



Emittance Tuning for the Future Circular Collider (FCC-ee)

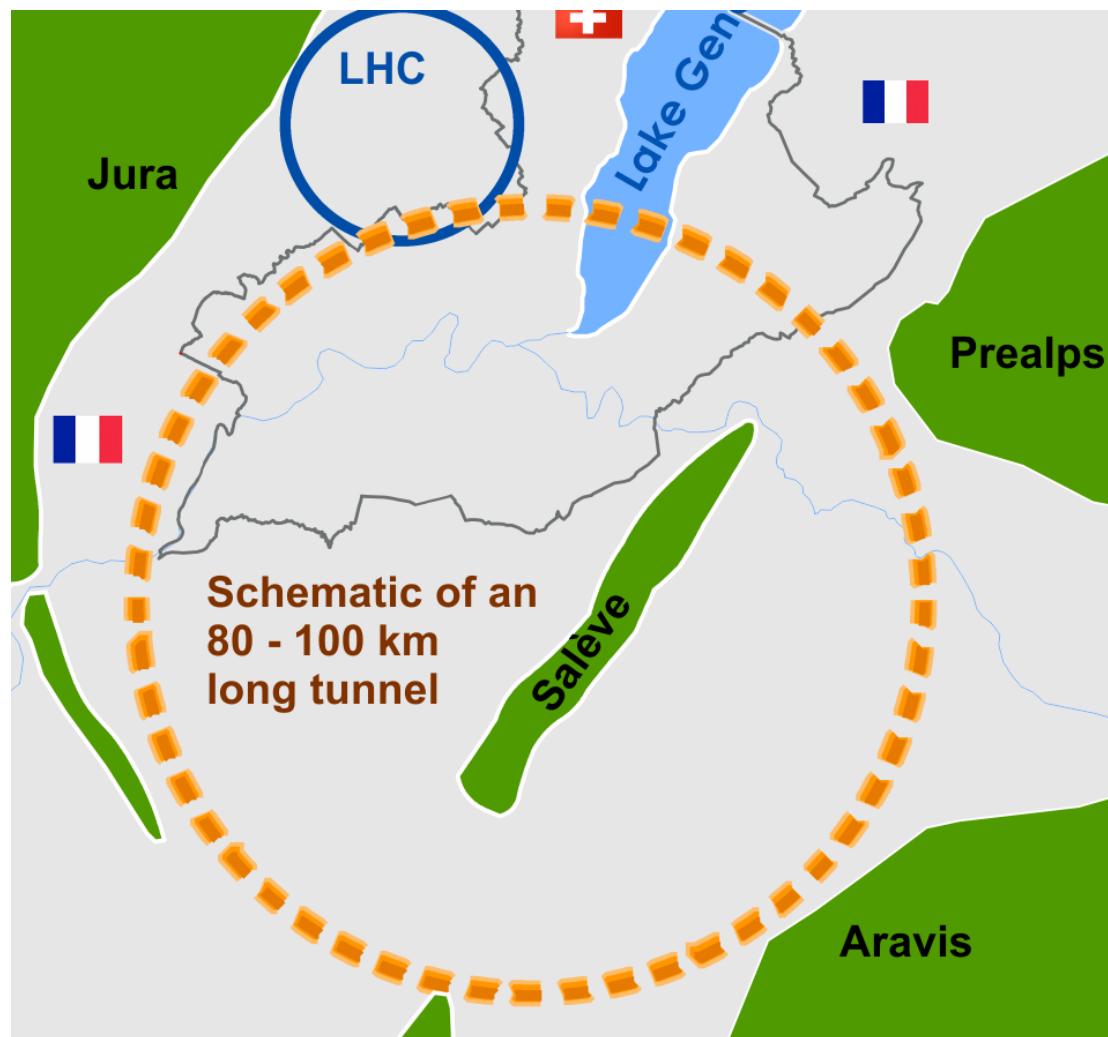
Tessa Charles

With thanks to:

S. Aumont, E. Gianfelice-Wendt, B. Holzer, K. Oide, T. Tydecks, F. Zimmermann
and the entire FCC-ee optics team

EPS HEP conference 13.07.2019

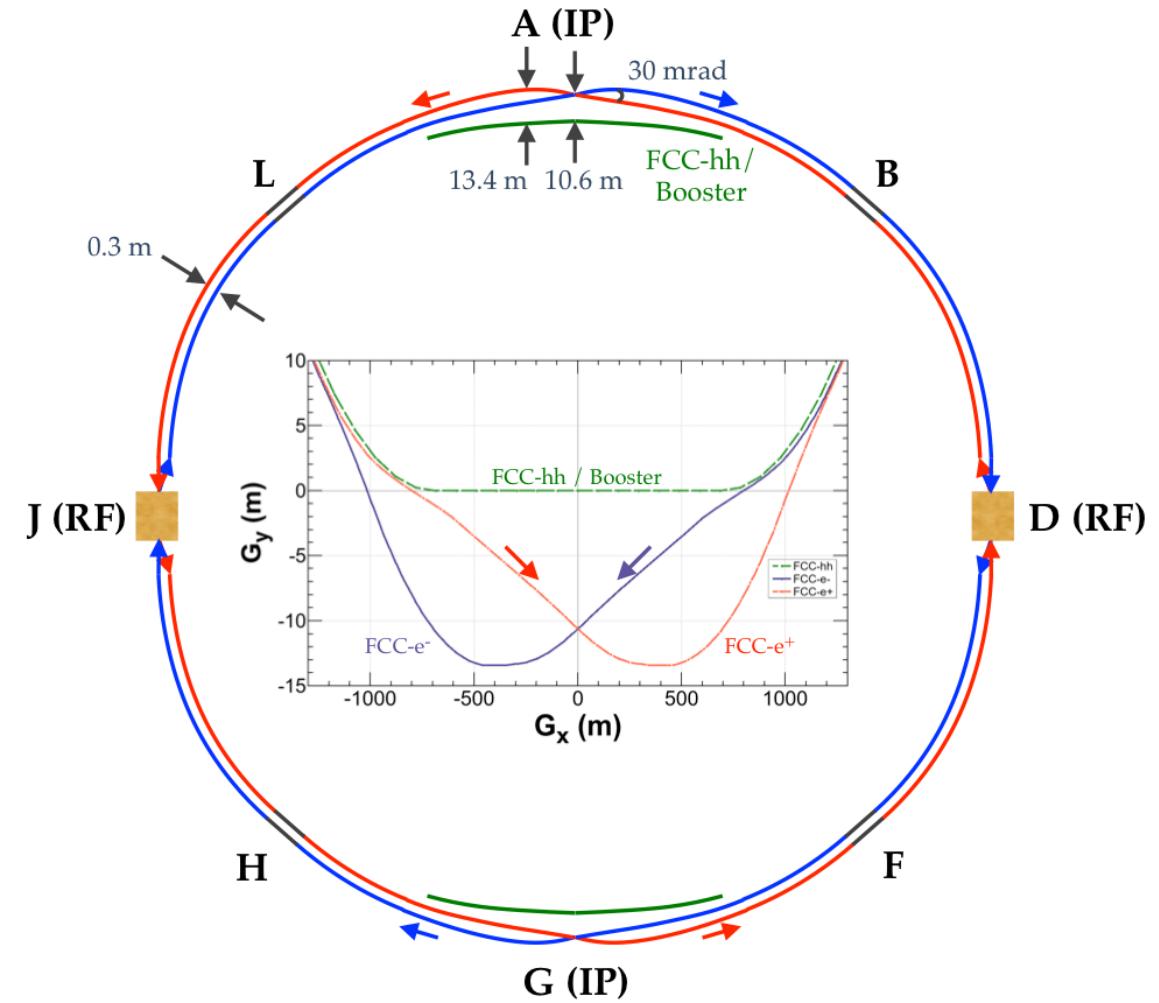
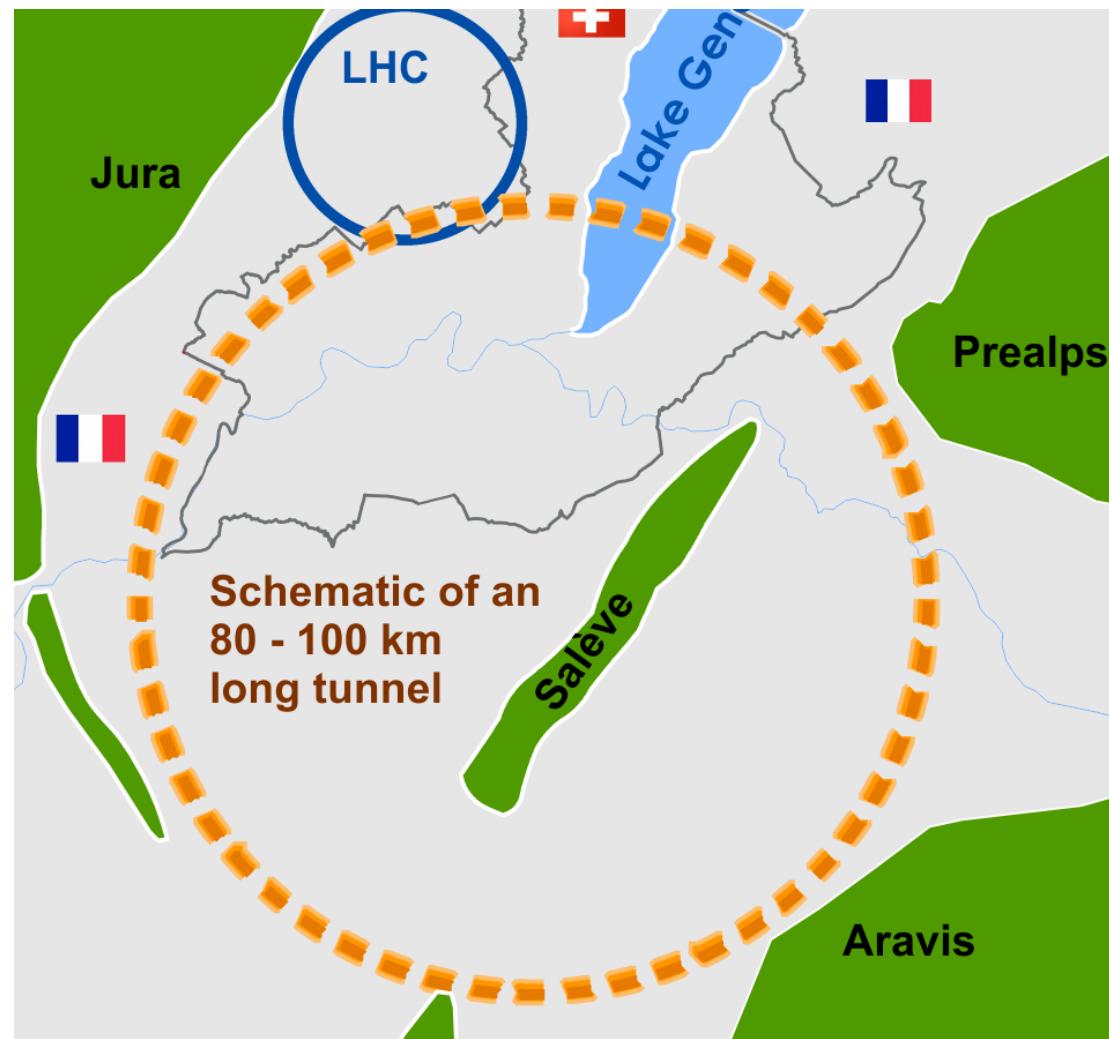
The Future Circular Collider (FCC-ee)



FCC – an International collaboration with CERN as host laboratory:

- exploring the feasibility of several particle collider scenarios with the aim of significantly expanding the current energy and luminosity frontiers.
 - 100 km tunnel infrastructure around Geneva area
 - Lepton collider as possible first step and 100 TeV proton collider as long-term goal

The Future Circular Collider (FCC-ee)



Key parameters for FCC-ee

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10 ¹¹]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10 ³⁴ cm ⁻² s ⁻¹]	>200	>25	>7	>1.4

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Synchrotron radiation power is limited to 50 MW/beam

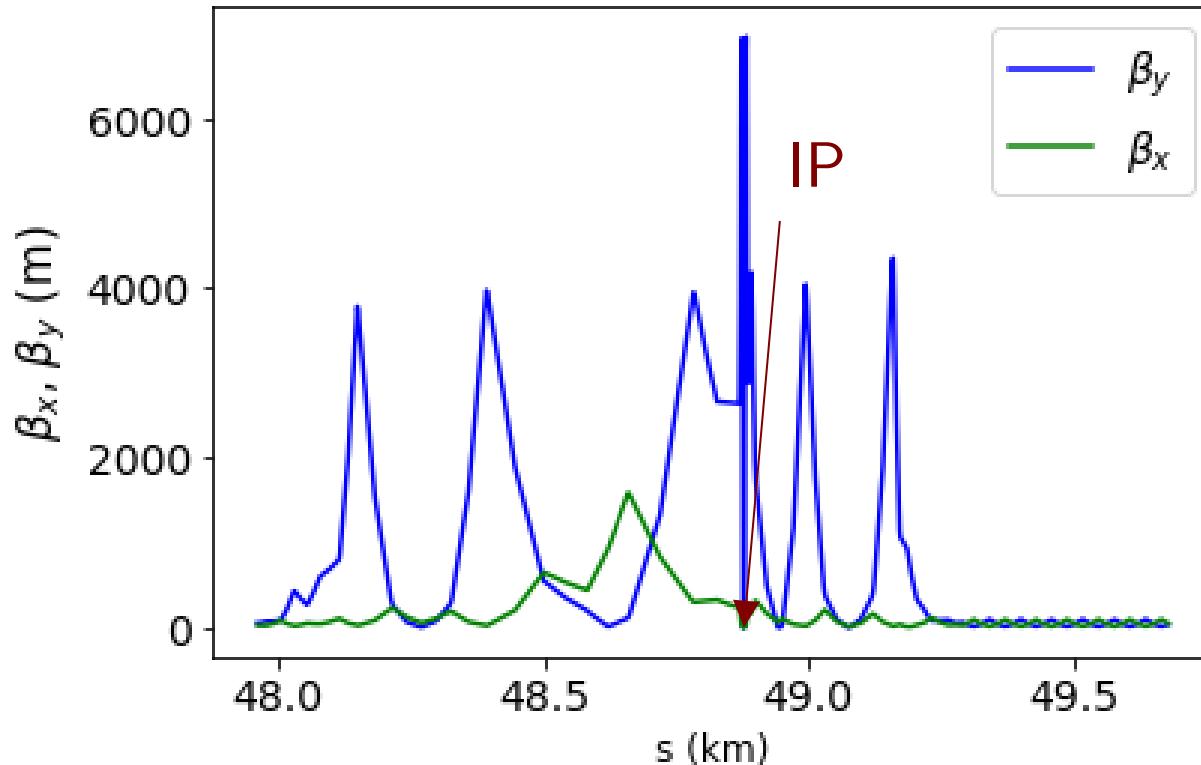
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FCC-ee Emittance Tuning: Challenges & Constraints



$$\beta_y^* = 1.6 \text{ mm}$$

$$\beta_{x,\max} = 1587.97 \text{ m}$$

$$\beta_{y,\max} = 6971.55 \text{ m}$$

Small emittance ratio $\epsilon_y/\epsilon_x = 0.201\%$

Vertical dispersion & betatron coupling dominate ϵ_y growth

Horizontal emittance:

$$\epsilon_x = \frac{C_g}{J_x} \gamma^2 \theta^3 F$$

$$F_{FODO} = \frac{1}{2\sin\gamma} \frac{5 + 3\cos\gamma}{1 - \cos\gamma} \frac{L}{l_B}$$

L : cell length

l_B : dipole length

ϕ : phase advance/cell

Vertical emittance:

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

Sources of vertical emittance growth:

- vertical dispersion D_y
- betatron coupling
- opening angle $\sim 1/\gamma$ (here negligible)

Correction Strategy

- Orbit correction:

- MICADO & SVD from MADx
 - Hor. corrector at each QF, Vert. corrector at each QD
1598 vertical correctors / 1590 horizontal correctors
 - BPM at each quadrupole
1598 BPMs vertical / 1590 BPMs horizontal

- Vertical dispersion and orbit:

- Orbit Dispersion Free Steering (DFS)

$$\begin{pmatrix} (1-\alpha)\vec{y} \\ \alpha\vec{D}_y \end{pmatrix} = \begin{pmatrix} (1-\alpha)\mathbf{A} \\ \alpha\mathbf{B} \end{pmatrix} \vec{\theta}$$

- Linear coupling:

- Coupling resonant driving terms (RDT)
 - 1 skew at each sextupole + skews correctors at the IP

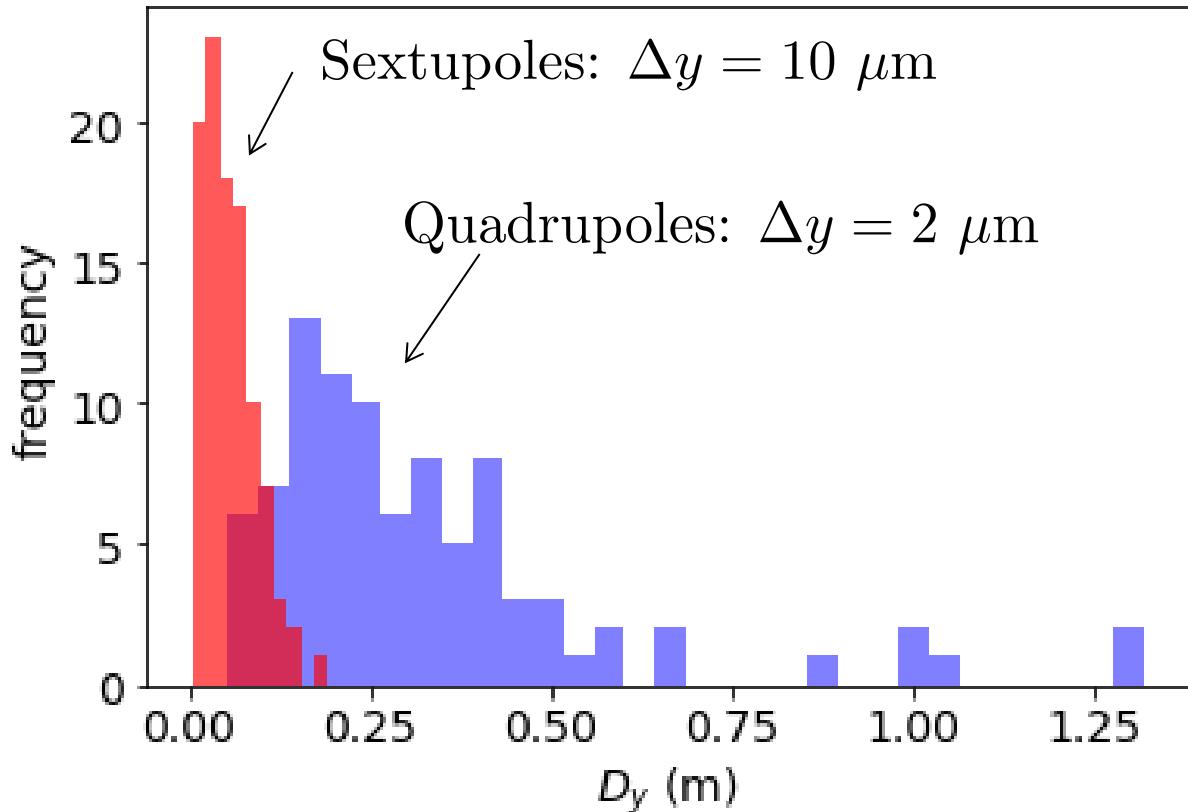
$$\begin{pmatrix} \vec{f}_{1001} \\ \vec{f}_{1010} \\ D_y \end{pmatrix} = -\mathbf{M} \vec{\mathbf{J}}$$

- Beta beating correction & Horizontal dispersion via Response Matrix:

- Rematching of the phase advance at the BPMs
 - 1 trim quadrupole at each sextupole

$$\begin{pmatrix} f_1 \left(\frac{\beta_1 - \beta_{y0}}{\beta_{y0}} \right) \\ f_2 \left(\frac{\beta_2 - \beta_{y0}}{\beta_{y0}} \right) \\ \dots \\ f_m \left(\frac{\beta_m - \beta_{y0}}{\beta_{y0}} \right) \end{pmatrix}_{meas} = \begin{pmatrix} f_1 (R_{11}, R_{12}, R_{13}, \dots, R_{1n}) \\ f_2 (R_{21}, R_{22}, R_{23}, \dots, R_{1n}) \\ \dots \\ f_m (R_{m1}, R_{m2}, R_{m3}, \dots, R_{mn}) \end{pmatrix} * \begin{pmatrix} k_1 \\ k_2 \\ \dots \\ k_n \end{pmatrix}$$

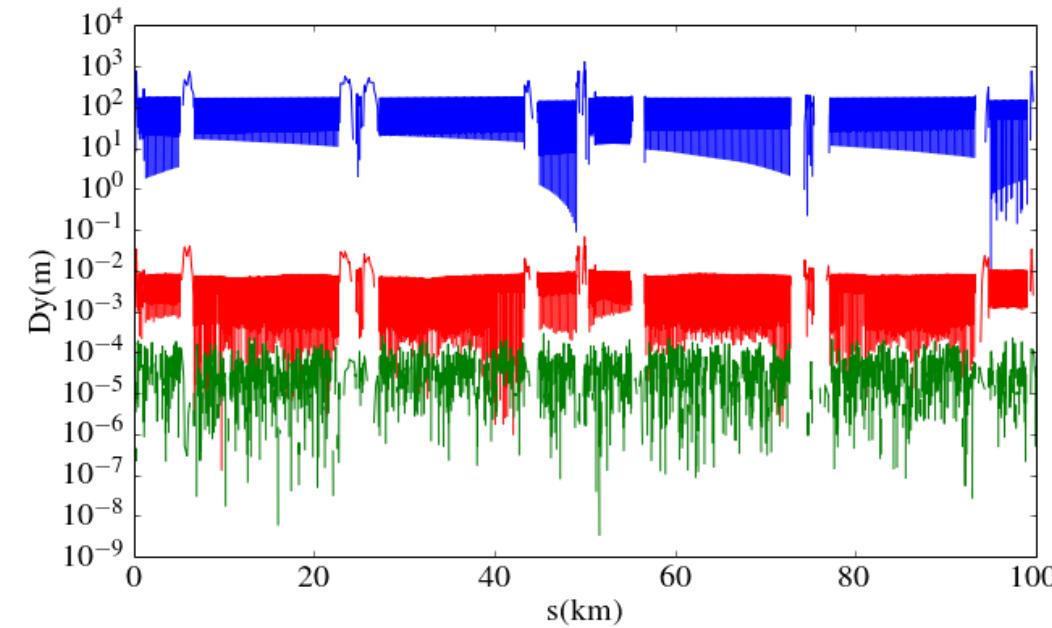
Sensitivity of FCC-ee to errors



Error type	y , rms (mm)	$D_{y,\text{rms}}$ (mm)
quad arc ($\Delta y = 2 \mu\text{m}$)	8.809	326.71
quad arc ($\Delta x = 10 \mu\text{m}$)	0.0	0.0
quad arc ($\Delta\phi = 10 \mu\text{rad}$)	0.0	2.677
sextupoles ($\Delta y = 10 \mu\text{m}$)	0.0245	57.13
sextupoles ($\Delta x = 10 \mu\text{m}$)	0.0	0.0
sextupoles ($\Delta\phi = 10 \mu\text{rad}$)	0.0	0.004

Correction methods applied to **only** Vertical Quadrupole Misalignments ($\sigma_y = 100 \mu\text{m}$)

Sextupoles turned off:



Initial D_y

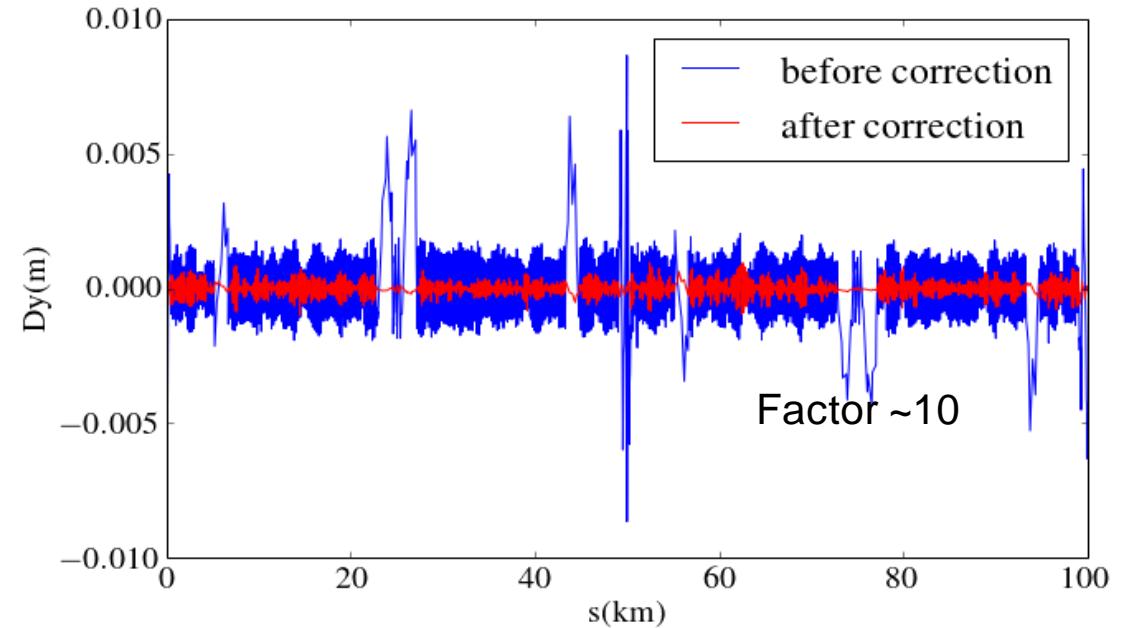
After orbit correction - factor 2e4 improvement

DFS - factor 50 improvement

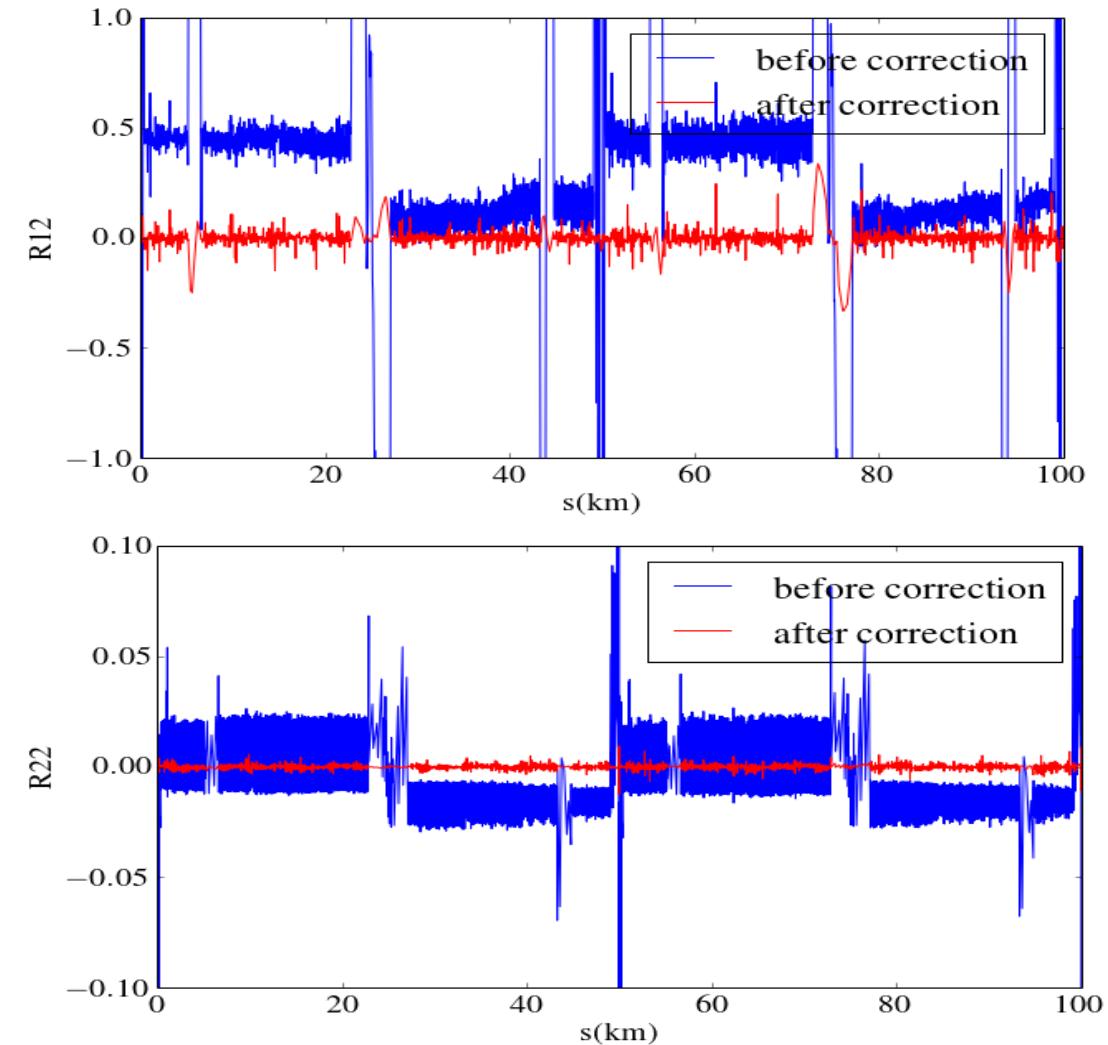
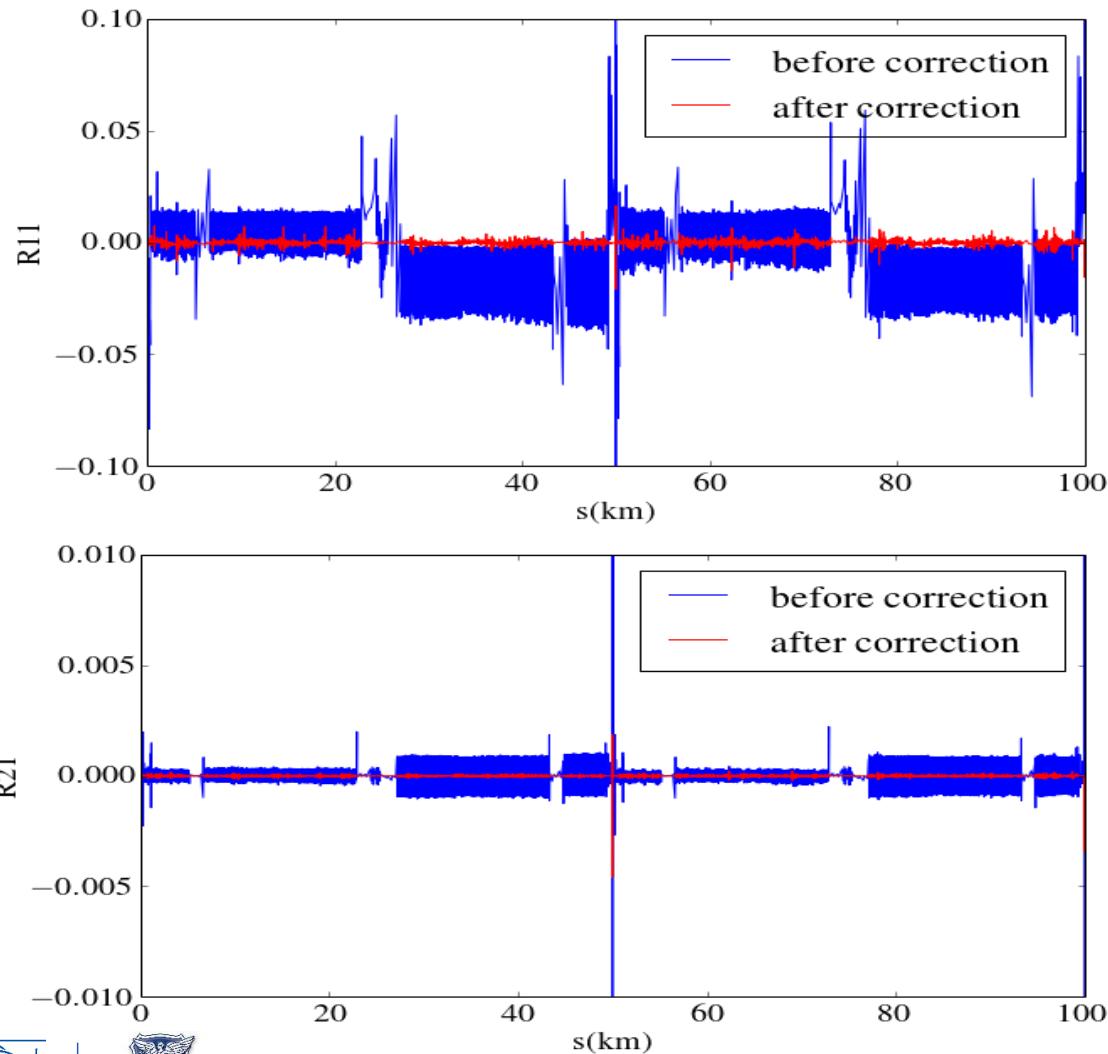
Switch on
sextupoles



Dispersion and coupling correction



Coupling matrix elements



Correction Strategy (1/2)

- **Sextupoles strengths set to 0**
 - x-y orbits correction
 - Rematch the tune
 - Beat-beat correction
 - *CHECK of tunes, orbit, $\beta_{y, \max}$*
 - Coupling correction
- 1 step Dispersion Free Steering w/o sextupole
 - +
 - 1 step coupling correction
- *CHECK of tunes, orbit, $\beta_{y, \max}$* Loop 8 times
- 1 step Dispersion Free Steering w/o sextupole
 - +
 - 1 step coupling correction
- *CHECK of tunes, orbit, $\beta_{y, \max}$* Loop 8 times
- Save x,x',y,y' at the beginning of the machine
- **Set sextupoles strength to 10% of their design current**
(details on next slide)
- **Final correction**
(details on next slide)

Correction Strategy (2/2)

- **Sextupoles strengths set to 0**

(details on previous slide)



- **Set sextupoles strength to 10% of their design current**

- x-y orbits correction
- Rematch the tune
- *CHECK of tunes, orbit*
- *CHECK $\beta_{y, max}$*
- coupling and dispersion correction
 - *CHECK of tunes, orbit, with each iteration*
 - *CHECK $\beta_{y, max}$, then beta beat correction if necessary*
 - *CHECK of tunes, orbit, with each iteration*
- ...
- increase by 10% the sextupole strength

These two steps
repeated
~12 times

Constant checking
of the tunes and
orbit avoids running
into resonances, or
failure to find the
closed orbit.

- **Final correction (at 100% sextupole strength)**

Loop 10 times

- *CHECK of tunes, orbit, $\beta_{y, max}$*
- Apply required corrections based upon checks
- *CHECK if $D_{y,RMS} > 0.001 \text{ m}$, then apply coupling and dispersion correction*

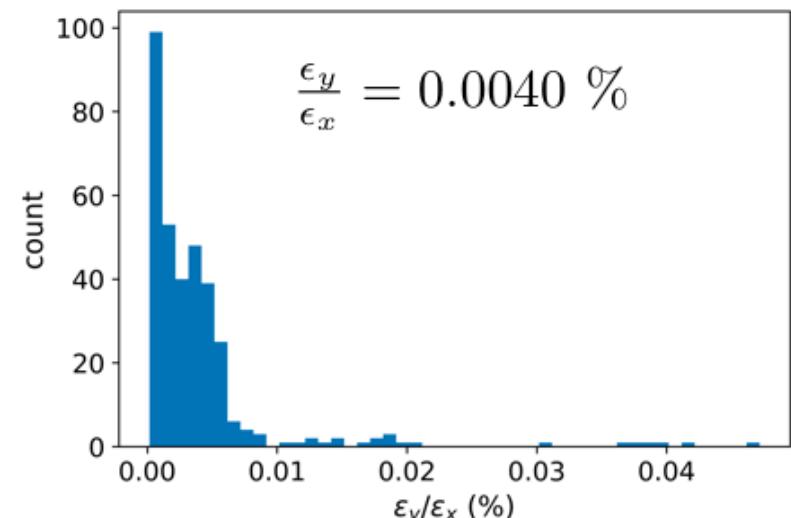
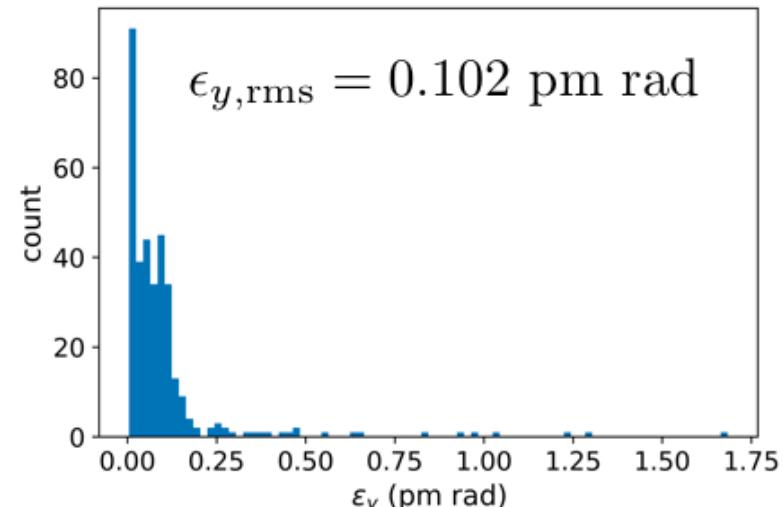
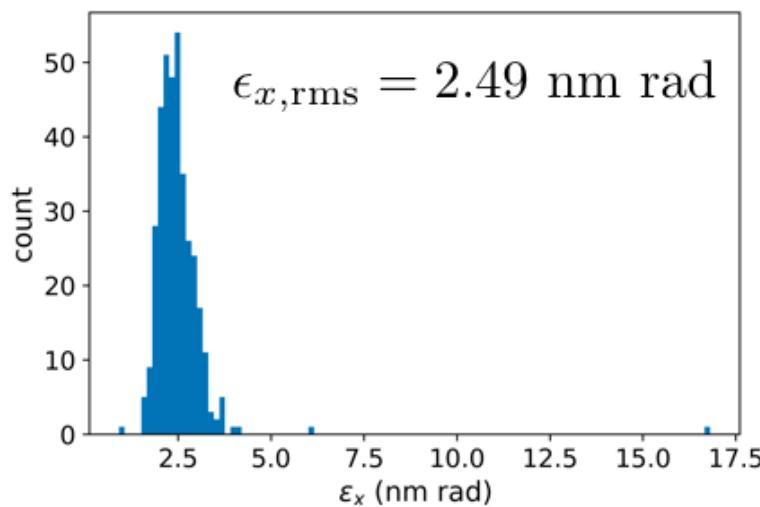
Corrected lattices

- Using the misalignments and roll angles :

(increasing the IP quad misalignments out to 50 microns and 50 microrad.)

	$\sigma_x(\mu\text{m})$	$\sigma_y(\mu\text{m})$	$\sigma_\theta(\mu\text{rad})$
arc quads	100	100	100
IP quads	50	50	50
sextupoles	100	100	100
dipoles	100	100	100

After correction:



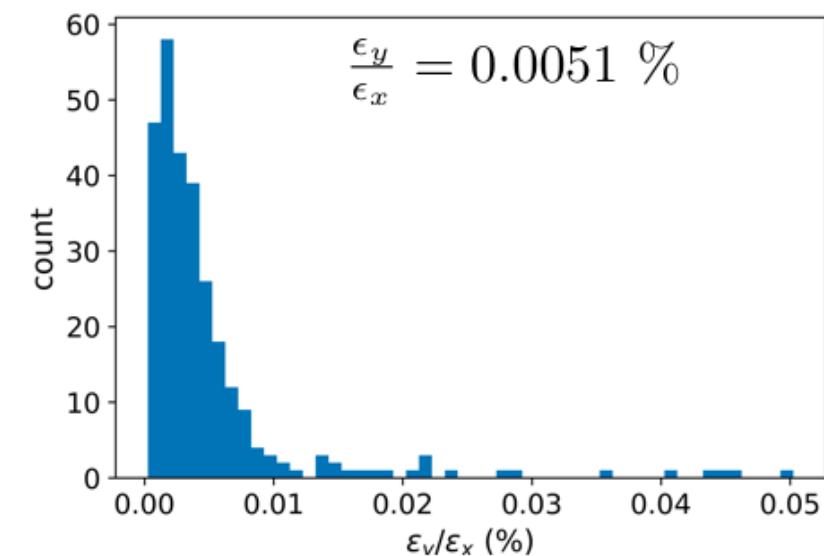
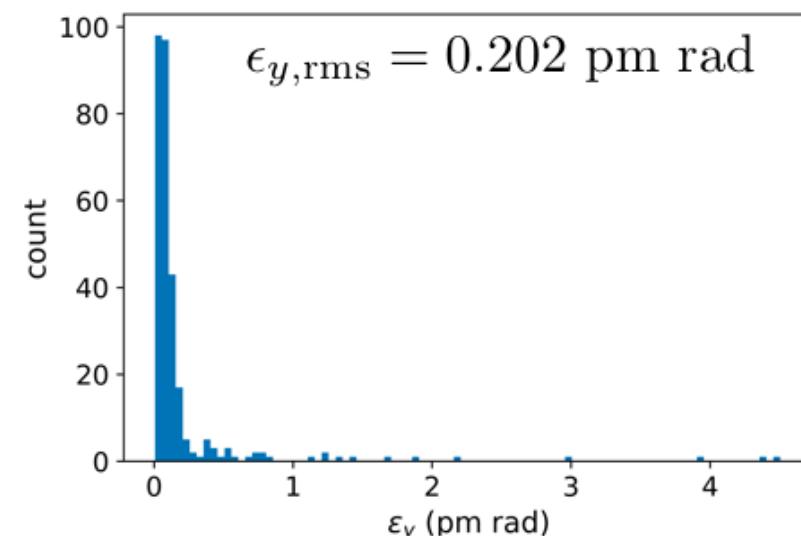
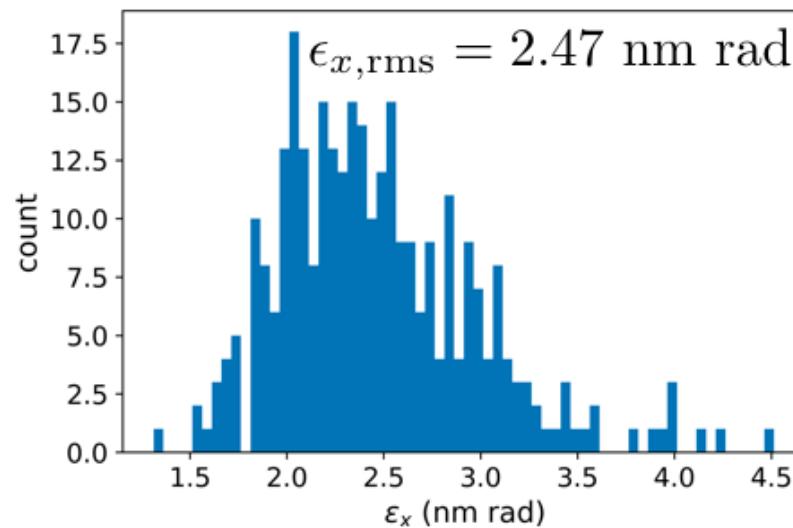
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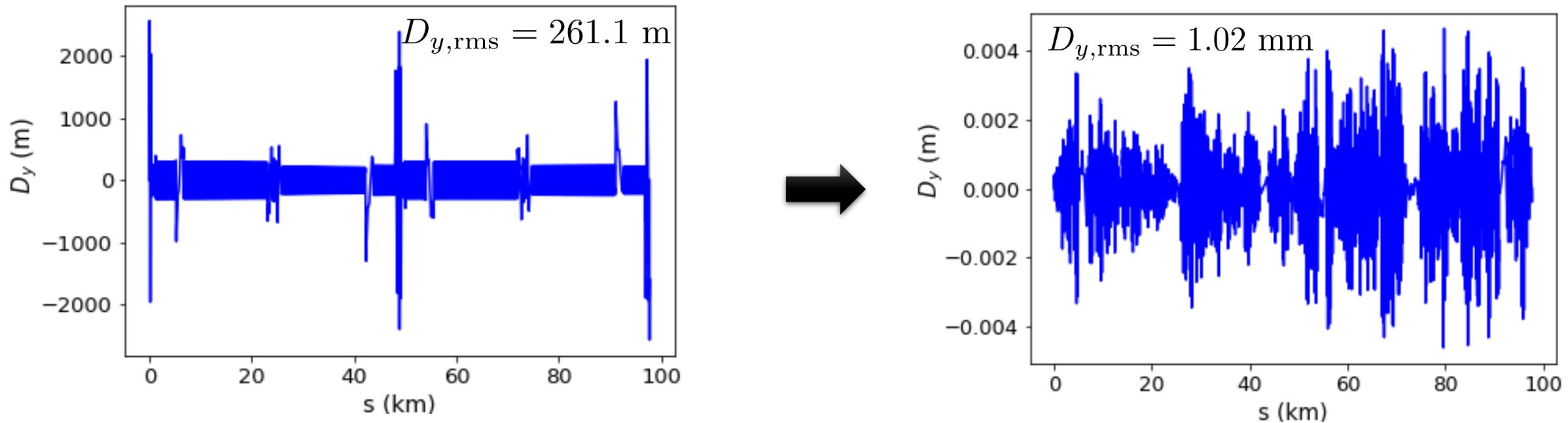
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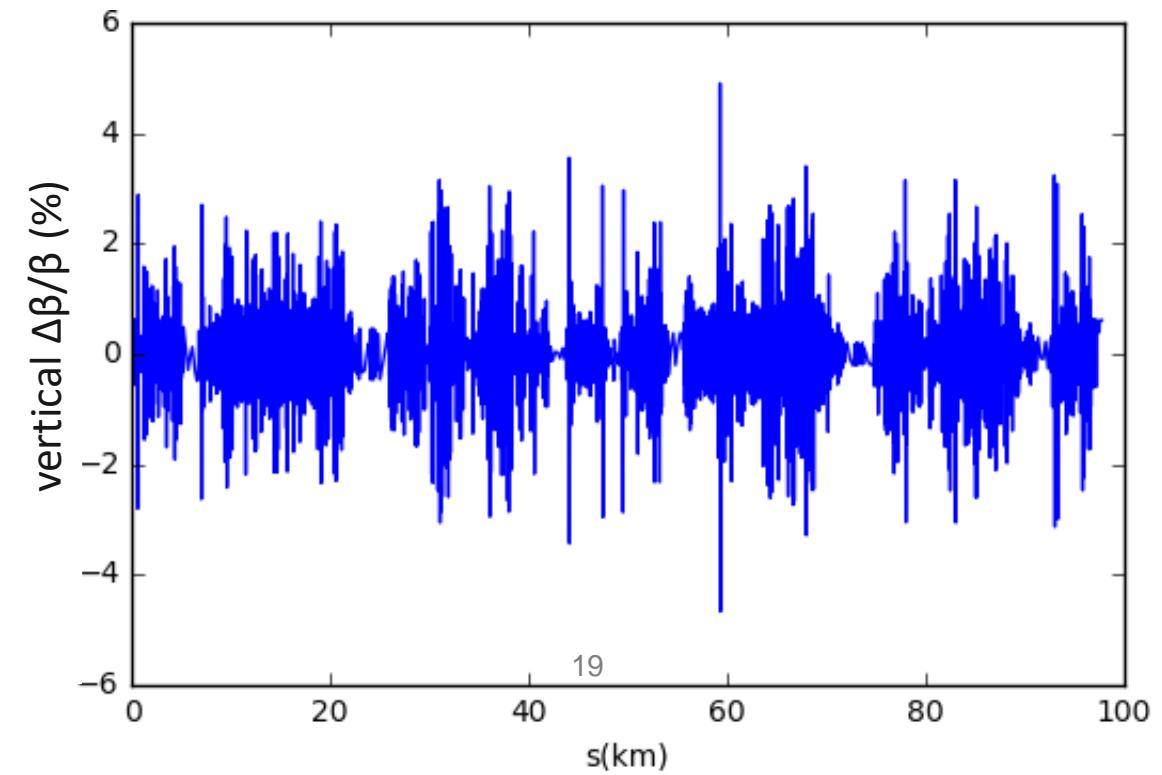
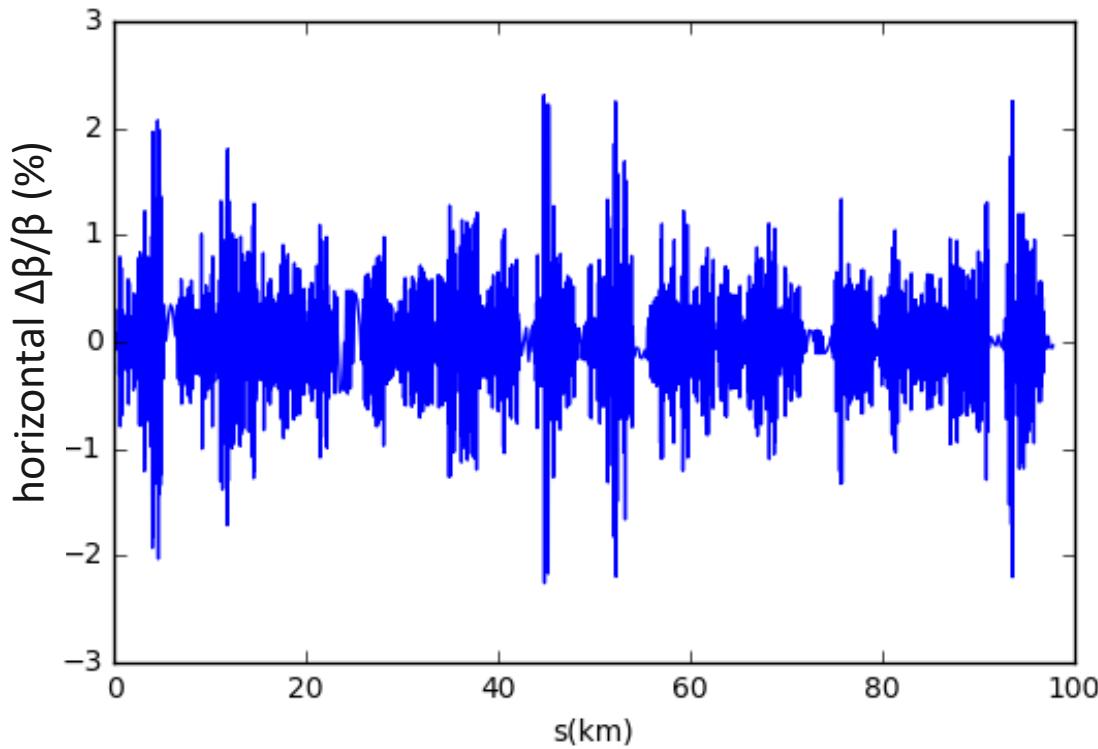


Vertical dispersion before and after correction

Dispersion introduced through:
quadrupoles: $\Delta x = 100 \mu\text{m}$, $\Delta y = 100 \mu\text{m}$, $\Delta\theta = 100 \mu\text{m}$
sextupoles: $\Delta x = 100 \mu\text{m}$, $\Delta y = 100 \mu\text{m}$, $\Delta\theta = 100 \mu\text{m}$
dipoles: $\Delta x = 100 \mu\text{m}$, $\Delta y = 100 \mu\text{m}$, $\Delta\theta = 100 \mu\text{m}$



Beta beat after correction



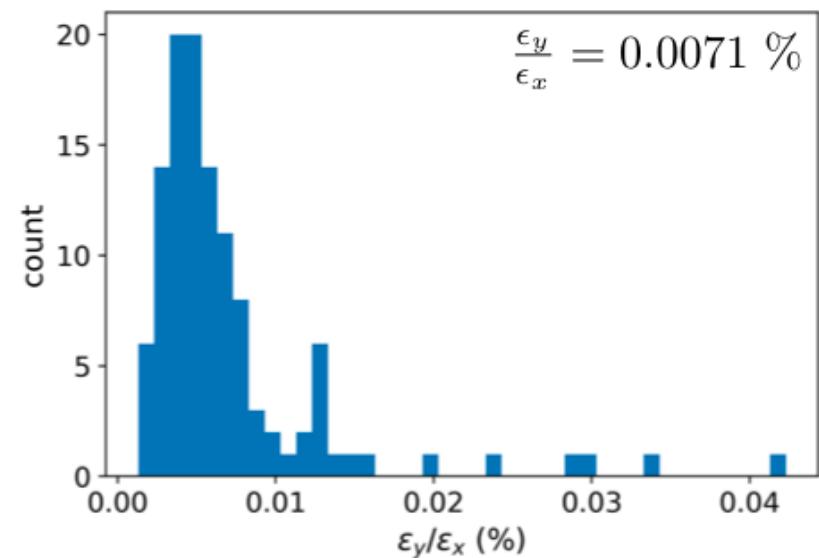
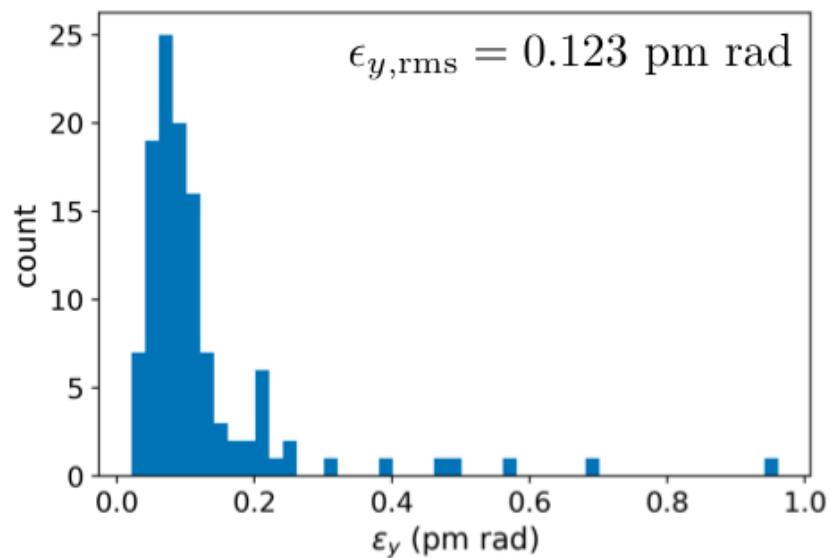
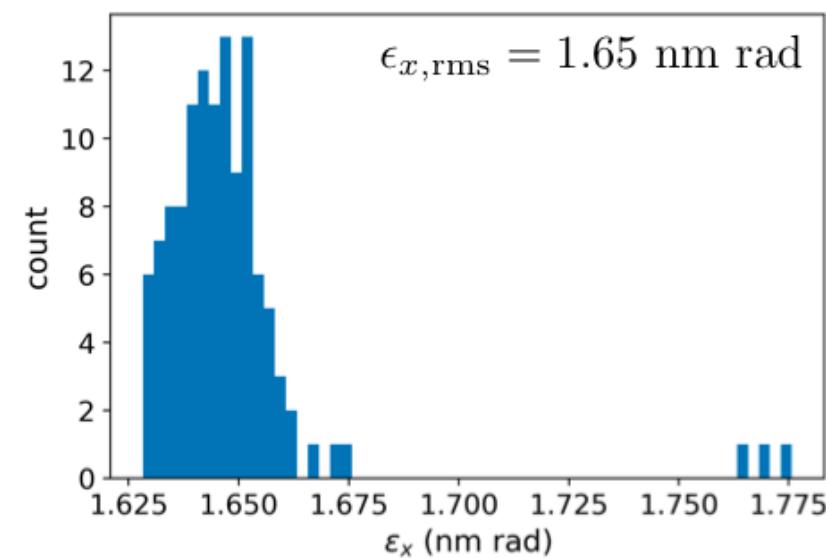
Corrected Lattices results

Using the misalignments and roll angles and field errors of :

	$\sigma_x(\mu\text{m})$	$\sigma_y(\mu\text{m})$	$\sigma_\theta(\mu\text{rad})$
arc quads	100	100	100
IP quads	100	100	100
sextupoles	100	100	100
dipoles	100	100	100
BPMs	20	20	150

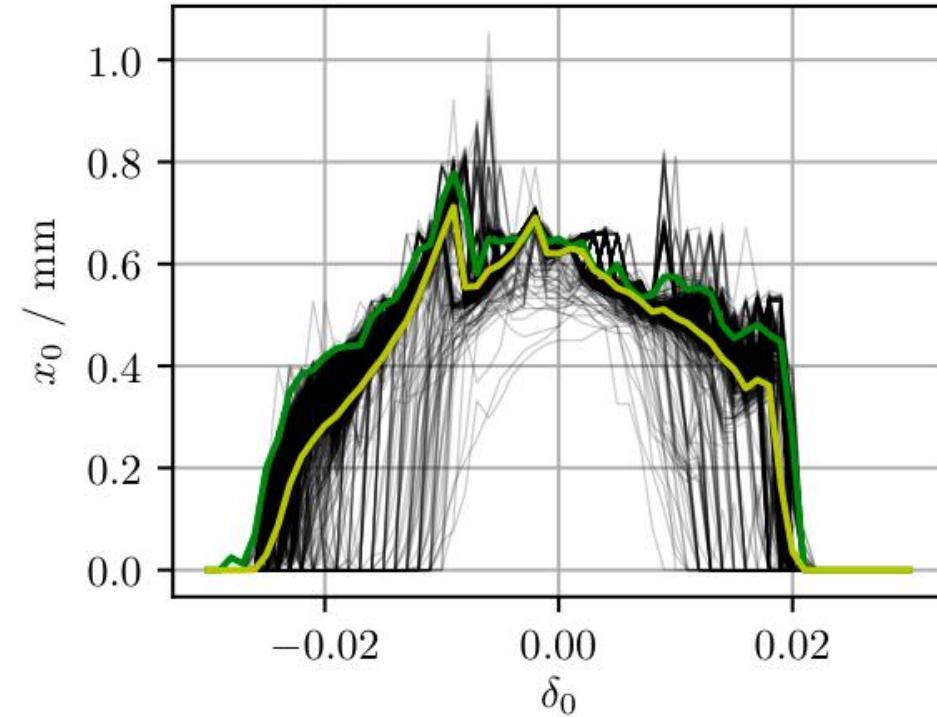
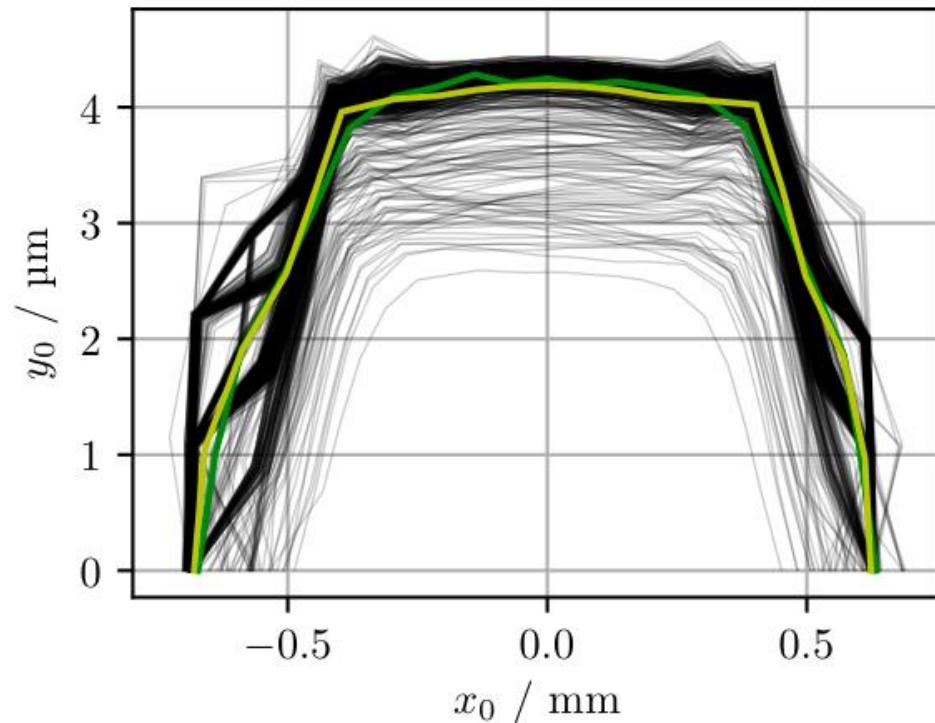
*BPM error relative to quadrupole position

After correction:



Dynamic and Momentum Aperture

Tracking
done by
T. Tydecks



Apertures sufficient for beam storage and injection.

	σ_x (μm)	σ_y (μm)	σ_θ (μrad)
arc quadrupoles	100	100	100
IP quadrupoles	50	50	50
sextupoles	100	100	0

Improving Dynamic and Momentum Aperture Using PSO

- A particle swarm optimiser (PSO) is an evolutionary algorithm with both cognitive and ‘social’ components

Whilst:

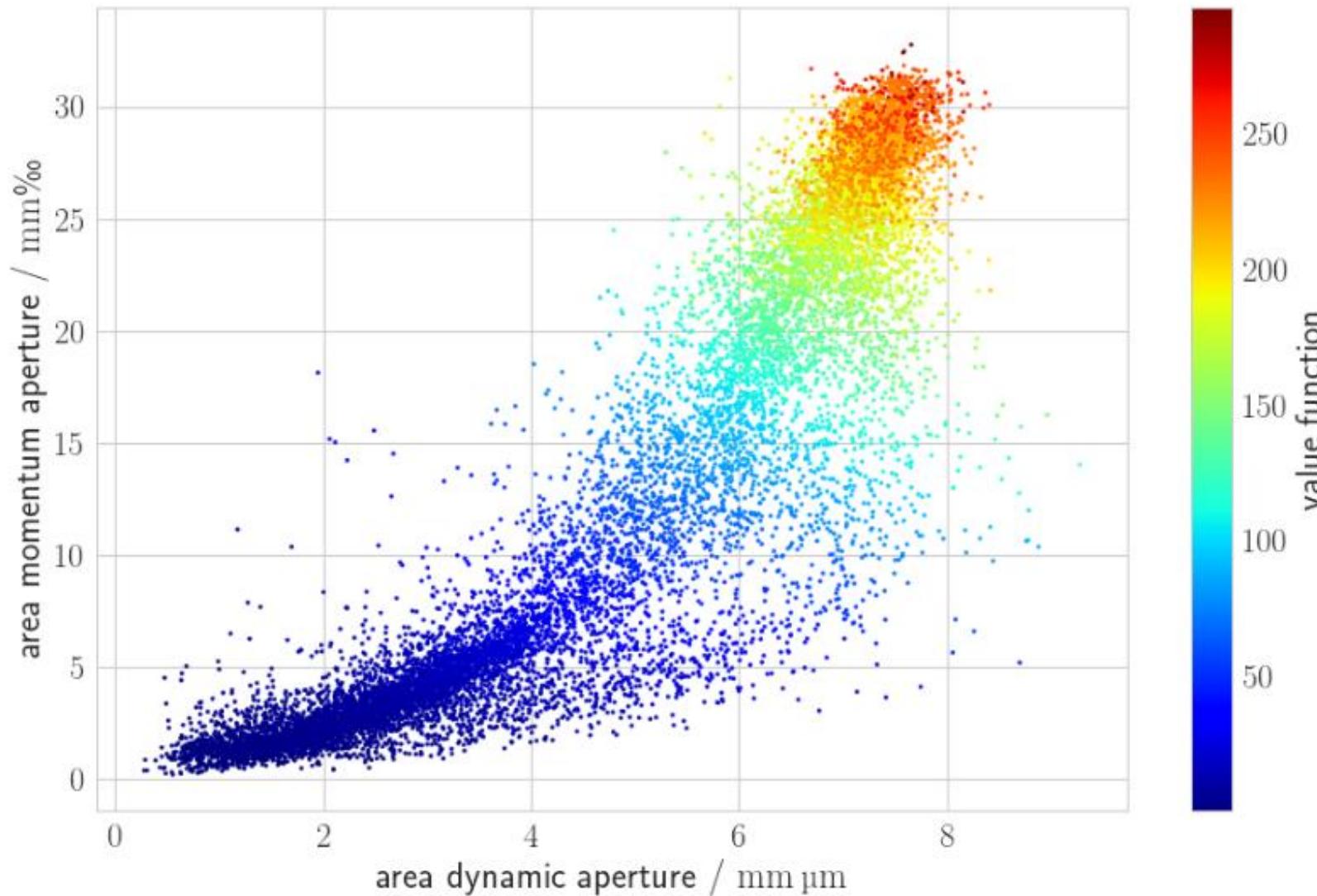
- keeping sextupole pairs for $-I$ transform
- maintain periodicity of machine
- constraint on final focus sextupole strength
 $\Rightarrow 294$ degrees of freedom



$$\vec{x}_{n+1} = \vec{x}_n + \vec{v}_{n+1},$$

$$\vec{v}_{n+1} = \omega \vec{v}_n + c_c r_1 (\vec{x}_{\text{p-best}} - \vec{x}_n) + c_s r_2 (\vec{x}_{\text{g-best}} - \vec{x}_n).$$

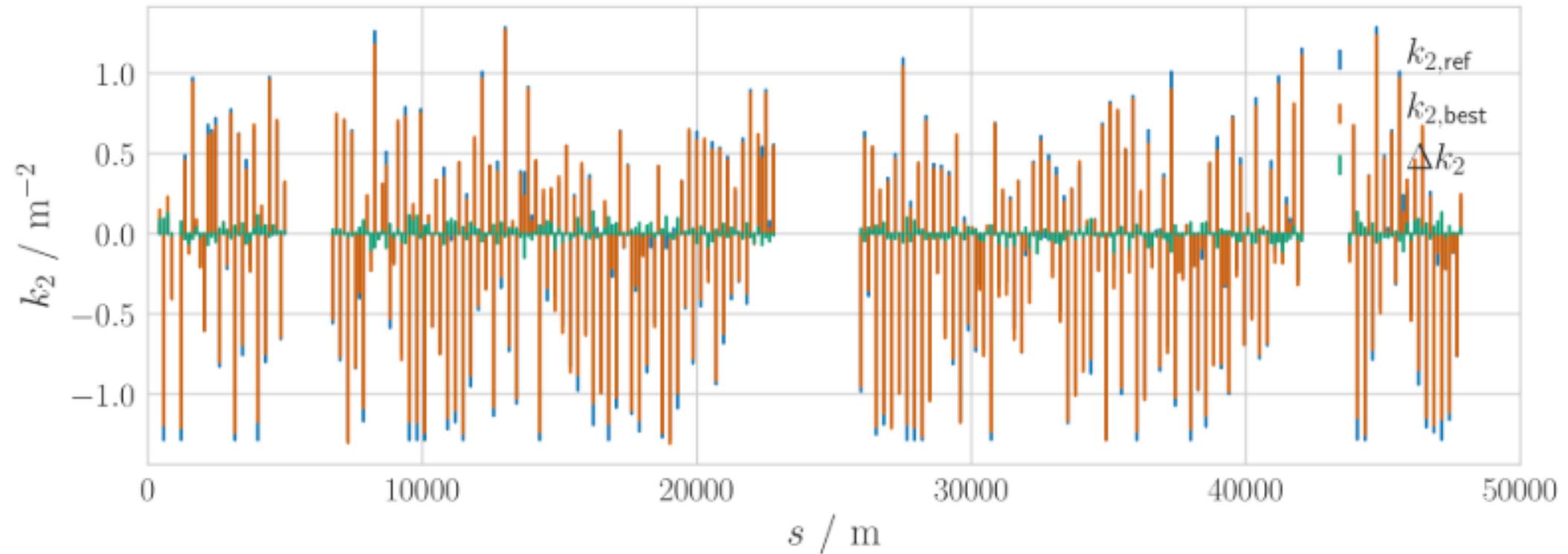
Accumulated set of solutions



yields an improvement of the area of momentum aperture of 18.0% compared to the reference lattice.

T. Tydecks

Change in Sextupole Strengths



T. Tydecks

Dynamic Aperture (left) & Momentum Aperture (right), before and after

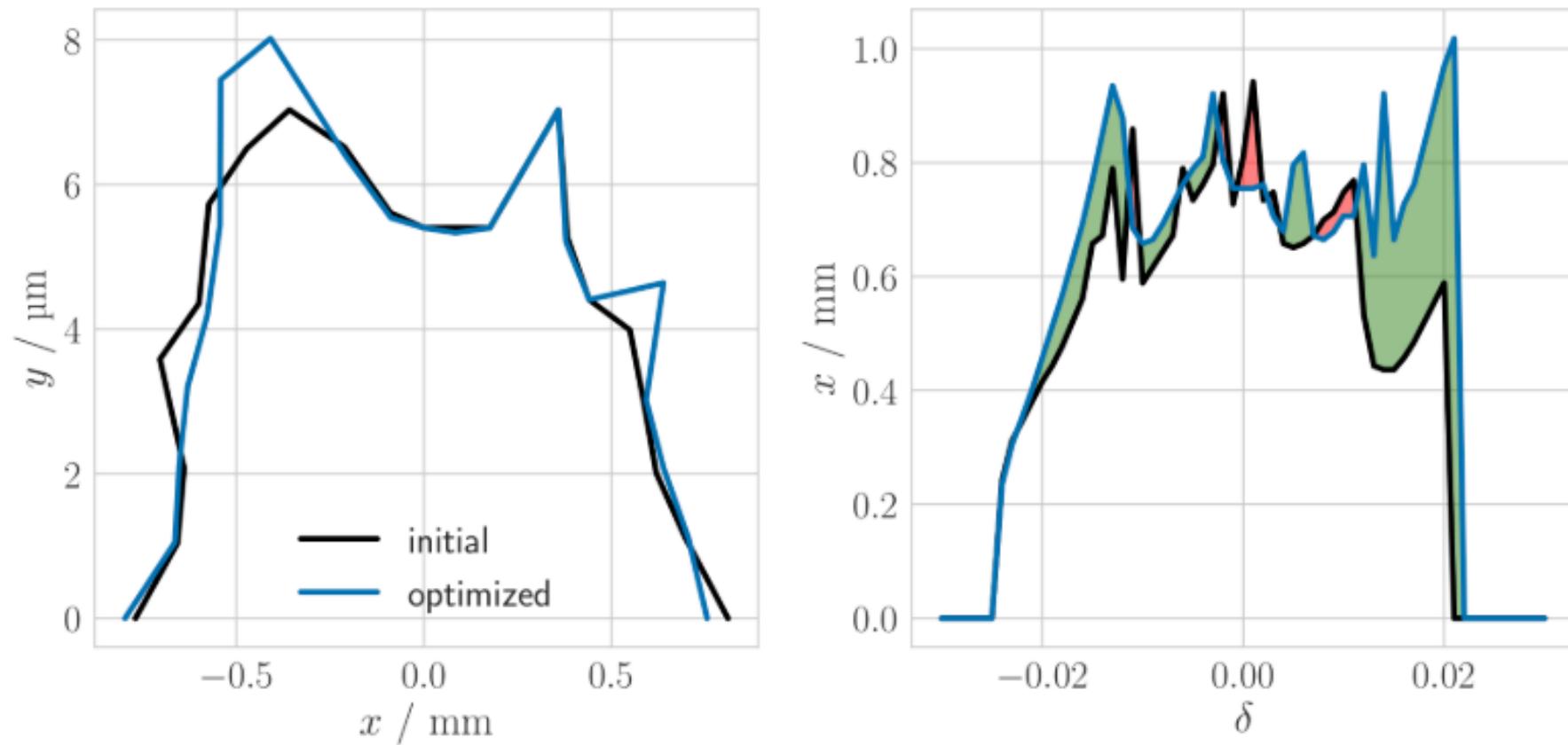


Figure 2.15: Dynamic aperture (left) and momentum aperture (right) for reference lattice (black) and optimised lattice (blue). The area of dynamic aperture is improved by 3.1 % while the area of momentum aperture is increased by 18.0 %.

Conclusions

FCC-ee poses a challenge for emittance tuning, however with **100 μm , 100 μrad misalignments and roll angles** in arc quads, IP quads & sextupoles and dipoles, and with BPM misalignments of **20 μm and 150 μrad** , the mean vertical emittance achieved after correction schemes applied is $\varepsilon_y = 0.123 \text{ pm rad}$ and a coupling ratio of 0.0071 %.

Thank you