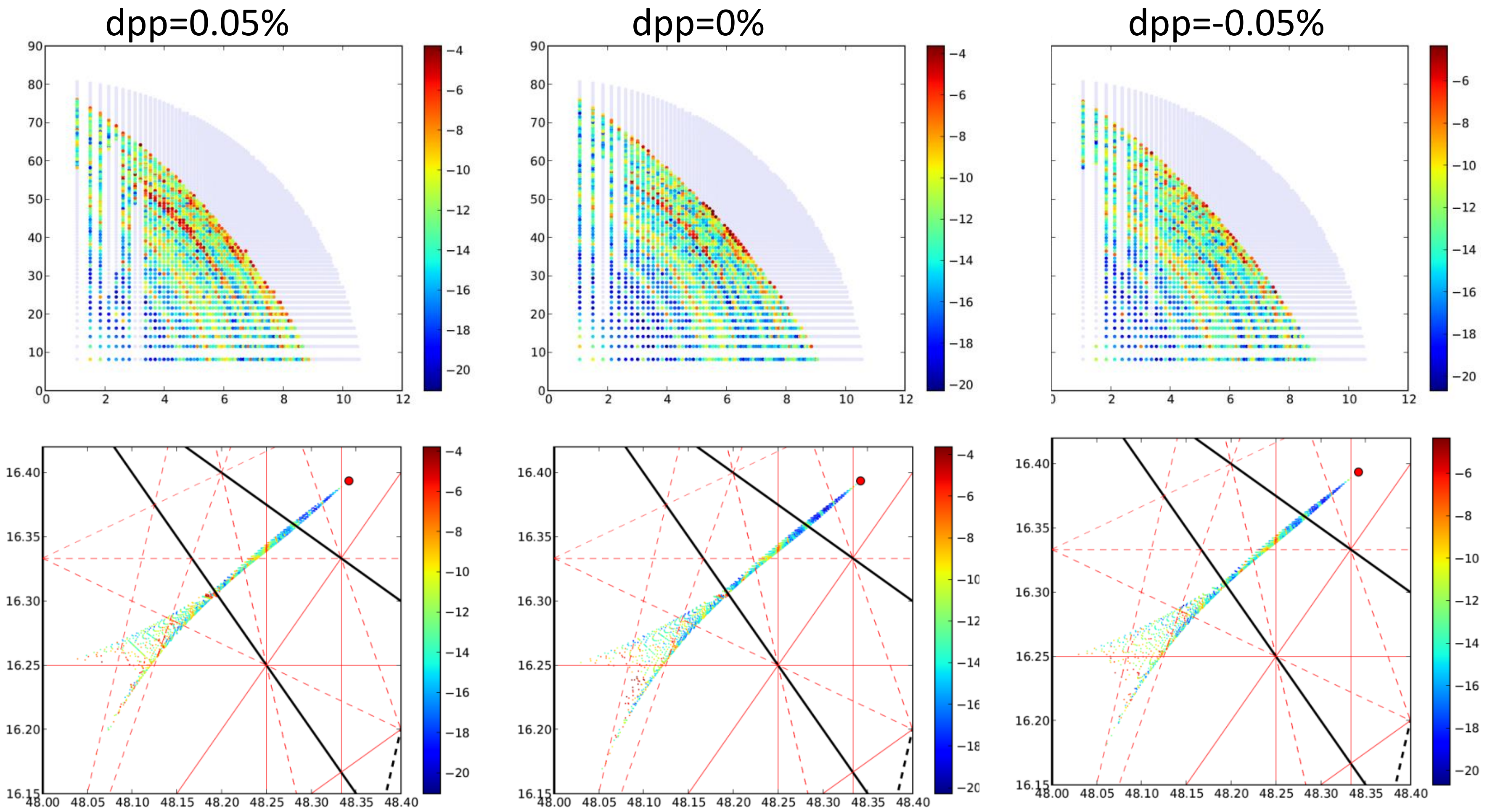
3 days runtime

No difference in DA at least in the spacing of scanned initial positions ($0.6\sigma_x$ and $6.5\sigma_y$):

Maximum difference in DA: 8%

- **Frequency Map**: Evolution of the tune of particles during the acceleration as a function of the initial off-set.
- No misalignments included.
- Color code: Diffusion parameter.

$$D = \log\left(\sqrt{|\nu_{x,1} - \nu_{x,2}|^2 + |\nu_{y,1} - \nu_{y,2}|^2}\right)$$



Summary

- A low emittance tuning to recover the nominal vertical emittance has been defined.
- Tolerances to main magnet misalignments have been found and are feasible.

Tolerances $(95\%\ \varepsilon_y < 1pm \cdot rad)$		
Quadrupole Vertical Offset	18	μm
Quadrupole Roll	138	μrad
Dipole Roll	180	μrad
Sextupole Vertical Offset	78	μm
BPM resolution	200	nm

- The Dynamic Aperture accomodates 5 σ_x.
- Multipole errors will be included (simulations ongoing).
- Additional sextupole families or octupoles could be installed to ameliorate the DA.

Thank you for your attention!

Table 3.3: Parameters required at the exit of the low energy linac and before injection to the pre-damping rings

Injected parameters	e^-	e^+
Bunch population [10^9]	4.3	6.6
r.m.s. Bunch length [mm]	4	5.4
r.m.s. Energy spread [%]	1	4.5
Hor., Ver. Norm. emittance [nm]	100×10^3	7×10^6

Table 3.4: Parameters required at the extraction of the damping rings

Extracted parameters	e^-/e^+
Bunch population [10^9]	4.1
Bunch spacing [ns]	0.5
Number of bunches/train	312
Number of trains	1
Repetition rate [Hz]	50
Normalized horizontal emittance [nm]	500
Normalized vertical emittance [nm]	5
Normalized longitudinal emittance [keV.m]	6

Table 3.5: CLIC PDR injected beam parameters (after injection and capture losses) [32] and required extracted parameters.

Parameters	Injected		Extracted
	e^-	e^+	
Bunch population [10^9]	4.3	4.3	4.3
r.m.s. bunch length [mm]	4	5.4	10
r.m.s. energy spread [%]	1	0.6	0.5
Long. emittance [keV.m]	114	93	143
Hor. Norm. emittance [μm]	100	7×10^3	63
Ver. Norm. emittance [μm]	100	7×10^3	1.5

Table 3.6: Design parameters for the PDRs

Parameter, Symbol [Unit]	2 GHz	1 GHz
Energy, E [GeV]	2.86	
Circumference, C [m]	389.15	
Bunch population, N [10^9]	4.3	
Basic cell type in the arc/LSS	TME/FODO	
Number of dipoles, N_d	38	
Dipole Field, B_0 [T]	1.2	
Horizontal and vertical tune, (Q_x,Q_y)	(16.39,12.26)	
Horizontal and vertical chromaticity, (ξ_x,ξ_y)	(-19.0,-22.9)	
Number of wigglers, N_w	36	
Wiggler peak field, B_w [T]	1.9	
Wiggler length, L_w [m]	3	
Wiggler period, λ_w [cm]	30	
Norm. equil. horizontal emittance, $\gamma\varepsilon_{x0}[\mu m]$	54	
Hor., vert. and long. damping time, (τ_x,τ_y,τ_l) [ms]	(2.7,2.7,1.35)	
Momentum compaction factor, α_c [10^{-3}]	3.7	
Energy loss/turn, U [MeV]	2.8	
Equil. energy spread (r.m.s.), σ_δ [%]	0.1	
RF Voltage, V_{RF} [MV]	10	
Synchrotron tune, Q_s	0.071	0.051
Bunches per train, n_b	312	156
Bunch spacing, τ_b [ns]	0.5	1
RF acceptance, ε_{RF} [%]	1.2	1.7
Harmonic number, h	2596	1298
Equil. bunch length (r.m.s.), σ_s [mm]	3.2	4.6

PDR

Table 3.8: Design parameters for the main DRs.

Parameters, Symbol [Unit]	2 GHz	1 GHz
Energy, E [GeV]	2.86	
Circumference, C [m]	427.5	
Bunch population, N [10^9]	4.1	
Basic cell type in the arc/LSS	TME/FODO	
Number of dipoles, N_d	100	
Dipole Field, B_0 [T]	1.0	
Norm. gradient in dipole [m^{-2}]	-1.1	
Horizontal and vertical tune, (Q_x,Q_y)	(48.35,10.40)	
Horizontal and vertical chromaticity, (ξ_x,ξ_y)	(-115,-85)	
Number of wigglers, N_w	52	
Wiggler peak field, B_w [T]	2.5	
Wiggler length, L_w [m]	2	
Wiggler period, λ_w [cm]	5	
Hor., vert. and long. damping time, (τ_x, τ_y, τ_l) [ms]	(2.0,2.0,1.0)	
Momentum compaction factor, α_c [10^{-4}]	1.3	
Energy loss/turn, U [MeV]	4.0	
Norm. horizontal emittance, $\gamma\epsilon_x$ [μm]	472	456
Norm. vertical emittance, $\gamma\epsilon_y$ [μm]	4.8	4.8
Energy spread (r.m.s.), σ_δ [%]	0.1	0.1
Bunch length (r.m.s.), σ_s [mm]	1.6	1.8
Longitudinal emittance, ε_l [keVm]	5.3	6.0
IBS growth factors hor./ver./long.	1.5/1.1/1.2	1.5/1.1/1.2
RF Voltage, V_{RF} [MV]	4.5	5.1
Stationary phase [^{o}]	62	51
Synchrotron tune, Q_s	0.0065	0.0057
Bunches per train, n_b	312	156
Bunch spacing, τ_b [ns]	0.5	1
RF acceptance, ε_{RF} [%]	1.0	2.4
Harmonic number, h	2851	1425

Table 3.10: CLIC DR parameters relevant to RF

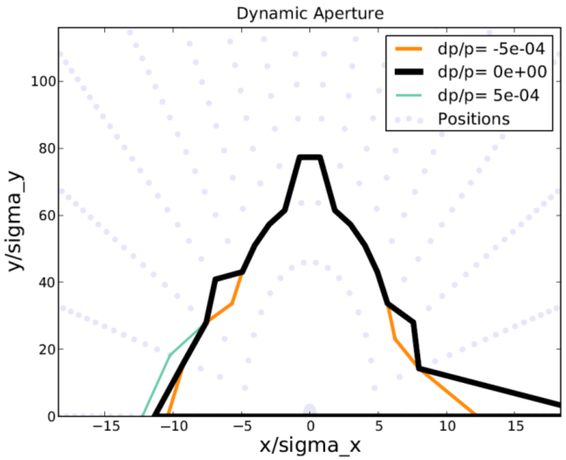
Parameter	DR @ 1 GHz	DR @ 2 GHz
Circumference [m]	427.5	
Energy [GeV]	2.86	
Mom. compaction factor	1.3×10^{-4}	
Energy loss per turn [MeV]	3.98	
Energy spread (r.m.s.) [%]	0.1	0.1
Bunch length (r.m.s.) [mm]	1.6	1.8
Longitudinal emittance [keVm]	5.3	6.0
RF voltage [MV]	5.1	4.5
RF stationary phase [^{o}]	62	51
Peak/Average current [A]	0.66/0.15	1.3/0.15
Peak/Average power [MW]	2.8/0.6	5.5/0.6

DR

Table 3.9: A list of the DR main magnets including CLIC DRs

Type	Location	Length [m]	Number	Families	Pole tip field [T]	Full aperture H/V [mm]
Dipoles	Arc DS-BM	0.58	96 4	1	0.97	80/20
Quadrupoles	Arc	0.20	376	2	1.0	20/20
	LSS	0.20	28 + 26	2		
	DS-BM	0.20	24	12		
	DS-BM	0.31	4	2		
Sextupoles	Arc	0.15	188 + 94	2	0.5	20/20
Wigglers	LSS	2.00	52	1	2.5	80/13

- Dynamic aperture: Region of the transverse space where tracked particles survive a given number of turns (1056 here).

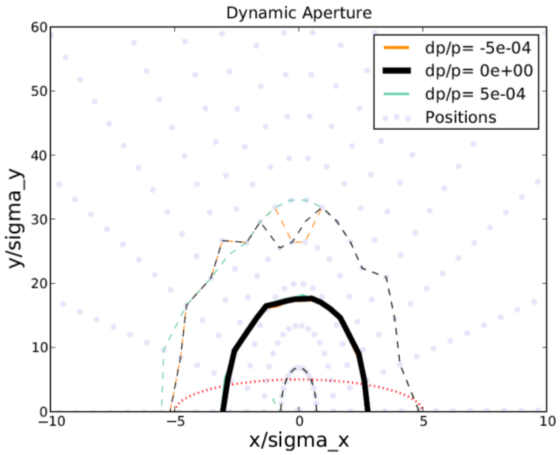


No error

DA:
10 σ_x
80 σ_y

At injection:

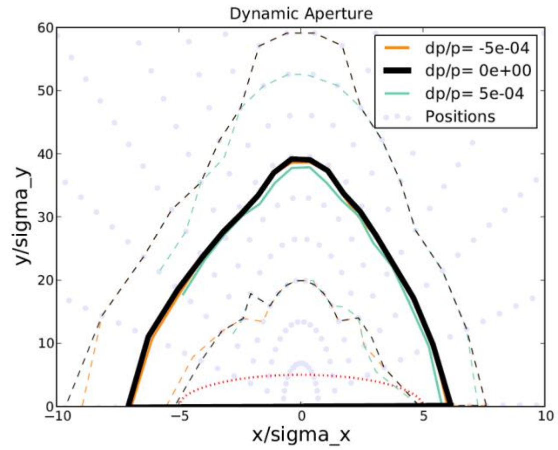
$$\sigma_x = 330\mu m$$
$$\sigma_y = 34\mu m$$



200 seeds

QV(rms) = 45 μm
QR(rms) = 345 μrad
DR(rms) = 450 μrad
SV(rms) = 195 μm
No BPM resolution

DA (mean):
3 σ_x
18 σ_y



200 seeds

QV(rms) = 18 μm
QR(rms) = 138 μrad
DR(rms) = 180 μrad
SV(rms) = 78 μm
BPM resolution = 200nm

DA (95% of lattices):
>5 σ_x
>40 σ_y