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

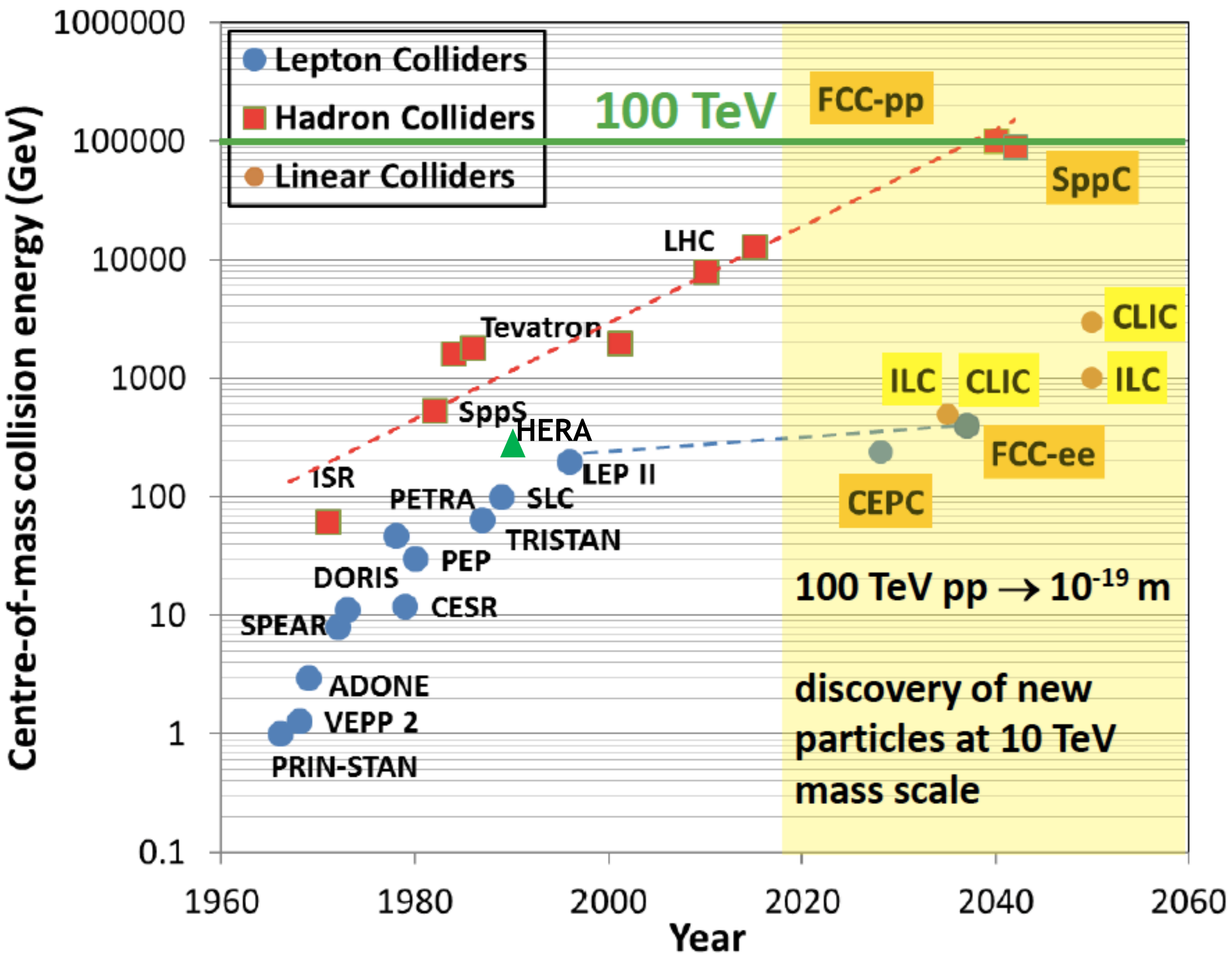
Tessa Charles

With thanks to:
S. Aumon, E. Gianfelice-Wendt, B. Holzer, K. Oide, T. Tydecks, F. Zimmermann and the entire FCC-ee optics team

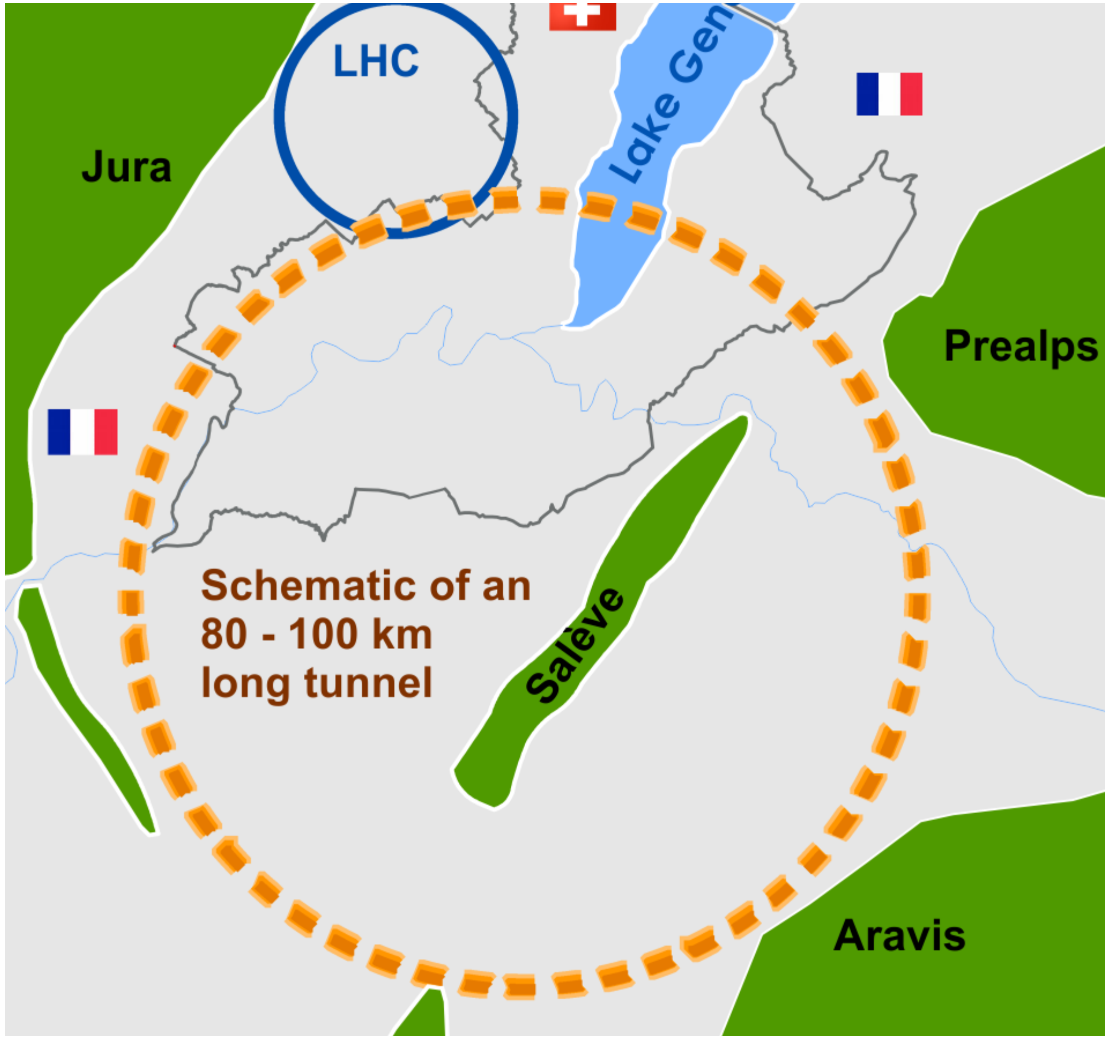
DESY seminar 18.06.2019

Continuing exploration …

Particle colliders are powerful instruments in physics for discoveries and high precision measurements because they provide well controlled experimental conditions in laboratory environment



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

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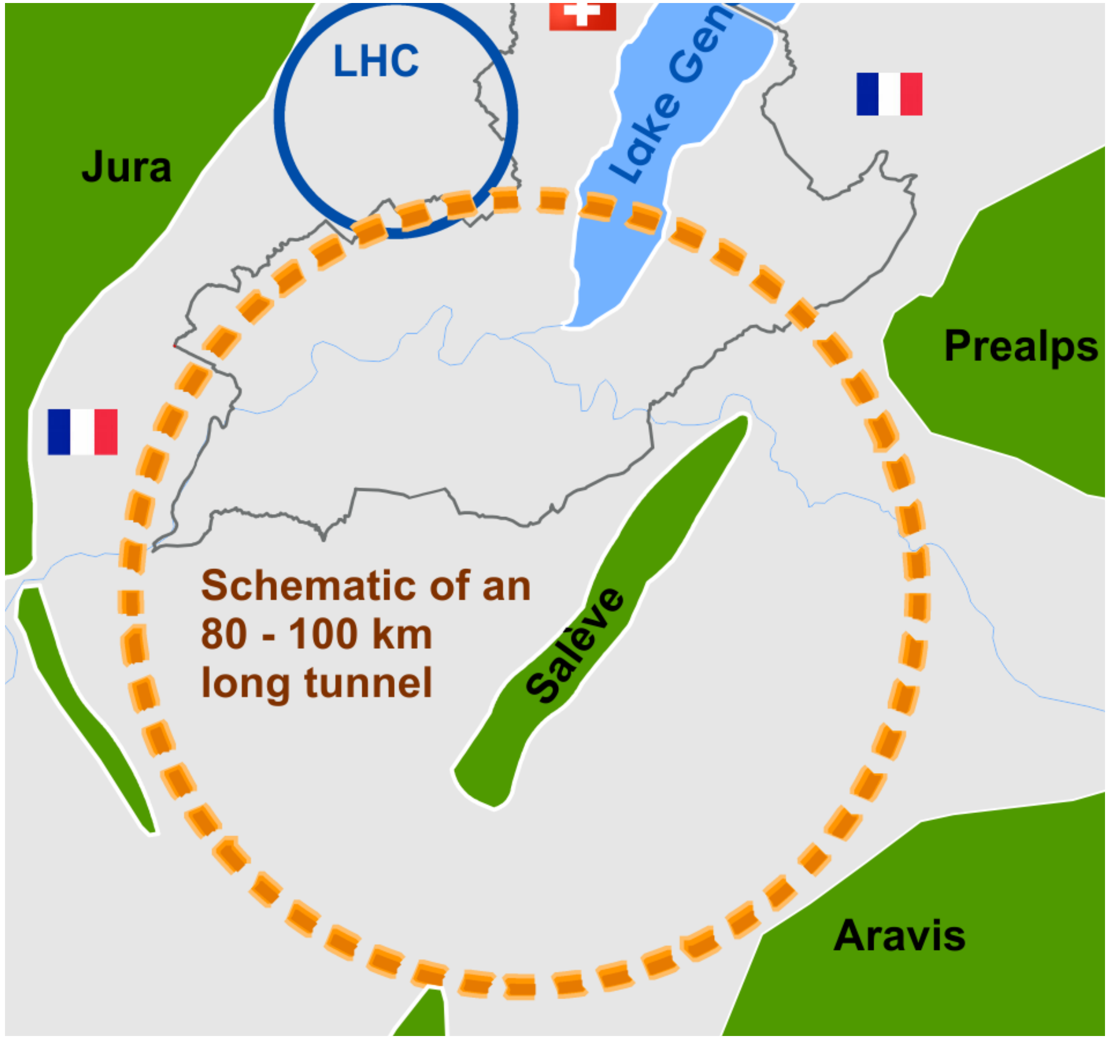

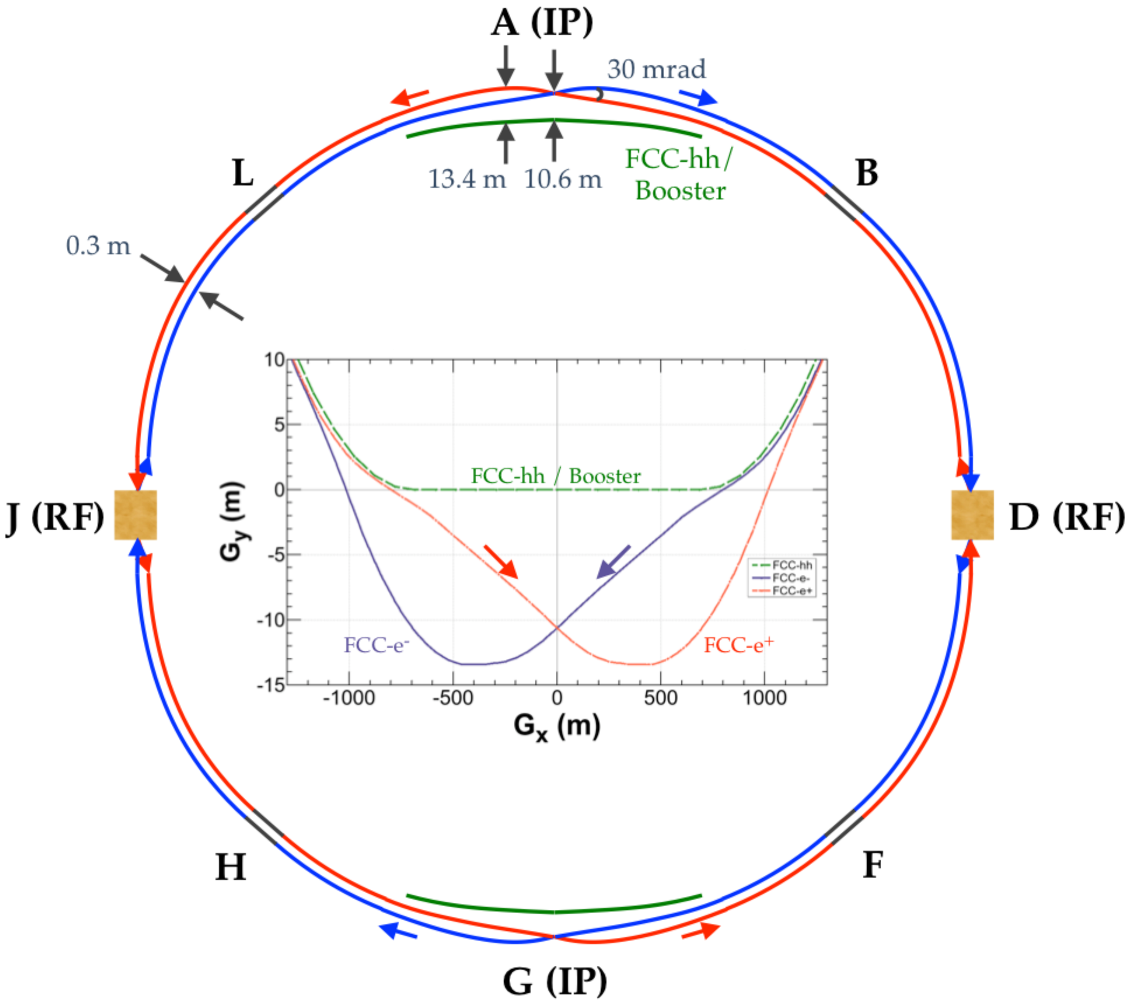

Key parameters for FCC-ee

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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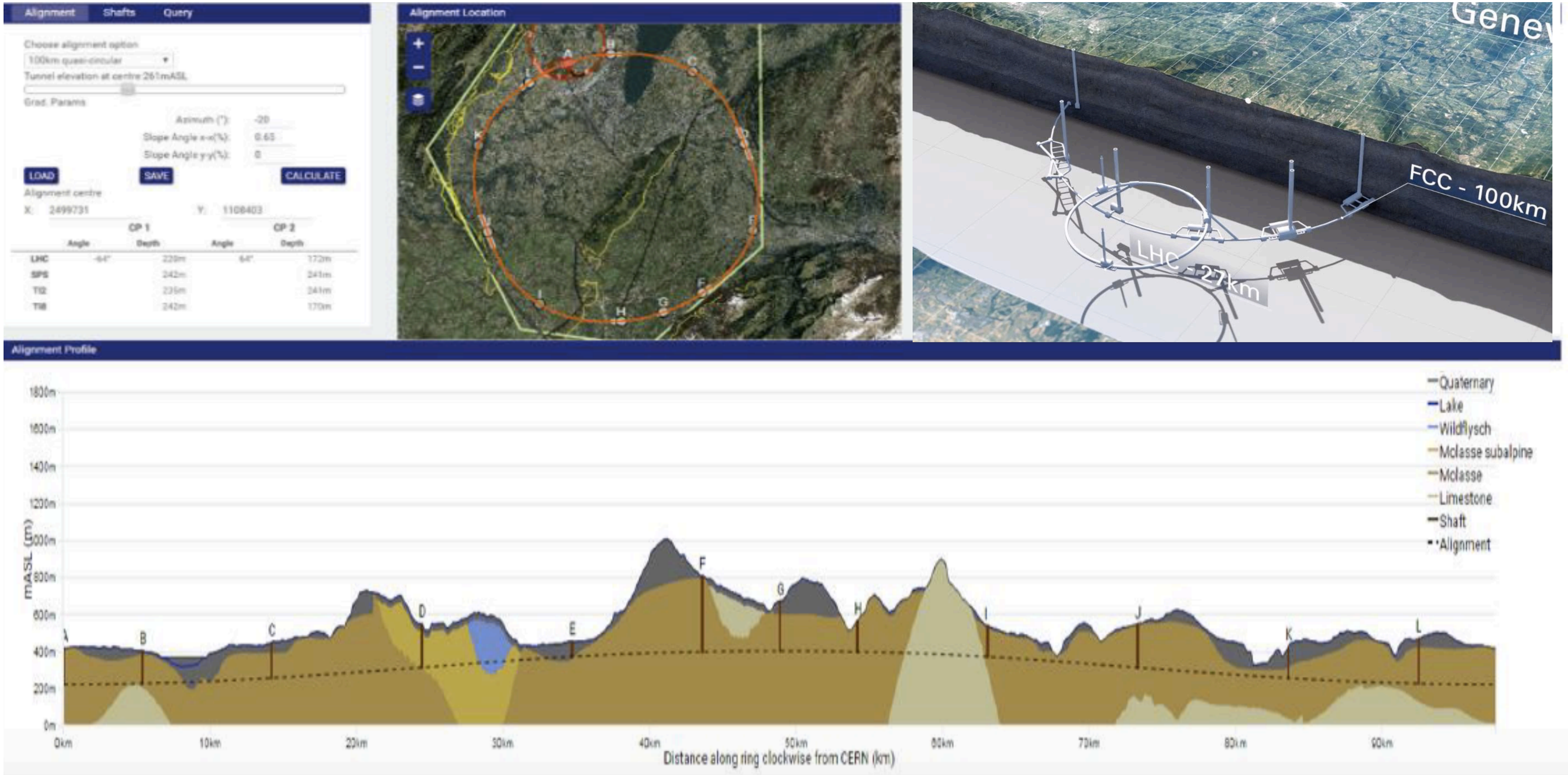
Geology and Civil Engineering studies, Implementation of the 100 km tunnel



M. Benedikt

Integrated FCC schedule

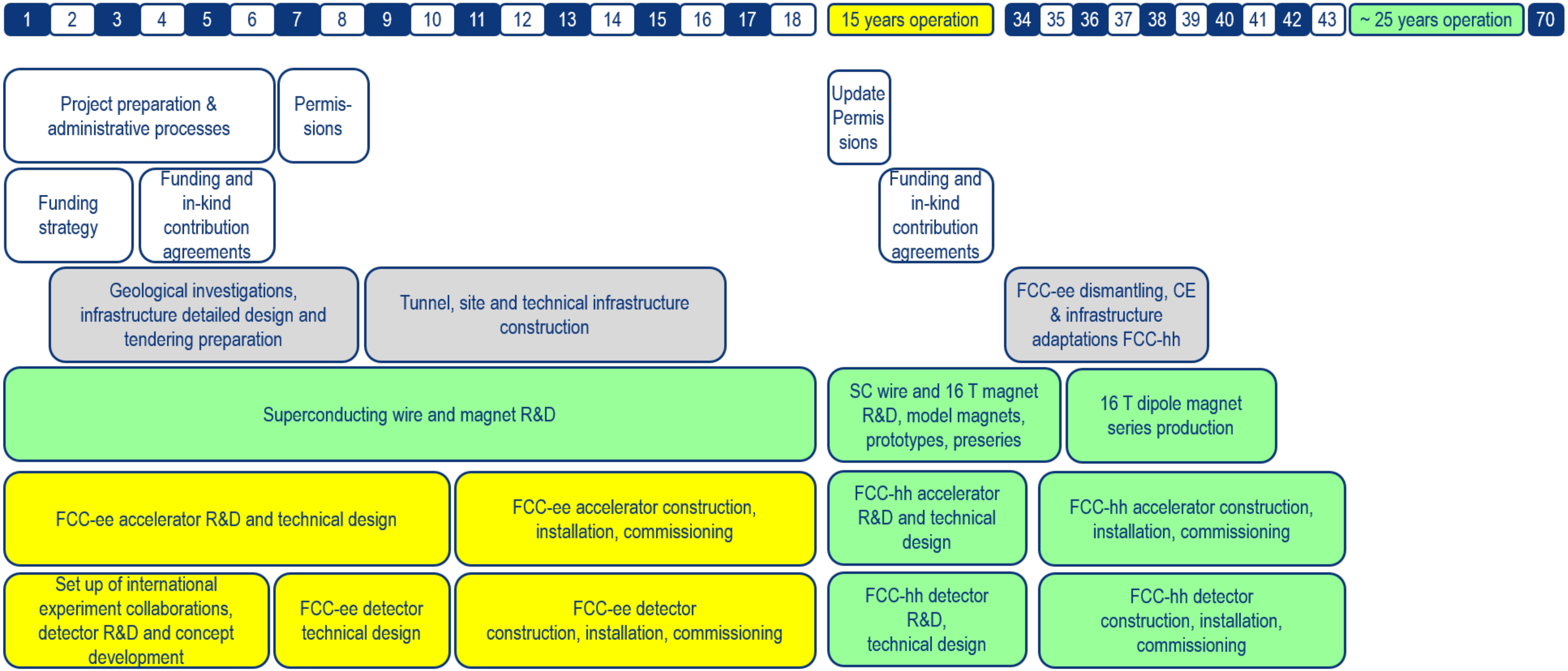
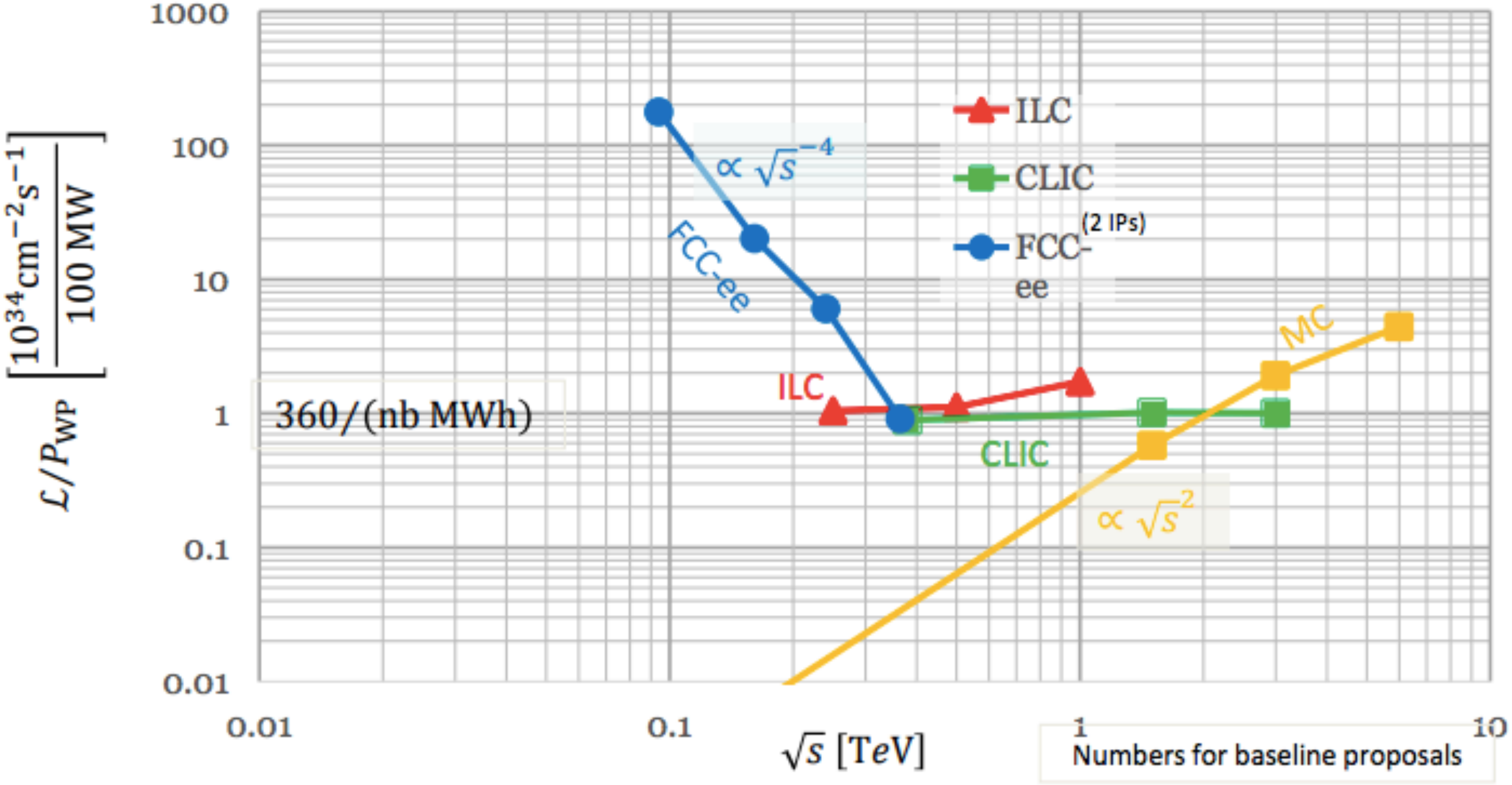


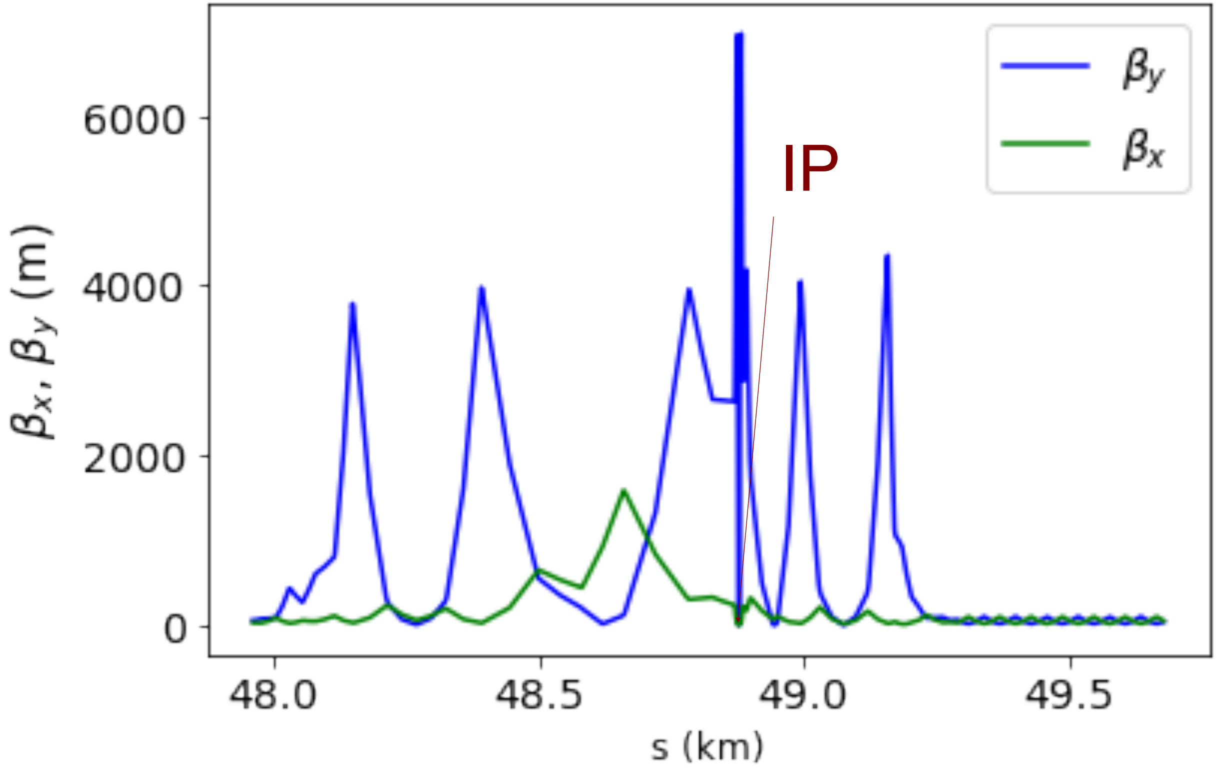
Figure of merit for proposed lepton colliders

Disclaimers:
1. This is not the only possible figure of merit
2. The presented numbers have different levels of confidence/optimism; they are still subject to optimisations



E. Jensen

FCC-ee Emittance Tuning: Challenges & Constraints



$\beta_y^* = 1.6$ mm

$\beta_{x,\mathtt{max}} = 1587.97$ m
$\beta_{y,\mathtt{max}} = 6971.55$ m

Large emittance ratio, $\epsilon_y/\epsilon_x = 0.201\%$

Vertical dispersion & betatron coupling dominate ε_y growth

Horizontal emittance:

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

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

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

Vertical emittance:

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

Sources of vertical emittance growth:

- vertical dispersion D_y
- betatron coupling
- opening angle ~ $1/\gamma$ (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)

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

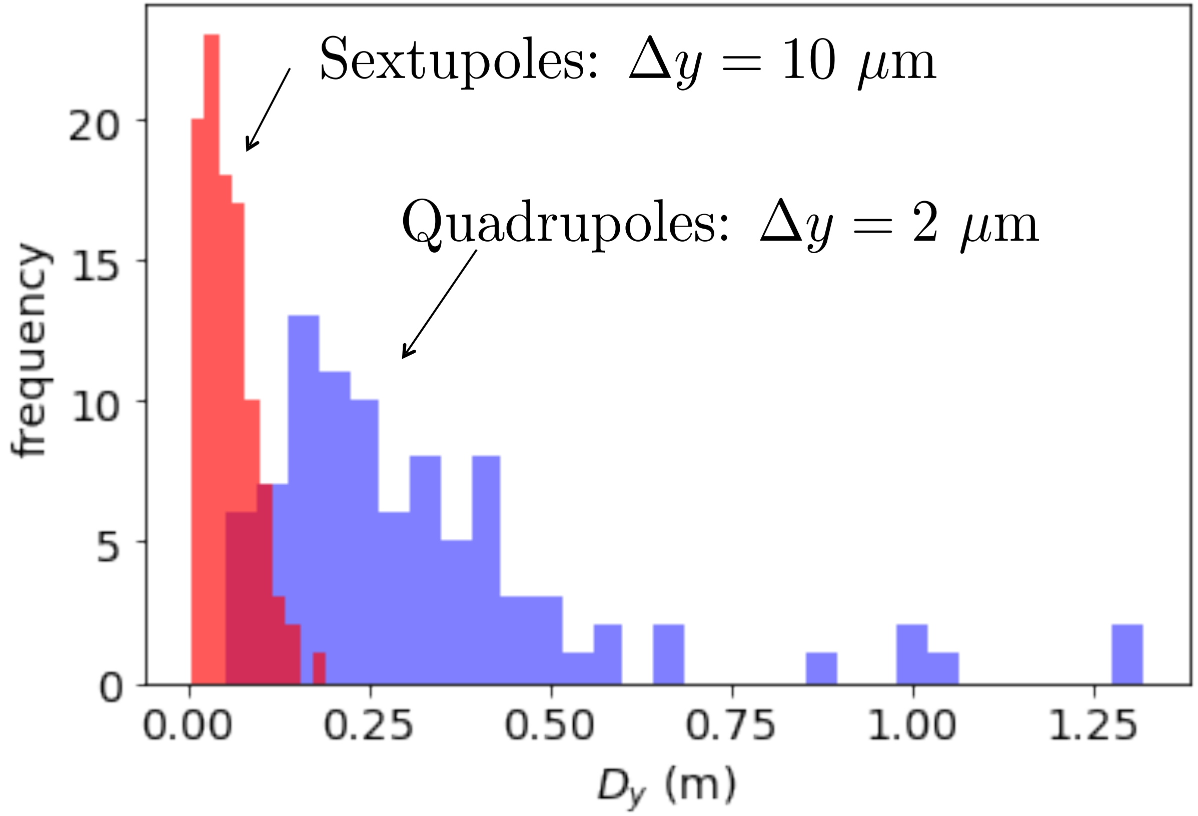
- Linear coupling:
  - Coupling resonant driving terms (RDT)
    - 1 skew at each sextupole + skews correctors at the IP

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

- Beta beating correction & Horizontal dispersion via Response Matrix:
  - Rematching of the phase advance at the BPMs
    - 1 trim quadrupole at each sextupole

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

Sensitivity of FCC-ee to errors



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

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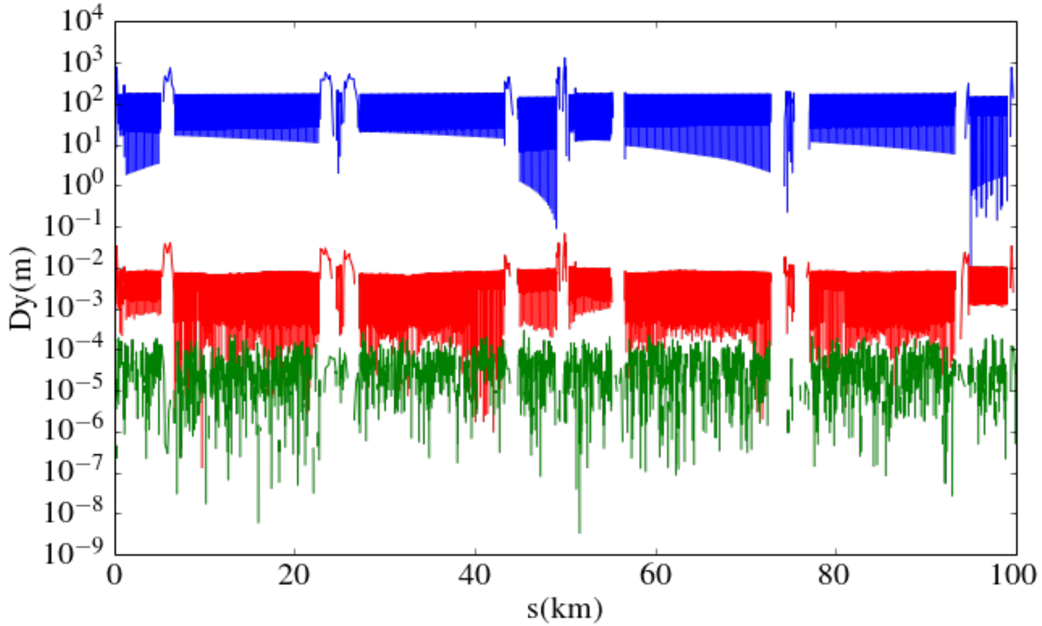
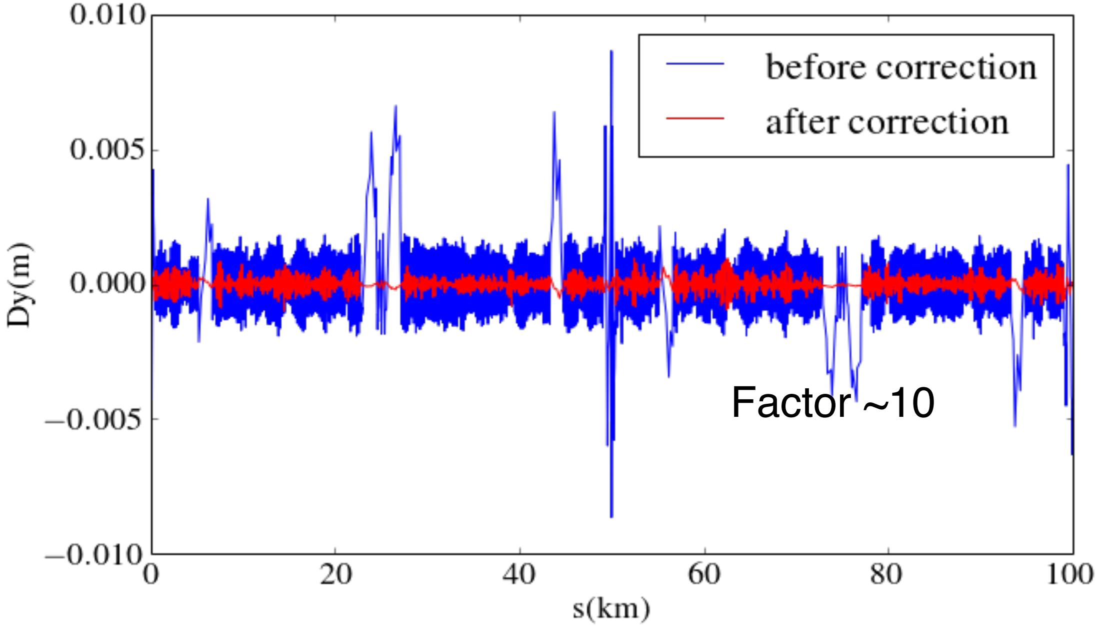
Correction methods applied to *only* Vertical Quadrupole Misalignments (σ_y =100 μm)

Sextupoles turned off:



Switch on sextupoles

Dispersion and coupling correction



Initial D_y

After orbit correction - factor 2e4 improvement

DFS - factor 50 improvement

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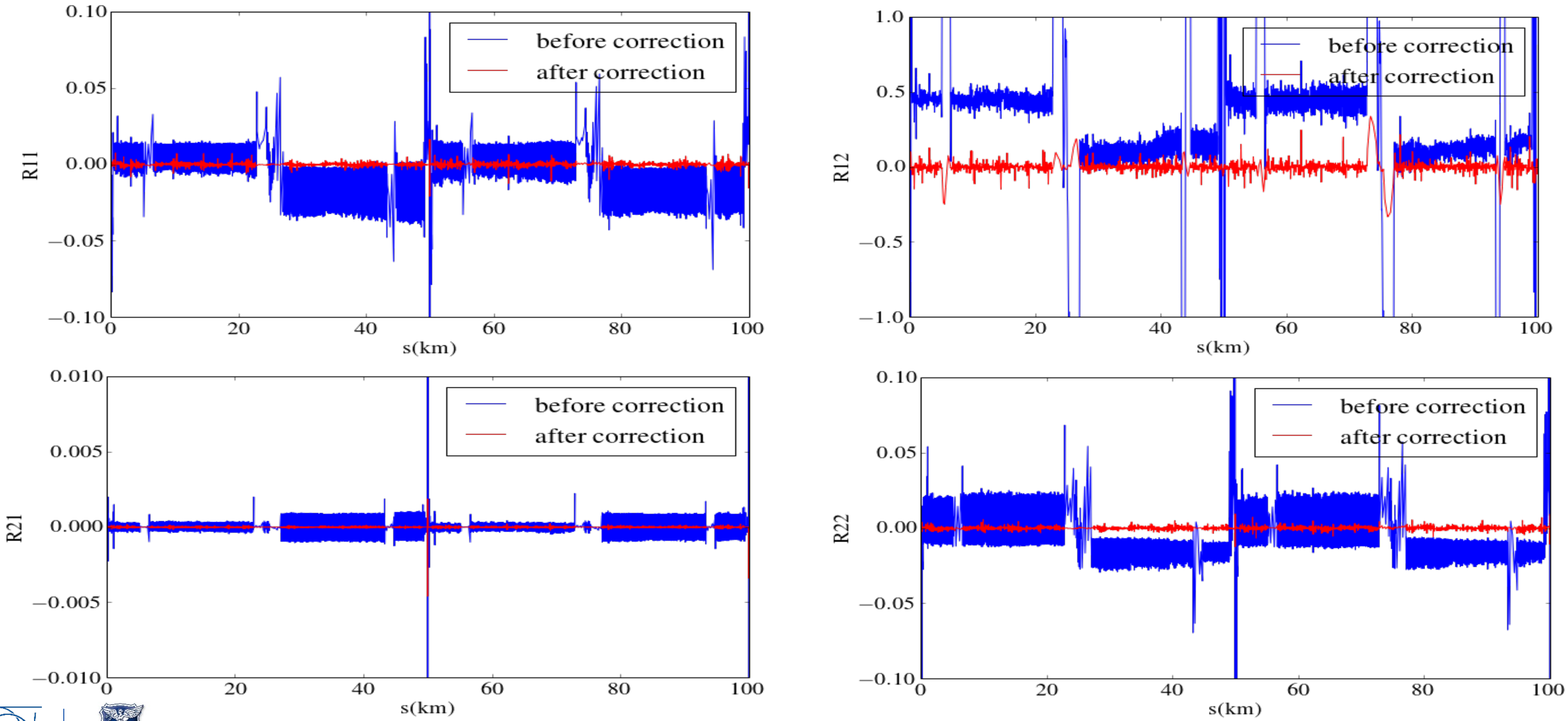
Coupling matrix elements



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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, $\beta_{y,\ max}$*
  - 1 step Dispersion Free Steering w/o sextupole
  - +
    1 step coupling correction
  - *CHECK of tunes, orbit, $\beta_{y,\ max}$*
  - Save x,x’,y,y’ at the beginning of the machine

Loop 8 times

Loop 8 times

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

  (details on next slide)

- **Final correction**

  (details on next slide)

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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

- **Final correction (at 100% sextupole strength)**
  - *CHECK of tunes, orbit, $\beta_{y,\ max}$*
  - Apply required corrections based upon checks
  - *CHECK if $D_{y,RMS} > 0.001$ m,* then apply coupling and dispersion correction

These two steps repeated ~12 times

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

Loop 10 times

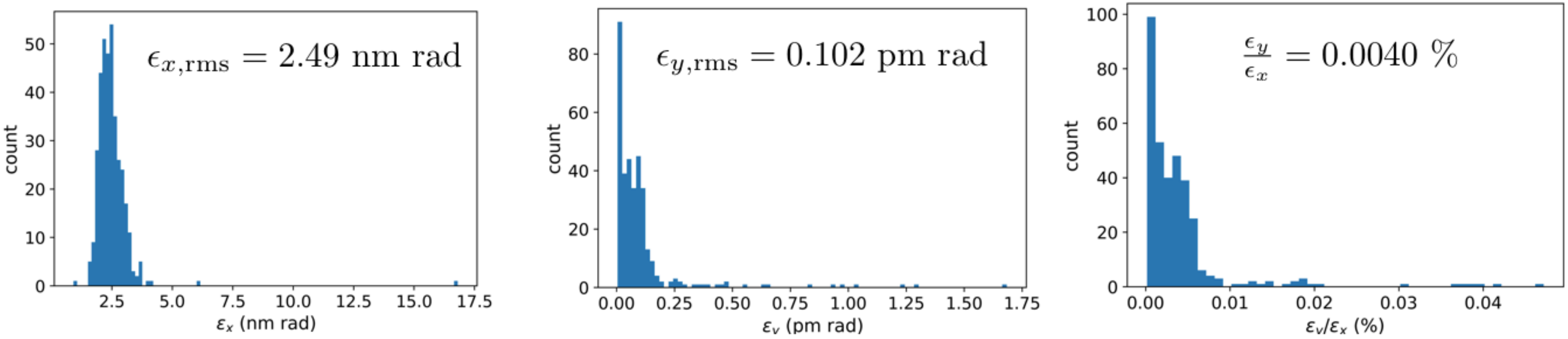
Corrected lattices

- 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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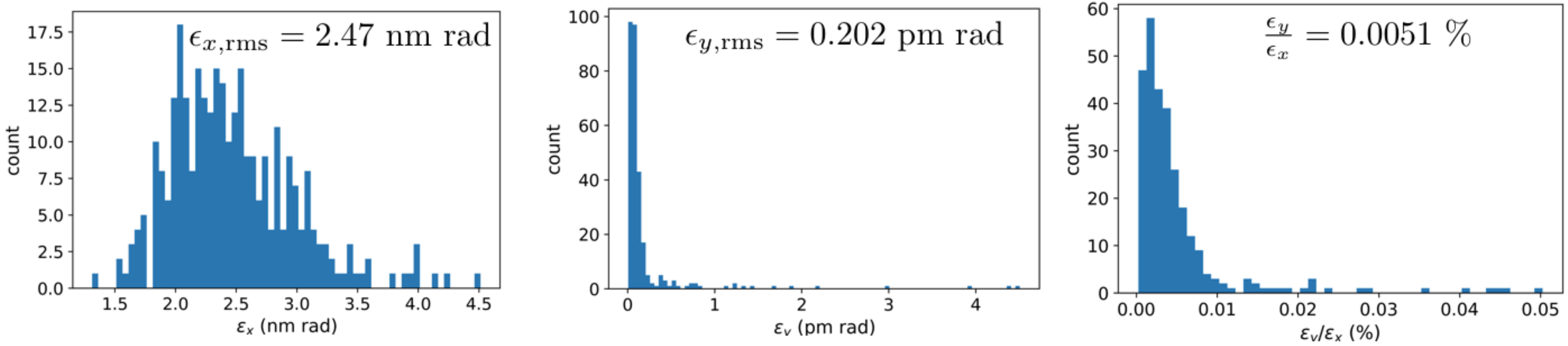

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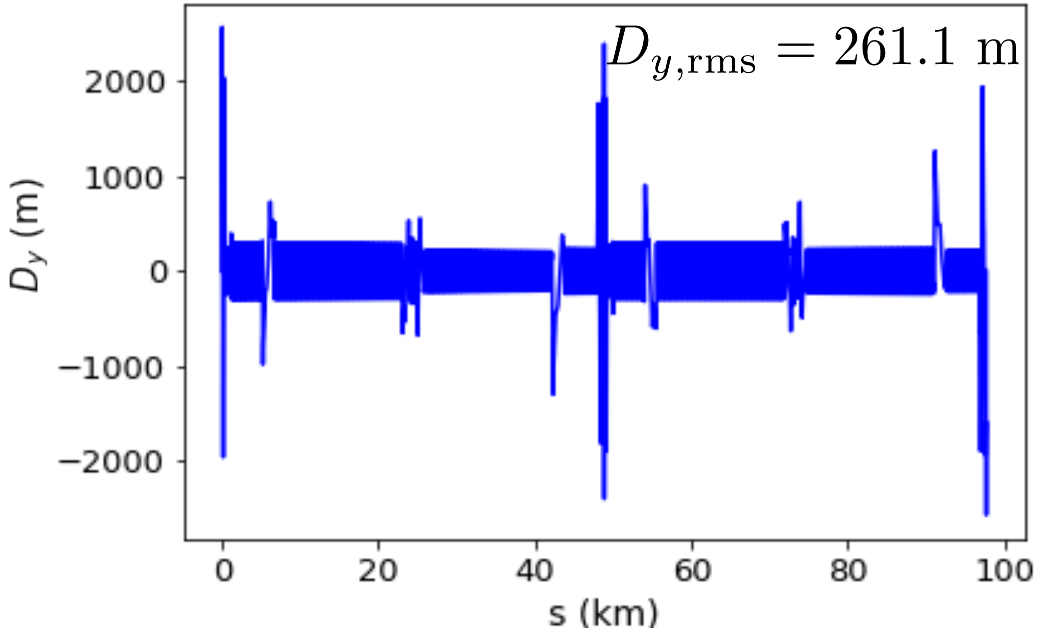
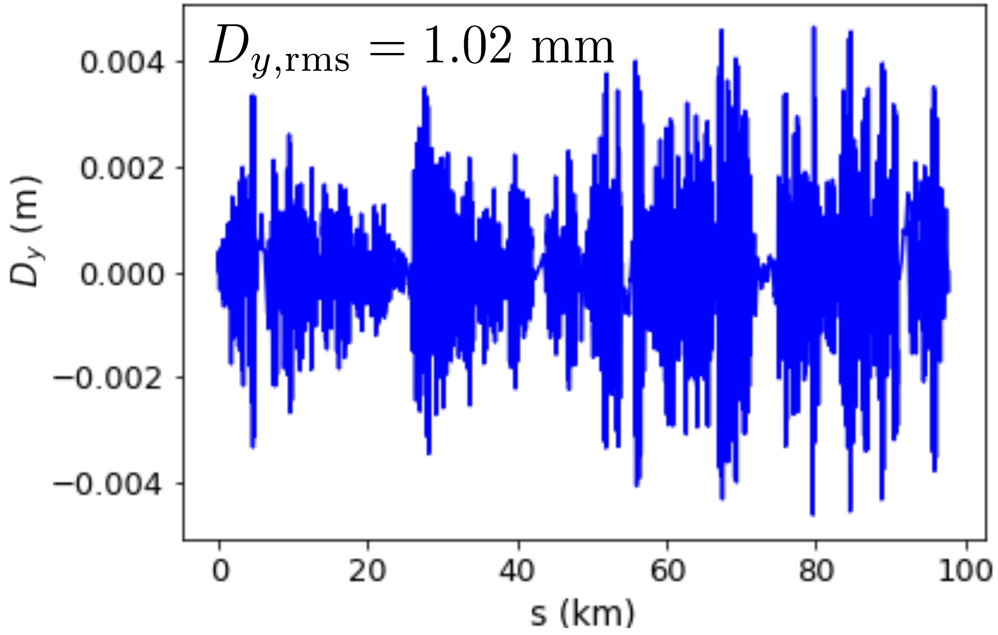
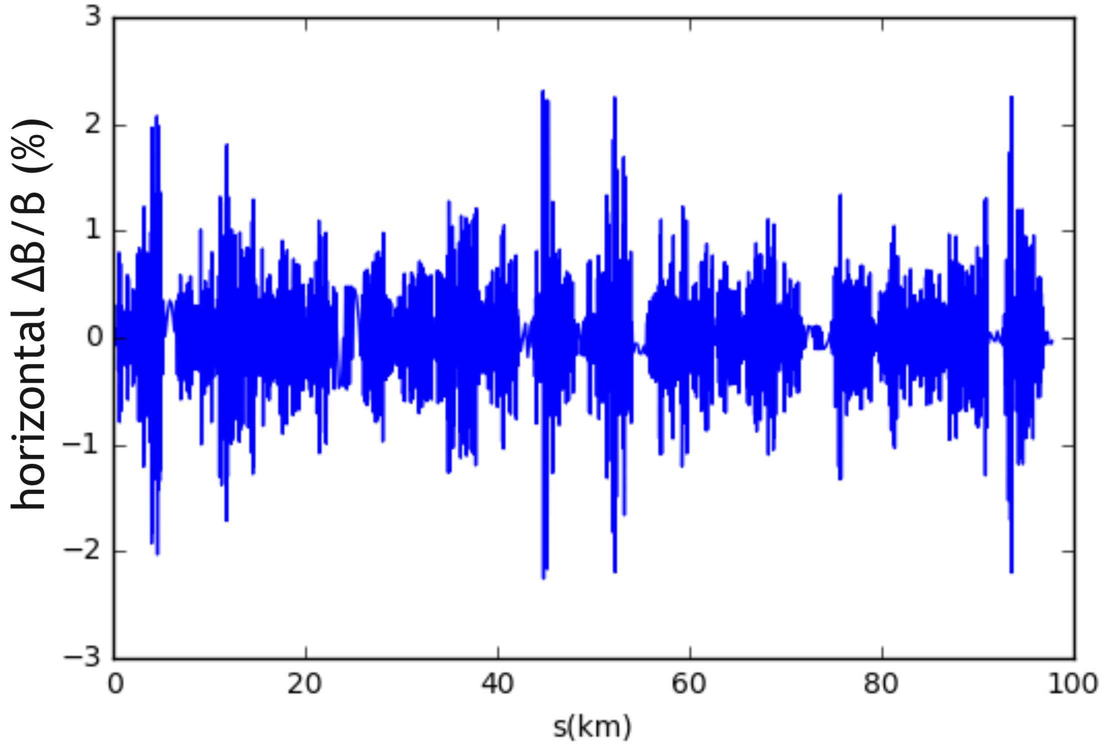
Vertical dispersion before and after correction

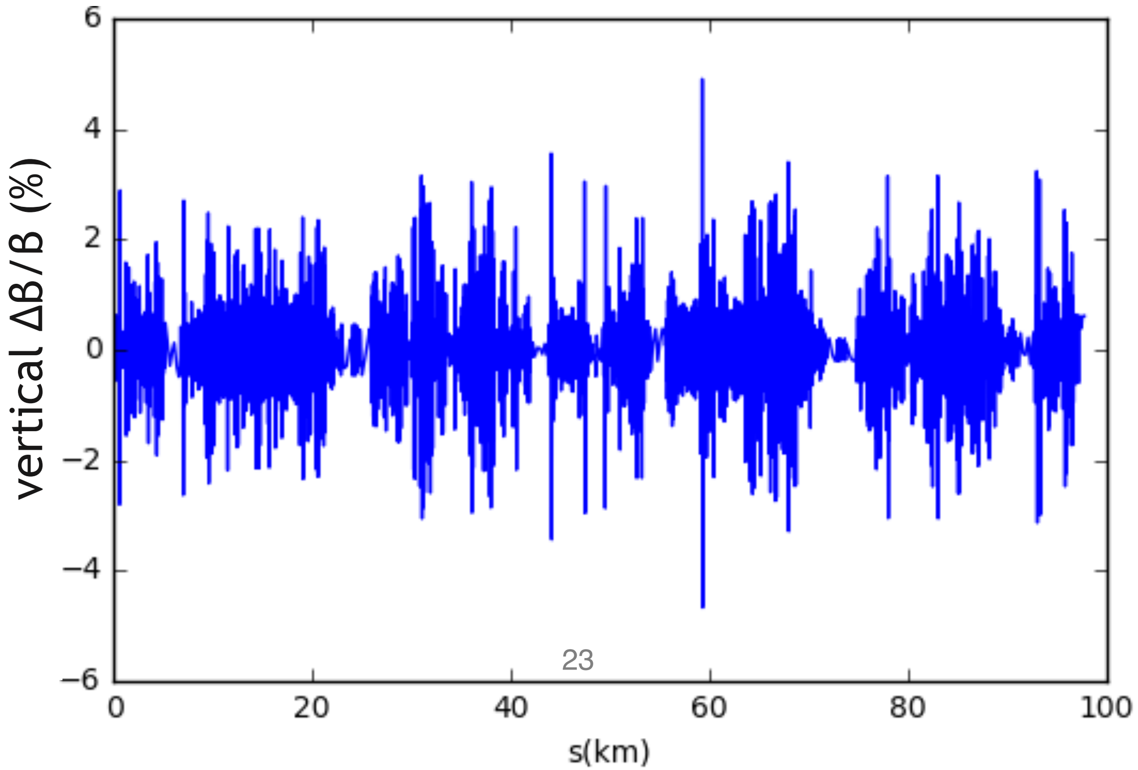
Dispersion introduced through: quadrupoles: Δx = 100 μm, Δy = 100 μm, Δθ = 100 μm
sextupoles: Δx = 100 μm, Δy = 100 μm, Δθ = 100 μm
dipoles: Δx = 100 μm, Δy = 100 μm, Δθ = 100 μm





Beta beat after correction





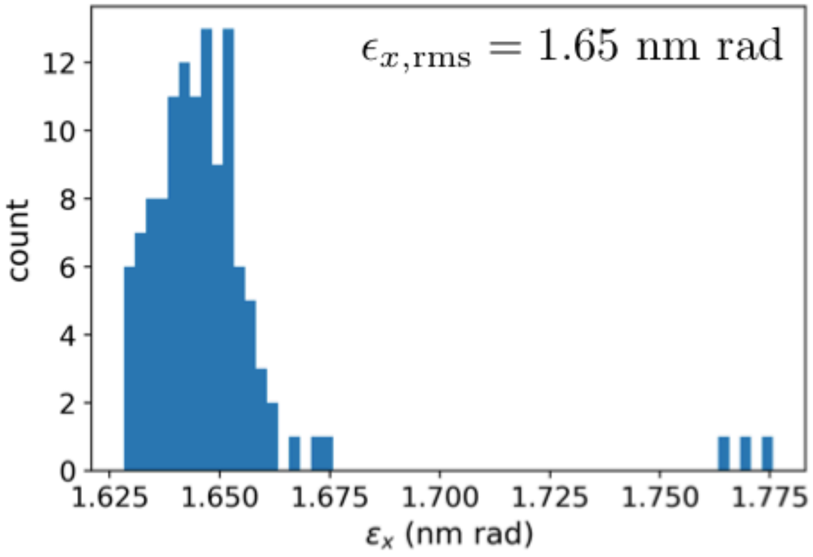
Corrected Lattices results

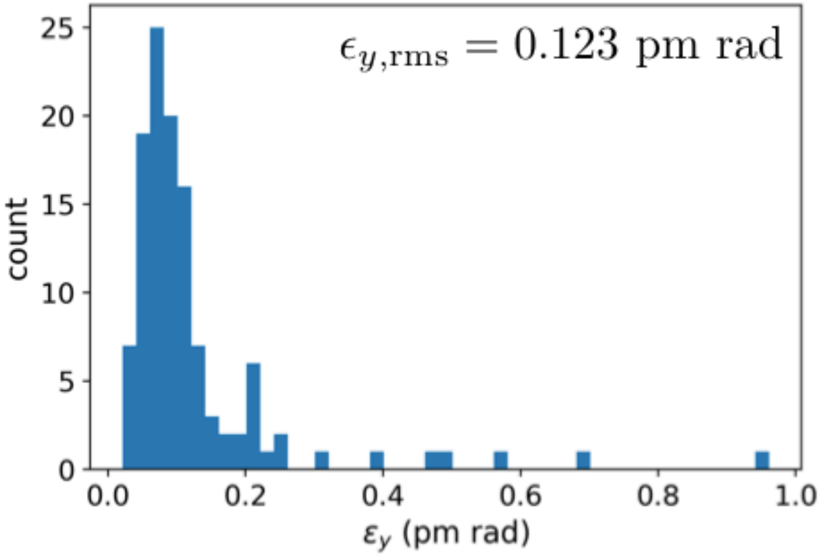
Using the misalignments and roll angles and field errors of :

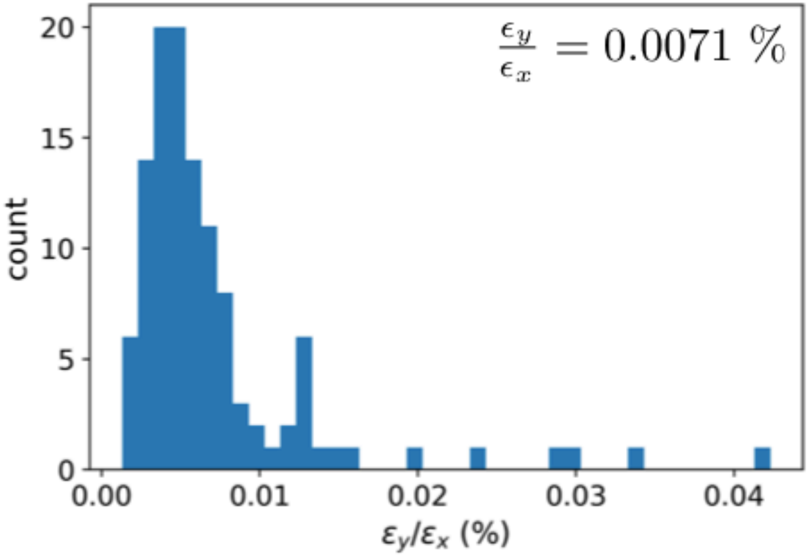
	$\sigma_x(\mu\text{m})$	$\sigma_y(\mu\text{m})$	$\sigma_\theta(\mu\text{rad})$
arc quads	100	100	100
IP quads	100	100	100
sextupoles	100	100	100
dipoles	100	100	100
BPMs	20	20	150

*BPM error relative to quadrupole position

After correction:

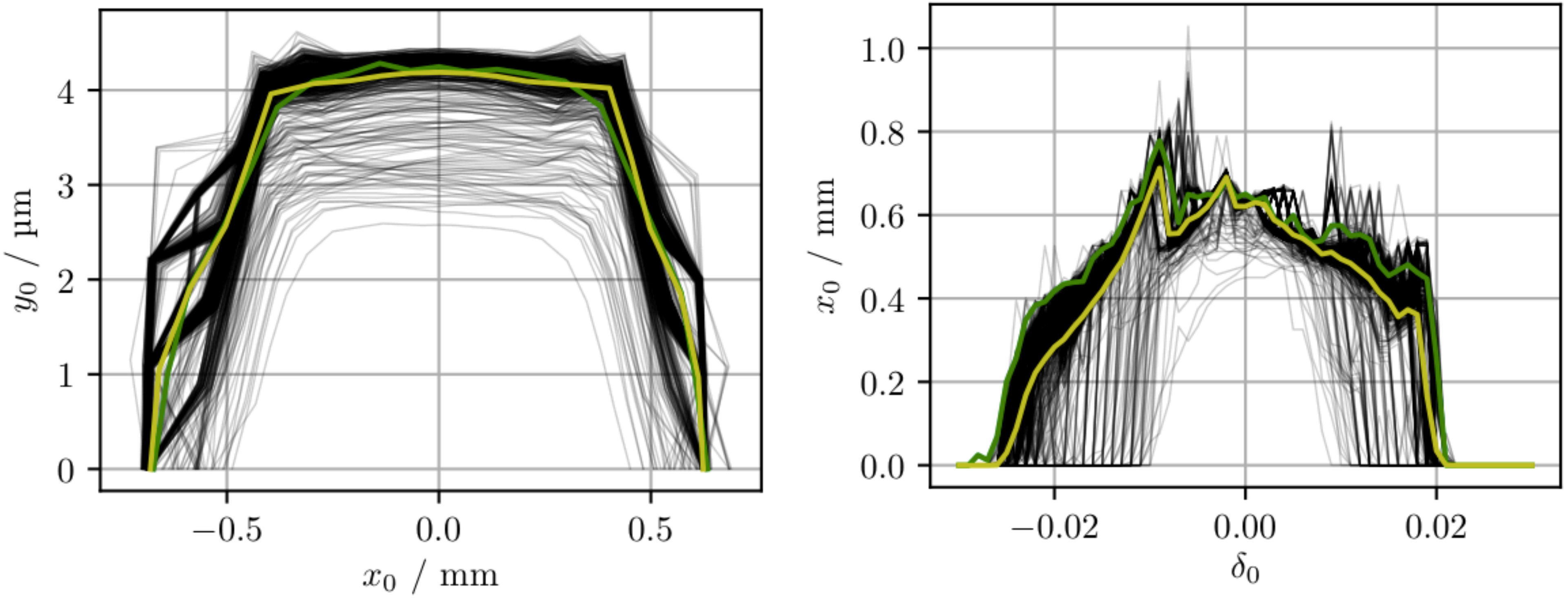






Dynamic and Momentum Aperture

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

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Improving Dynamic and Momentum Aperture Using PSO

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

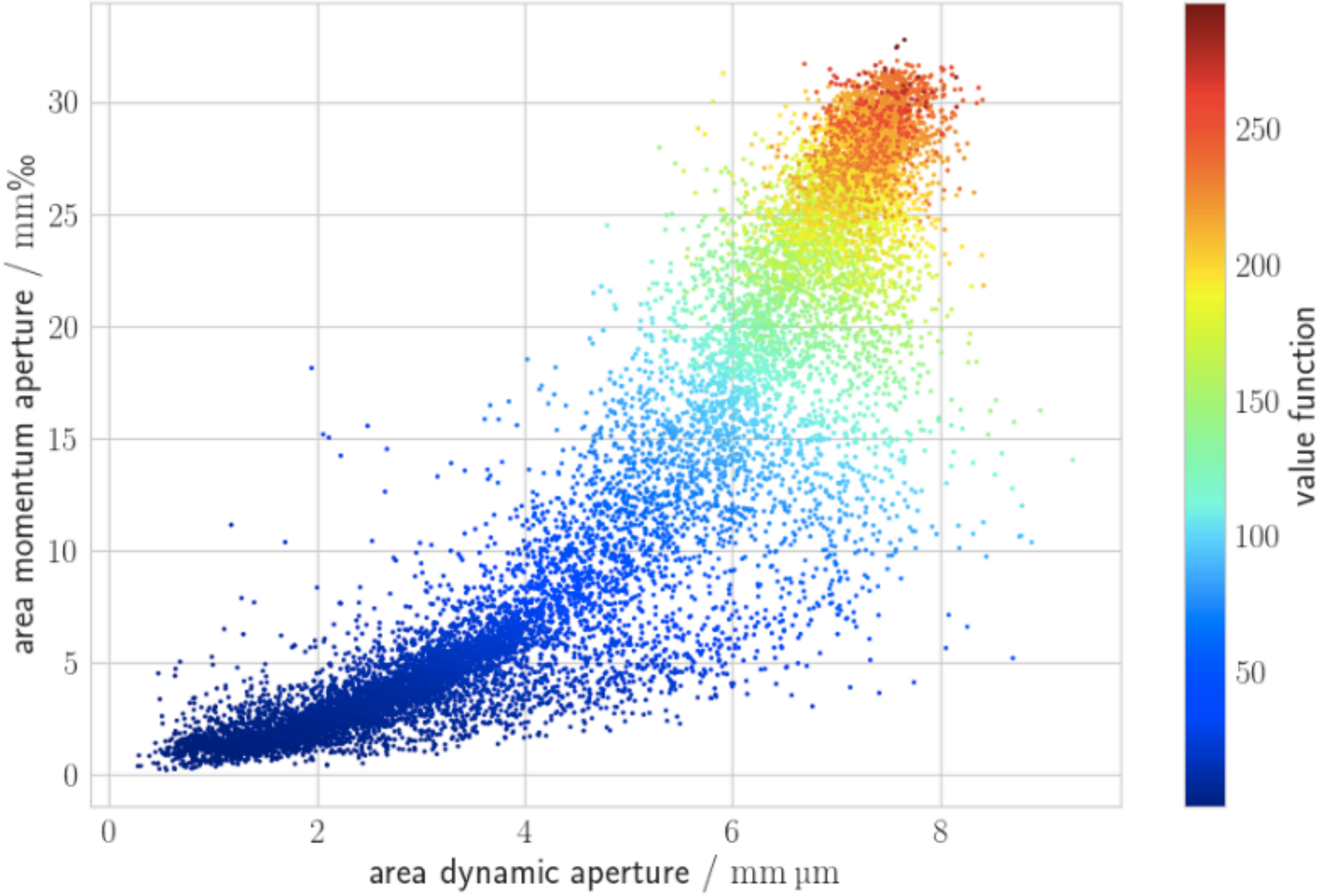
Whilst:

- keeping sextupole pairs for –I transform
- maintain periodicity of machine
- constraint on final focus sextupole strength

$\Rightarrow$ 294 degrees of freedom

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

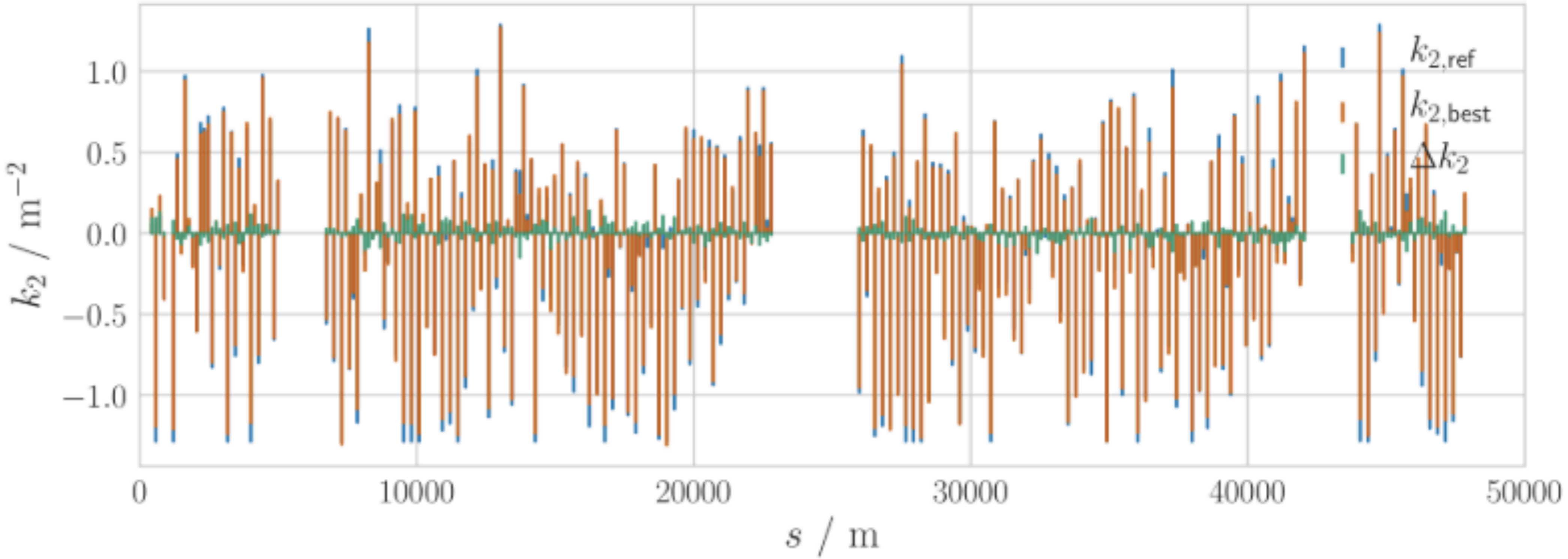
Accumulated set of solutions



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

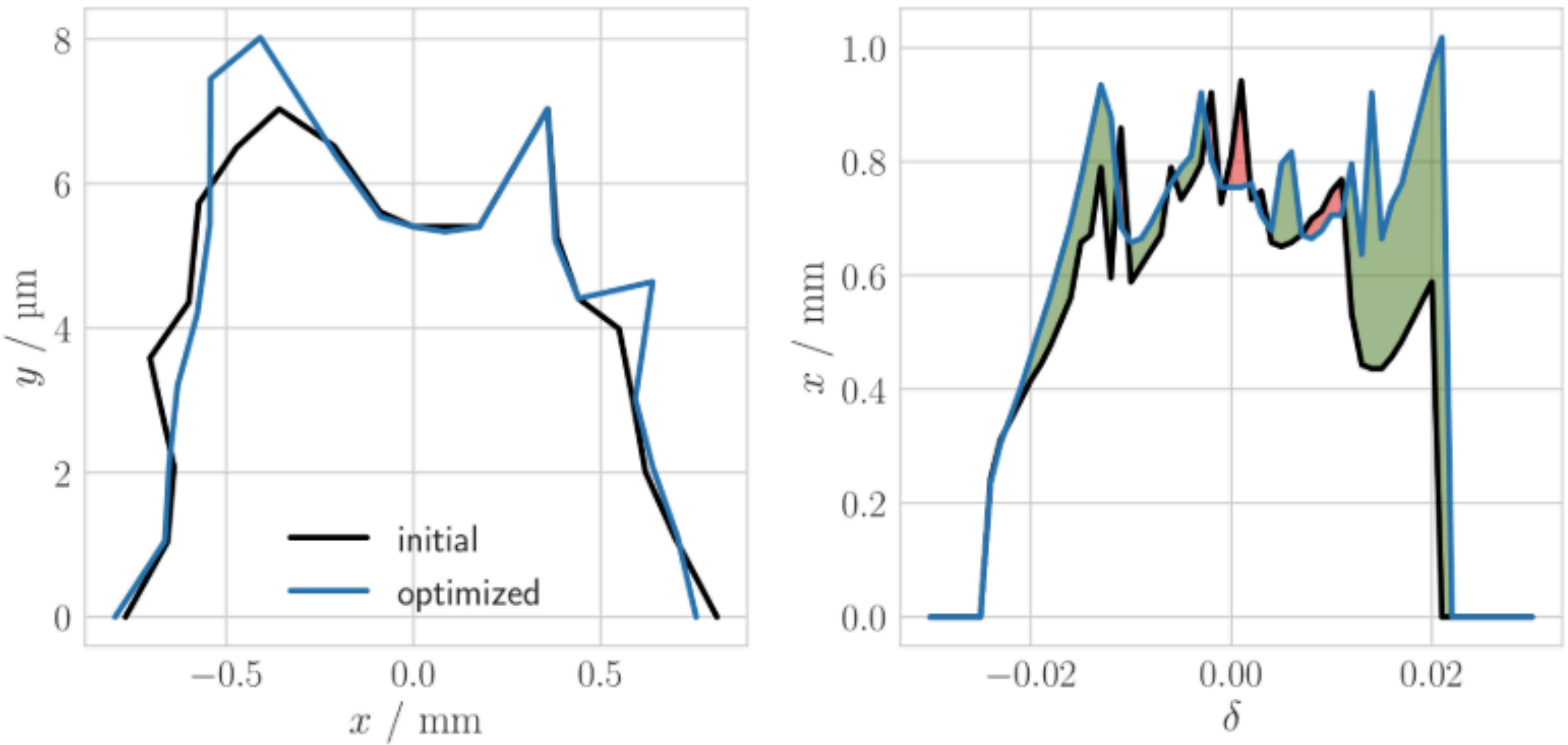


Figure 2.15: Dynamic aperture (left) and momentum aperture (right) for reference lattice (black) and optimised lattice (blue). The area of dynamic aperture is improved by 3.1 % while the area of momentum aperture is increased by 18.0 %.

T. Tydecks

Conclusions

FCC-ee poses a challenge for emittance tuning, however with

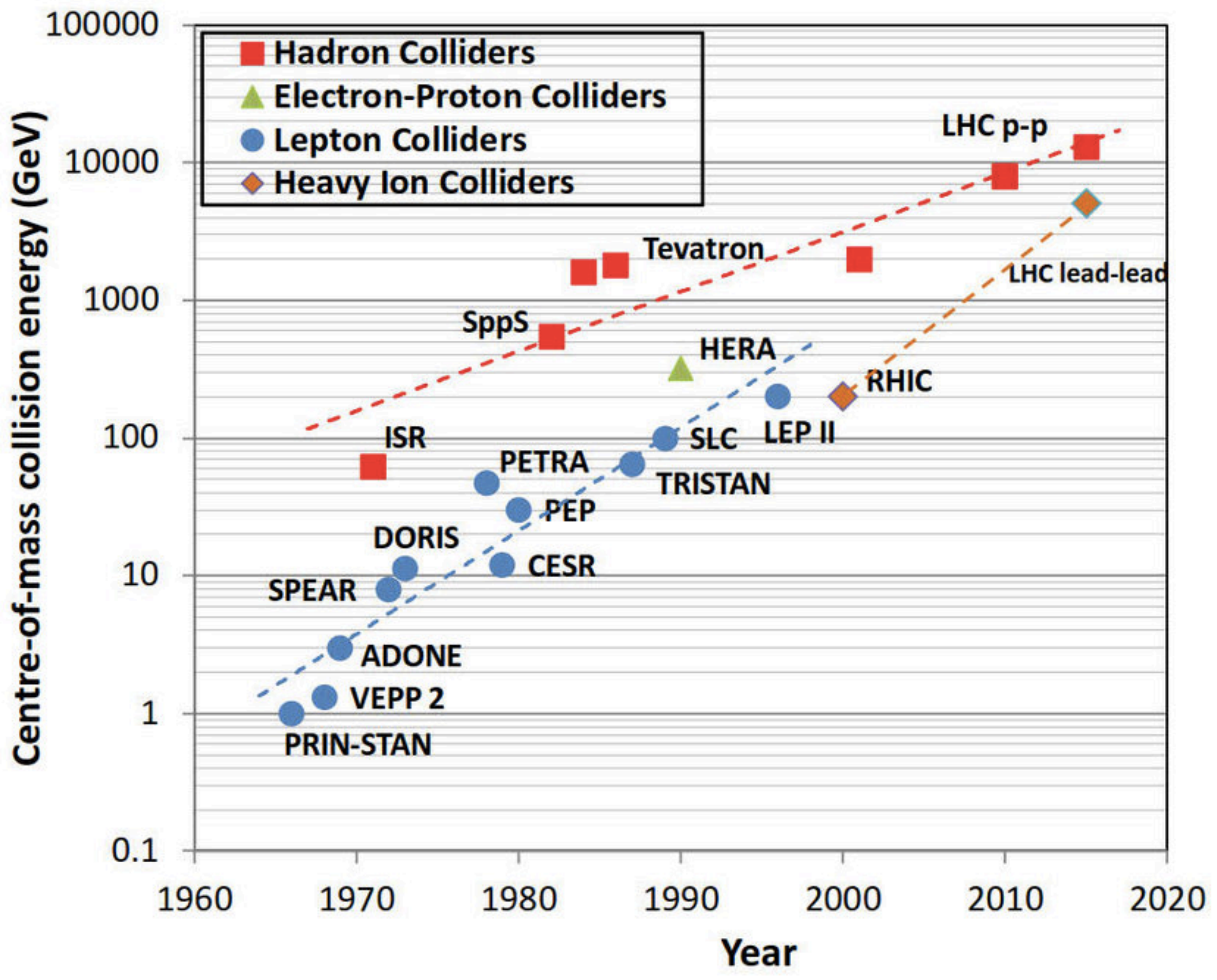
100 µm, 100 µrad misalignments and roll angles in arc quads, IP quads & sextupoles and dipoles, and

with BPM misalignments of 20 µm and 150 µrad,

the mean vertical emittance achieved after correction schemes applied is ε_y = 0.123 pm rad and a coupling ratio of 0.0071 %.

Thank you

Back up slides



Hadron Colliders
Electron-Proton Colliders
Lepton Colliders
Heavy Ion Colliders
Centre-of-mass collision energy (GeV)
100000
10000
1000
100
10
1
0.1
1960
1970
1980
1990
2000
2010
2020
Year
LHC p-p
Tevatron
LHC lead-lead
SppS
HERA
RHIC
LEP II
SLC
ISR
PETRA
TRISTAN
PEP
DORIS
CESR
SPEAR
ADONE
VEPP 2
PRIN-STAN

Comparison of costings

1 GILCU = 10^9 ILC Units = 1G$ 2012

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

D. Schulte

Introduction

- *Resonant de-polarization* has been proposed for accurate beam energy calibration ($\ll$ 100 keV) at 45 and 80 GeV beam energy.
  It relies on the relationship $\nu_{spin}=a\gamma$ [a].
- Beam polarization is obtained "for free" through Sokolov-Ternov effect.
  The effect is in practice restricted to a limited range of values of machine size and beam energy because
  - of the build-up rate
  - it is jeopardized by machine imperfections (spin/orbital motion resonances) which affects the reachable level of polarization in particular at high energy.
- 10% beam polarization is estimated to be enough for the purpose of energy calibration.

[a] a = gyromagnetic anomaly

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E. Gianfelice-Wendt

Sokolov-Ternov polarization

Beam get vertically polarized in the ring guiding field

$$P_\infty^{\mathrm{ST}} = 92.3\% \qquad \tau_p^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_0 C}\oint\frac{ds}{|\rho|^3}$$

FCC-e^+e^-

E (GeV)	τ_{pol} (h)	$\tau_{10\%}$ (*) h
45	256	29
80	14	1.6

← wiggler magnets needed at 45 GeV for decreasing $\tau_{10\%}$ to a couple of hours.

(*) Time needed to reach P=10% for energy calibration

$$\tau_{10\%} = -\tau_p \times \ln(1 - 0.1/P_\infty)$$

E. Gianfelice-Wendt

Polarization in real storage rings

A perfectly planar machine (w/o solenoids) is always *spin transparent*.

Sokolov-Ternov effect in the guiding dipole field	Perturbations (v-bends, vertical orbit in quads etc.)
↓	↓
Polarisation	Depolarisation
↘	↙

Equilibrium polarisation $(< P_{\infty}^{\mathrm{ST}})$

Spin diffusion may be particularly large when spin and orbital motions are in resonance

$$\nu_{spin} \pm mQ_x \pm nQ_y \pm pQ_s = \text{integer}$$

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Assumed misalignments:

	IR Quads	other Quads	Sexts
δx (μm)	50	100	100
δy (μm)	50	100	100
$\delta\theta$ (μrad)	50	100	100

- BPMs are supposed perfectly aligned to the near-by quadrupole.
- Tune shift and coupling are corrected by 1204 normal + 1204 skew *thin lenses* quadrupoles.

SITROS can't treat thin lenses $\longrightarrow$ replaced by 5 mm long quadrupoles.

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Seed 13, with radiation, no wigglers

	x_{rms} (μm)	y_{rms} (μm)	ϵ_x (pm)	ϵ_y (pm)
MADX (thin)	23	22	276.4	0.04
MADX (thick)	35	22	278.4	0.04
SITROS (analytic)	34	21	262.8	0.38

Seed 13, with radiation, 8 wigglers, B_w for $\tau_{10\%}$=1.7 h

	x_{rms} (μm)	y_{rms} (μm)	ϵ_x (pm)	ϵ_y (pm)
MADX (thin)	23	22	239.7	0.114
MADX (thick)	35	22	241.5	0.113
SITROS (analytic)	35	21	229.3	0.382

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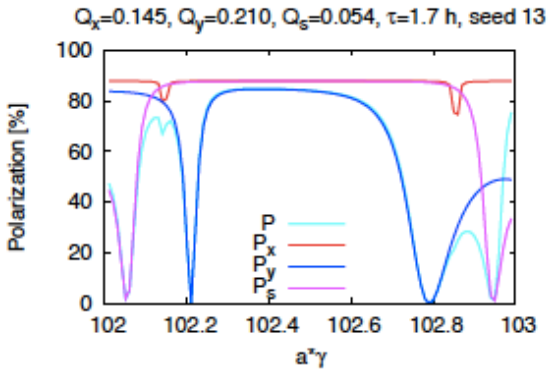
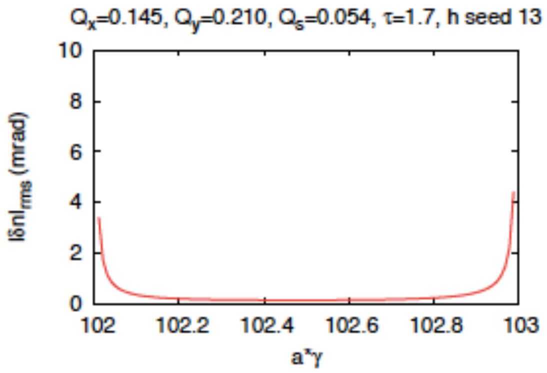
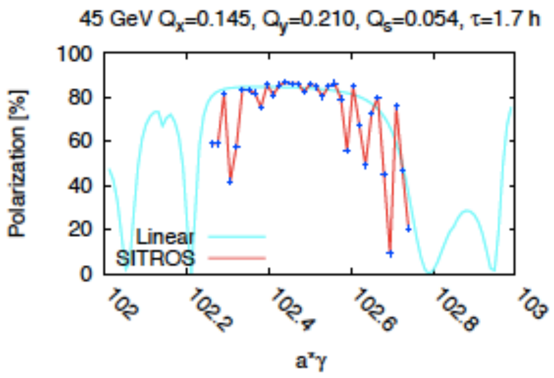
45 GeV optics with 8 wigglers for $\tau_{10\%}$=1.7 h, seed 13.







Beam size at IP1

	σ_x (μm)	σ_y (nm)	σ_ℓ (mm)
analytical	5.966	19.7	5.721
SITROS Tracking	7.114	21.2	5.681

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