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Karlsruhe Institute of Technology

FCC-ee: Lattice optimisation and emittance tuning

Bastian Haerer (CERN, Geneva; KIT, Karlsruhe) for the FCC-ee Lattice Design Team

Physics goals of FCC-ee

Provide highest possible luminosity for a wide physics program ranging from the Z pole to the tt production threshold.

- Beam energy range from 45 GeV to 175 GeV

Main physics programs / energies (+ scan around central values):

- Z (45.5 GeV): Z pole, high precision of M_Z and $\Gamma_{Z,}$
- W (80 GeV): W pair production threshold,
- H (120 GeV): H production,
- T (175 GeV): tt threshold.

All energies quoted refer to BEAM energies

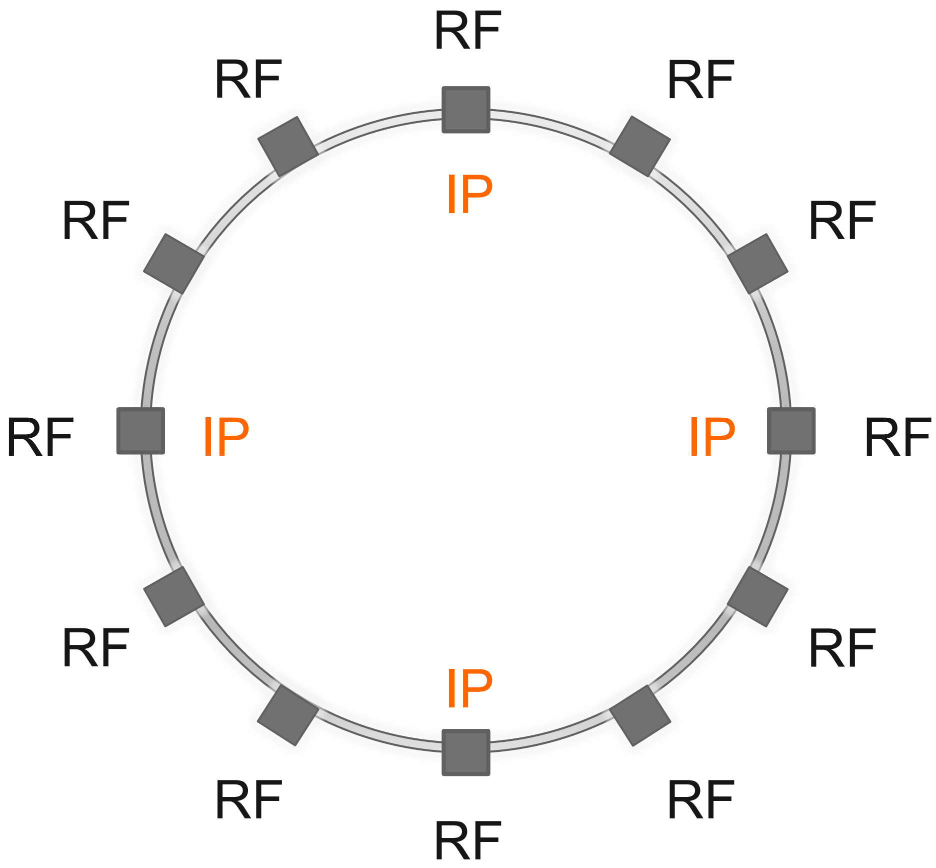
Main challenge: the parameter list

	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
Beam current [mA]	1450	152	30	6.6
Bunches / beam	16700	4490	1330	160
Bunch population [10^{11}]	1.8	0.7	0.46	0.83
Transverse emittance ε - **Horizontal [nm]** - **Vertical [nm]**	 29.2 0.06	 3.3 0.007	 0.94 0.0019	 2 0.002
Momentum comp. [10^{-5}]	18	2	0.5	0.5
Betatron function at IP β* - **Horizontal [mm]** - **Vertical [mm]**	 500 1	 500 1	 500 1	 1000 1
Energy loss / turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	2.5	4	5.5	11

- Design & optimise a lattice for 4 different energies
- Horizontal emittance is increasing with reduced energy

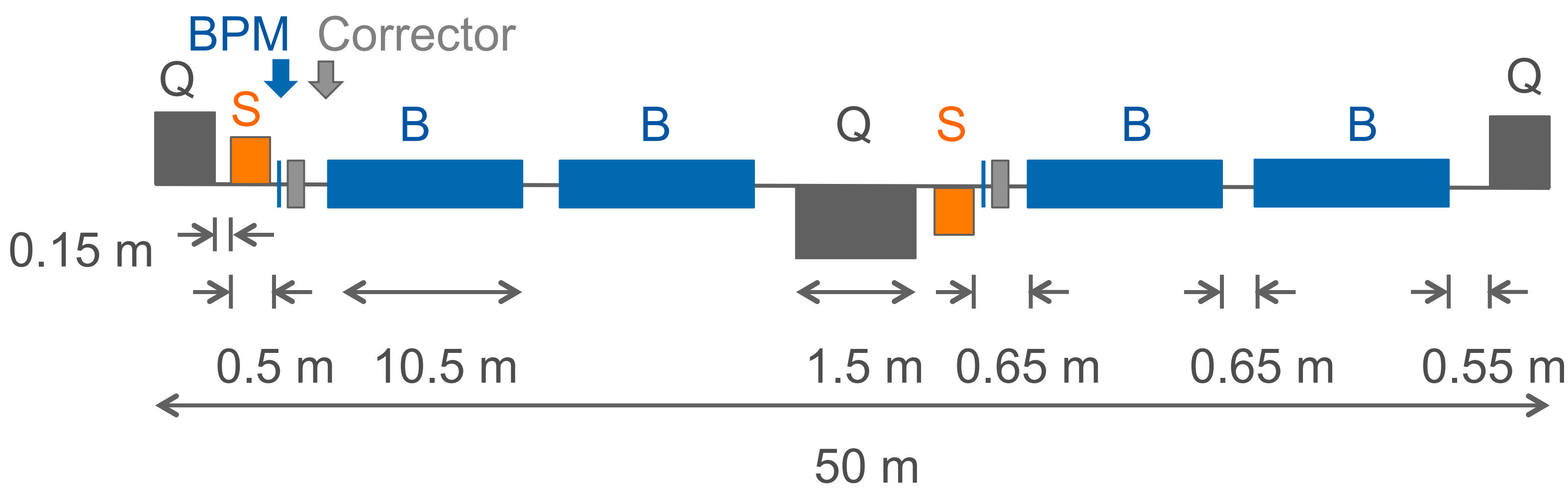
The FCC-ee Layout

- 100 km circumference
- 12 arcs (2 x 3.4 km)
- 12 long straight sections (1.5 km)
  → RF installations
- ~~4 mini-beta insertions~~
- 2 rings side-by-side



FODO cell for 175 GeV

Layout already considers max. dipole length, drift spaces for absorbers, flanges etc.



B = bending magnet, Q = quadrupole, S = sextupole

$N_{dipoles}$ = 6432 (384 half bend) (LHC: 1232)

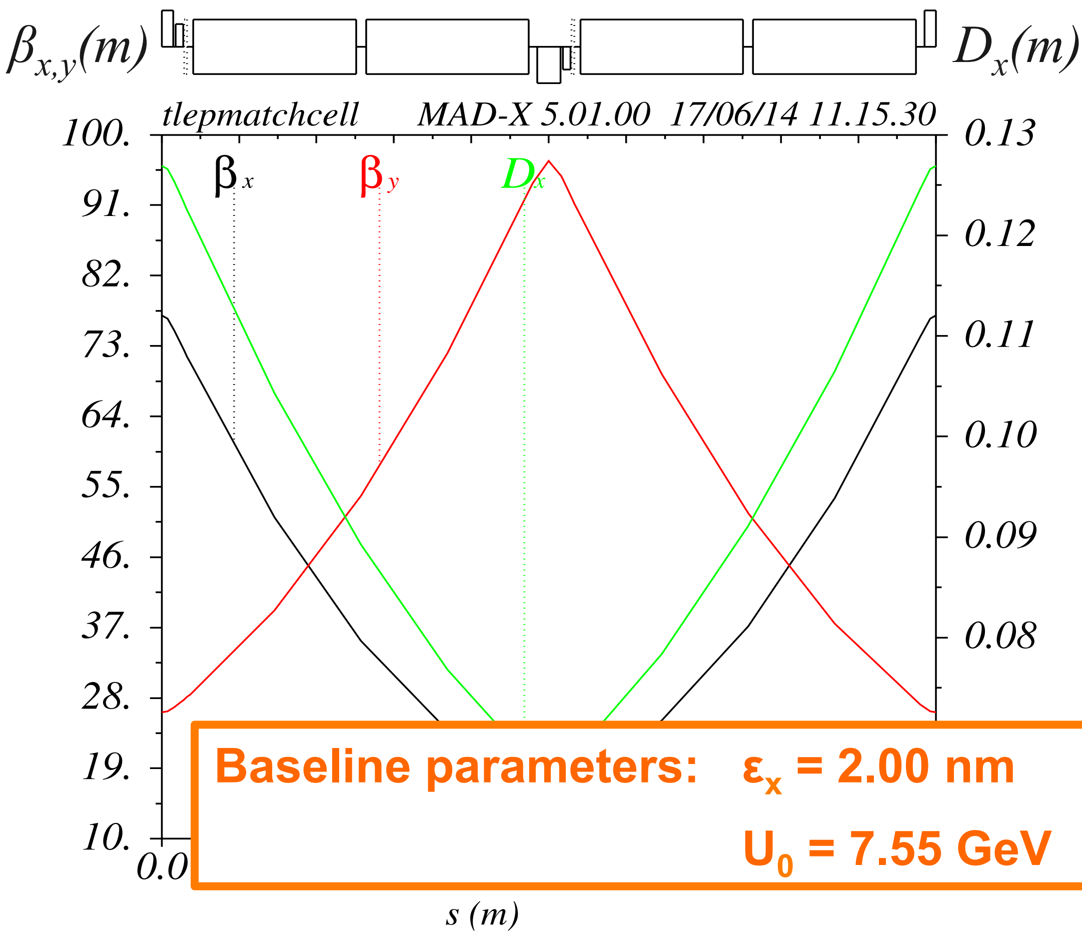
$N_{quadrupoles}$ = 4704 (LHC: 478)

$\rho \approx 10.6$ km

$\theta = 0.99$ mrad

B = 55 mT

FODO cell for 175 GeV



Baseline parameters: ε_x = 2.00 nm

U_0 = 7.55 GeV

- L = 50 m
- Ψ = 90°/60°
- $\beta_{x,max}$ = 76.9 m
- $\beta_{y,max}$ = 96.6 m
- $D_{x,max}$ = 12.7 cm

MADX Emit:

- ε_x = 1.00 nm
- U_0 = 7.72 GeV

Emittance in electron storage rings

Fermilab

TM-1269
0102.000

Minimizing the Emittance in Designing the
Lattice of an Electron Storage Ring

L.C. Teng

June 1984

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

C_g = 3.832 × 10^{-13} m, J_x = damping partition number, γ = Lorentz factor,

θ = bending angle, F = numerical factor controlled by the lattice design

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

Analytic calculation: ε_x **= 1.04 nm**

MADX Emit: ε_x **= 1.00 nm** ✔

120 GeV

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

If the beam energy will be decreased from 175 GeV to 120 GeV the beam emittance is expected to shrink!

F(Ψ=90°) = 2.976,   γ(175 GeV) = 342466,   γ(120 GeV) = 234834

- Analytic calculation: ε_x = 0.491 nm
- MADX Emit: ε_x = 0.488 nm ✔
- Baseline parameter: 0.5 × ε_x = 0.47 nm (ε_x = 0.94 nm)

We can keep the 175 GeV optics for 120 GeV beam energy!

45.5 GeV and 80.0 GeV

80.0 GeV: γ = 156556

- Baseline parameter: $0.5 \times \varepsilon_x = 1.65$ nm ($\varepsilon_x = 3.30$ nm)
- Analytic calculation: $\varepsilon_x = 0.218$ nm

45.5 GeV: γ = 89041

- Baseline parameter: $0.5 \times \varepsilon_x = 14.60$ nm ($\varepsilon_x = 29.20$ nm)
- Analytic calculation: $\varepsilon_x = 0.071$ nm

How can the beam emittance be increased?

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

Changing the emittance for lower energies

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

$$\hat{D} = \frac{L_{cell}^2}{\rho} \cdot \left(1 + \frac{1}{2}\sin\left(\frac{\psi_{cell}}{2}\right)\right) \Big/ \sin^2\left(\frac{\psi_{cell}}{2}\right)$$

There are two different possibilities:

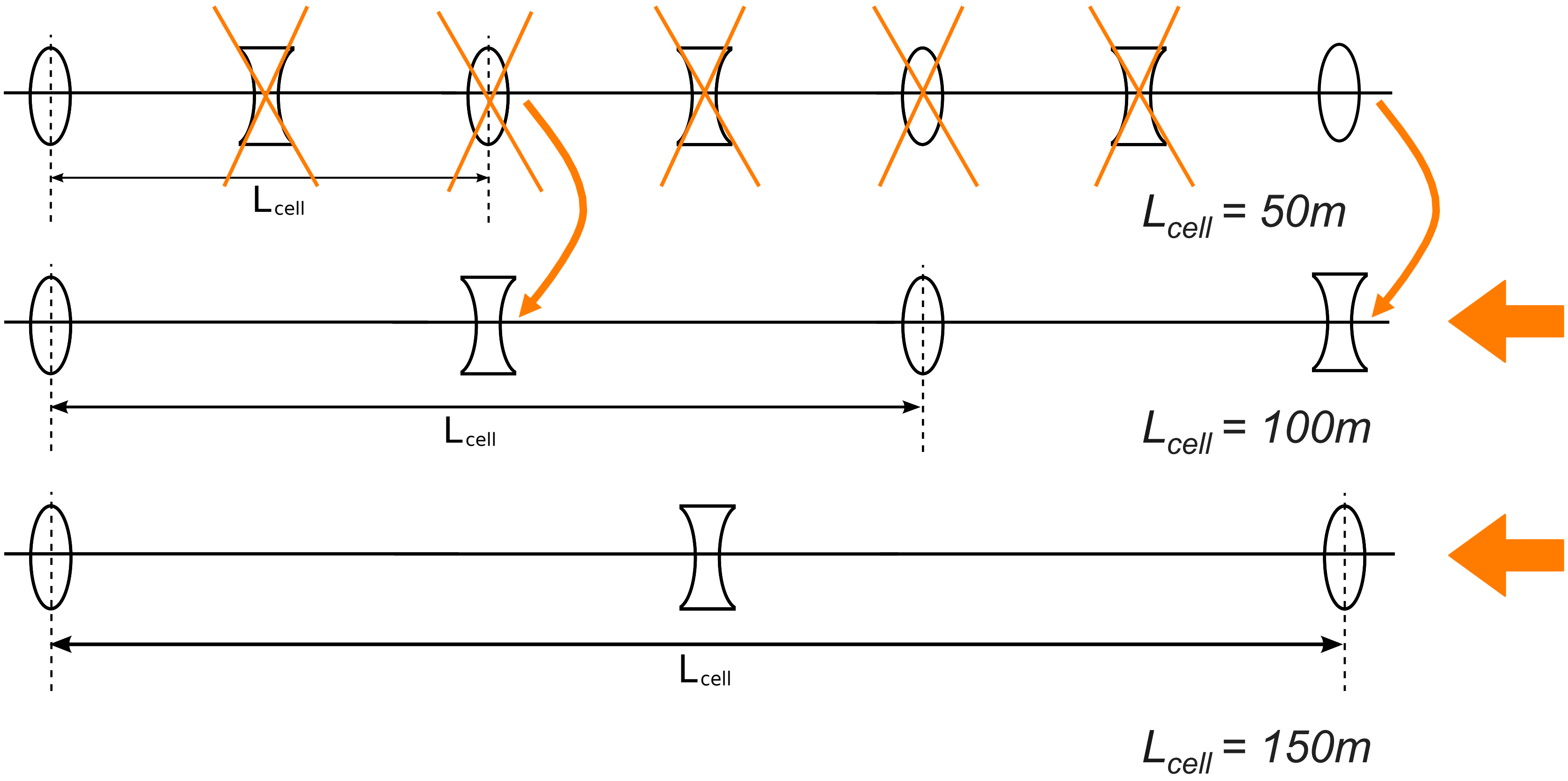
1) Changing of the cell length

→ Larger emittance: increase cell length

→ $2 \times L_{cell}$, $3 \times L_{cell}$, $4 \times L_{cell}$, …

- Recabeling of quadrupoles necessary
- Dispersion suppressors need to be adjusted

1) Changing of the cell length



Changing the emittance for lower energies

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

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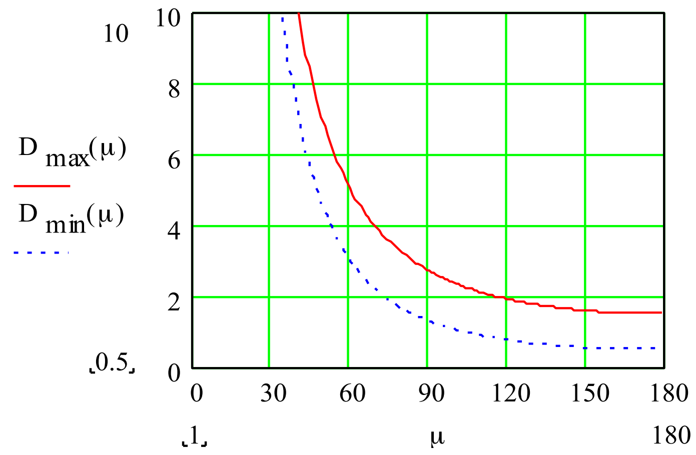


Court. B. Holzer

There are two different possibilities:

2) Change the phase advance Ψ of the FODO cell

+ No recabeling of hardware necessary
– Dispersion suppressors need to be adjusted
– Sextupole scheme? → 45°, 60°, 72°, 90°, …
– Only within certain limits possible: 40°<Ψ<135°

Feasible Lattice Changes

80 GeV beam energy:

Cell length L	Phase advance Ψ	Emittance ε_x
Baseline parameter:	2 ×	1.65 nm
50 m	45°	1.50 nm (Teng)
100 m	90°	1.74 nm (Teng)

45.5 GeV beam energy:

Cell length L	Phase advance Ψ	Emittance ε_x
Baseline parameter:	2 ×	14.60 nm
200 m	60°	13.56 nm (Teng)
250 m	72°	15.91 nm (Teng)
300 m	90°	15.24 nm (Teng)

Objectives

- Introduce dispersion suppressors based on quadrupoles
  → Geometry must stay the same

- Beta functions in dispersion suppressor and matching sections should stay in the same order of magnitude as in the arcs

- Keep straight sections the same
  → Space is limited
  → No change of optics for injection, IR, etc. necessary

Lattices for 80 GeV

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

Half-bend dispersion suppressor

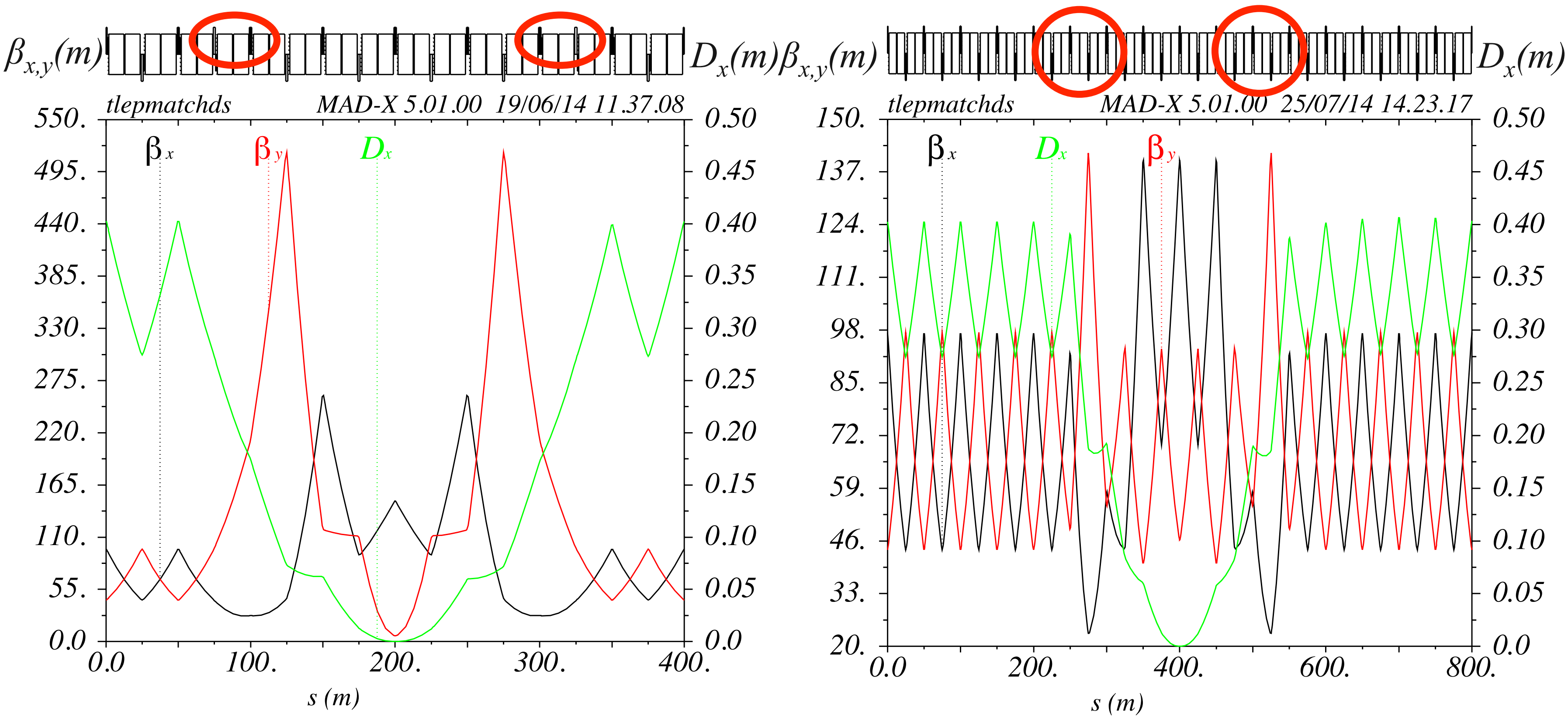
80 GeV: L_{cell} = 50 m, Ψ = 45°/45°

Dispersion suppressor based on quadrupoles

80 GeV: L_{cell} = 100 m, Ψ = 90°/60°

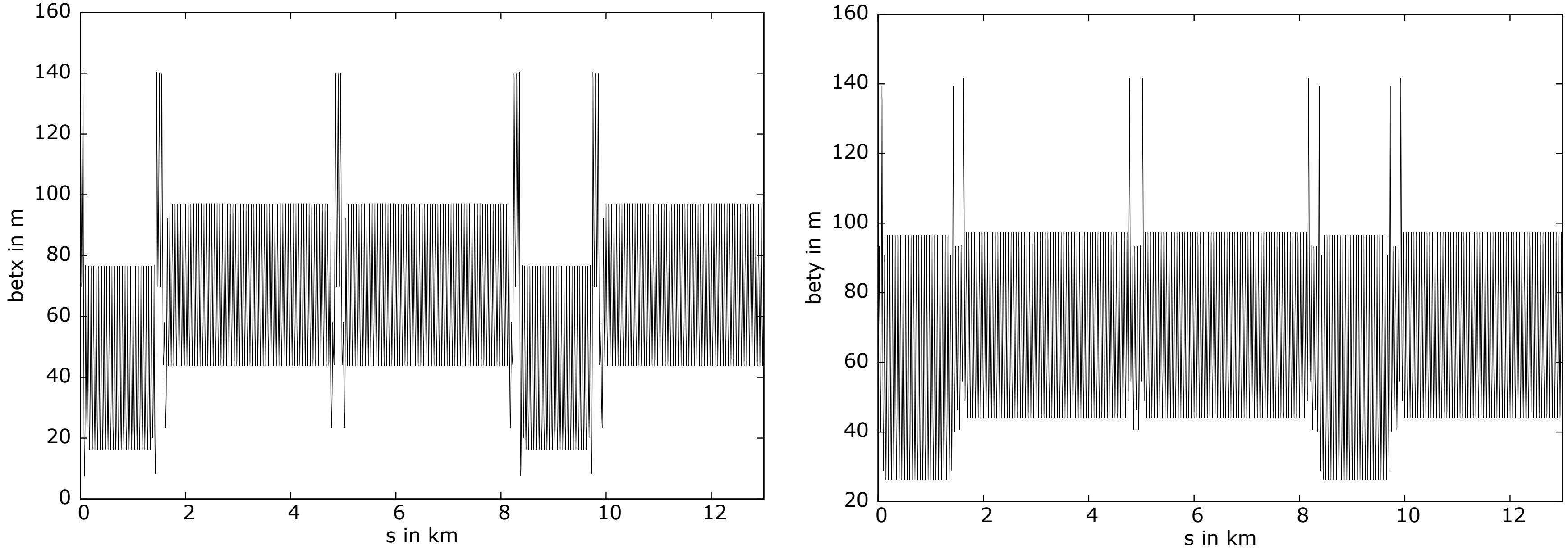
- **Arc cells**
- **Dispersion Suppressor**
- **Straight matching section (with RF)**
- **Straight cells (with RF)**

80 GeV: 1) Ψ=45°



Using 4 additional quadrupoles instead of 2 reduces the betafunction in the dispersion suppressor.

80 GeV: 1) Ψ=45°

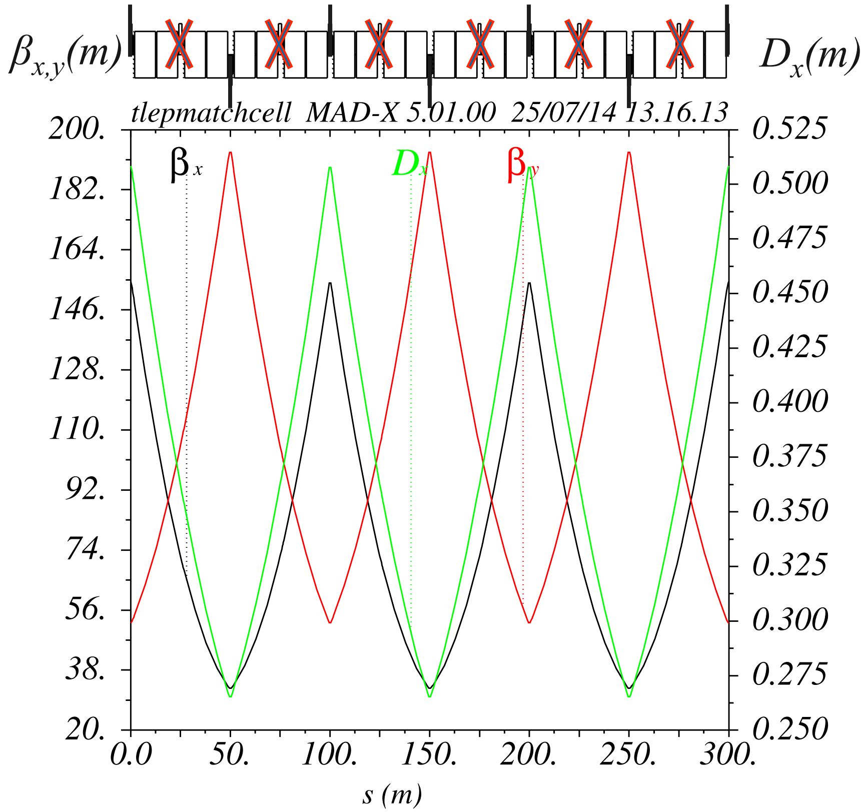


FCC-ee baseline parameter: **$0.5 \times \varepsilon_x = 1.65$ nm**

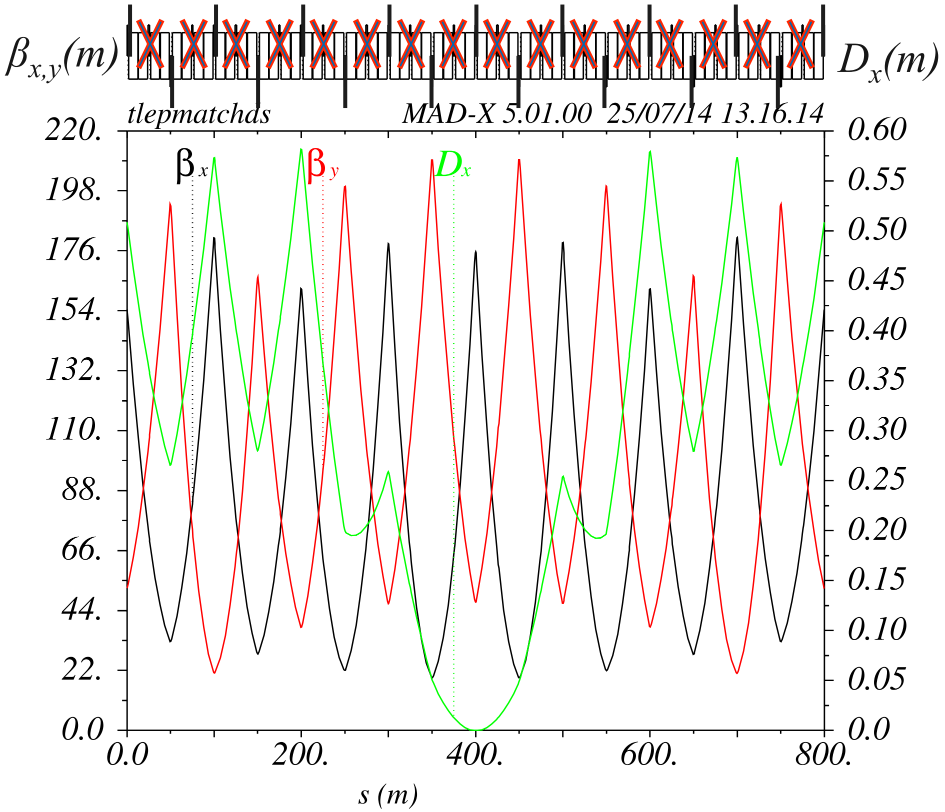
Analytical calculation: **$\varepsilon_x = 1.50$ nm**

MADX Emit: **$\varepsilon_x = 1.47$ nm**

80 GeV: 2) 100 m cell length

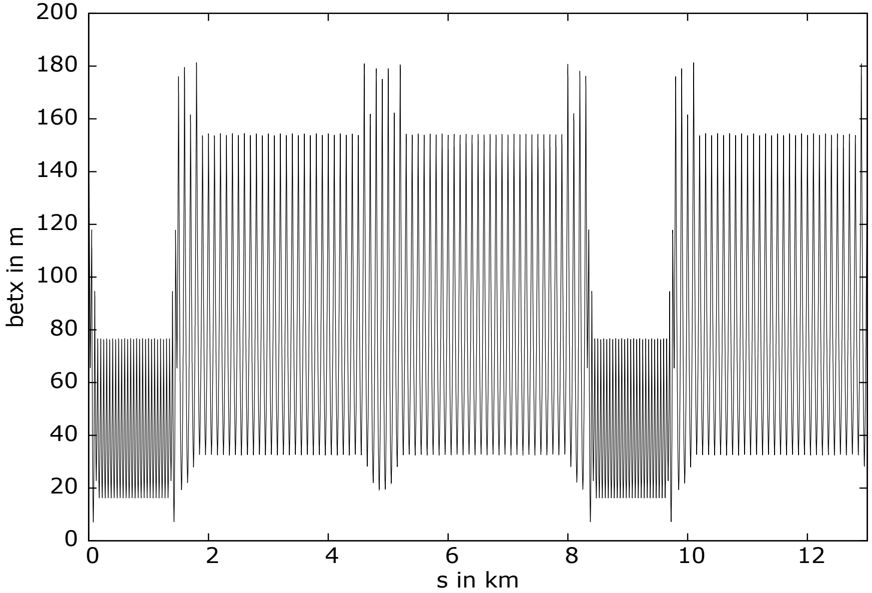


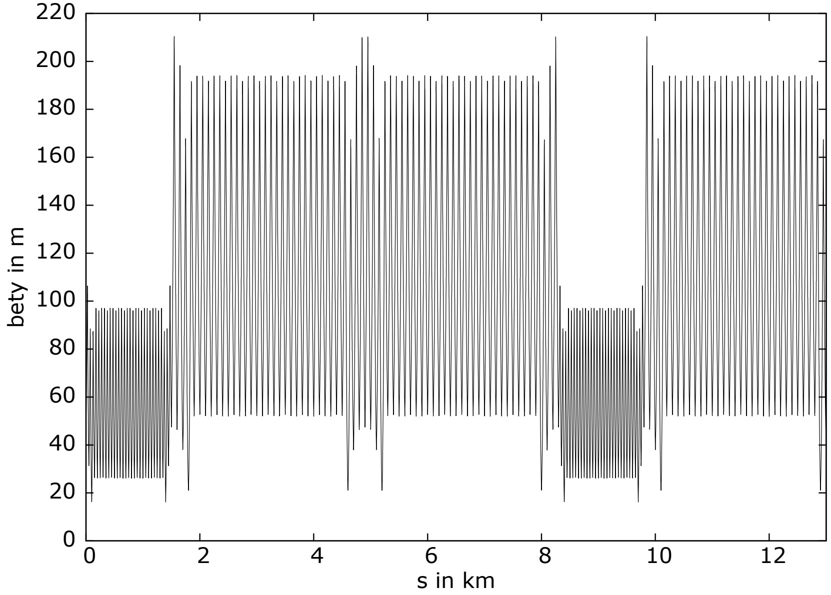
3 FODO cells



Dispersion suppressor

80 GeV: 2) 100 m cell length





FCC-ee baseline parameter: **$0.5 \times \varepsilon_x = 1.65$ nm**

Analytical calculation: **$\varepsilon_x = 1.74$ nm**

MADX Emit: **$\varepsilon_x = 1.70$ nm**

Lattices for 45.5 Gev

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

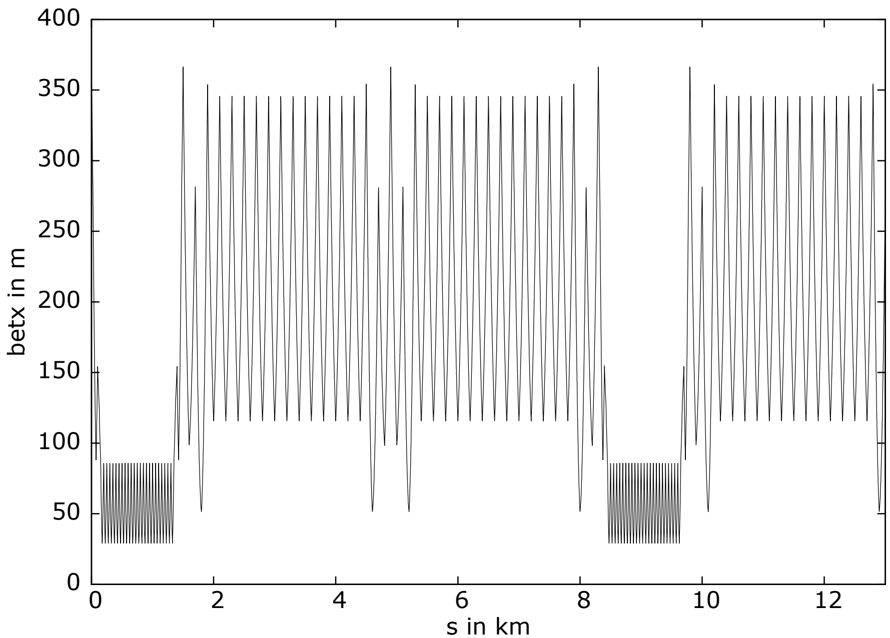
45.5 GeV: L_{cell} = 200 m, Ψ = 60°/60°

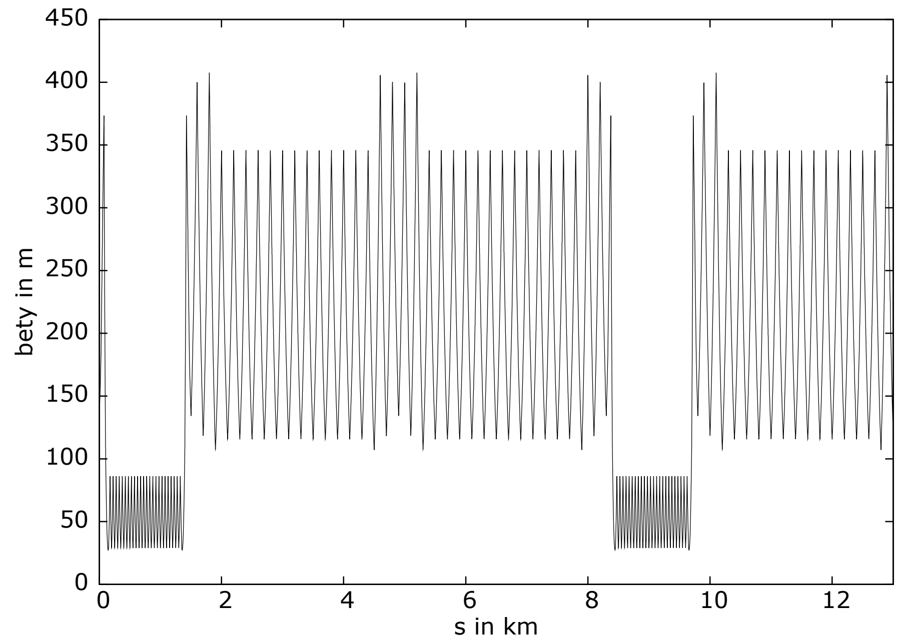
Dispersion suppressor based on quadrupoles

45.5 GeV: L_{cell} = 250 m, Ψ = 72°/72°

45.5 GeV: L_{cell} = 300 m, Ψ = 90°/60°

45.5 GeV: 200 m cell length



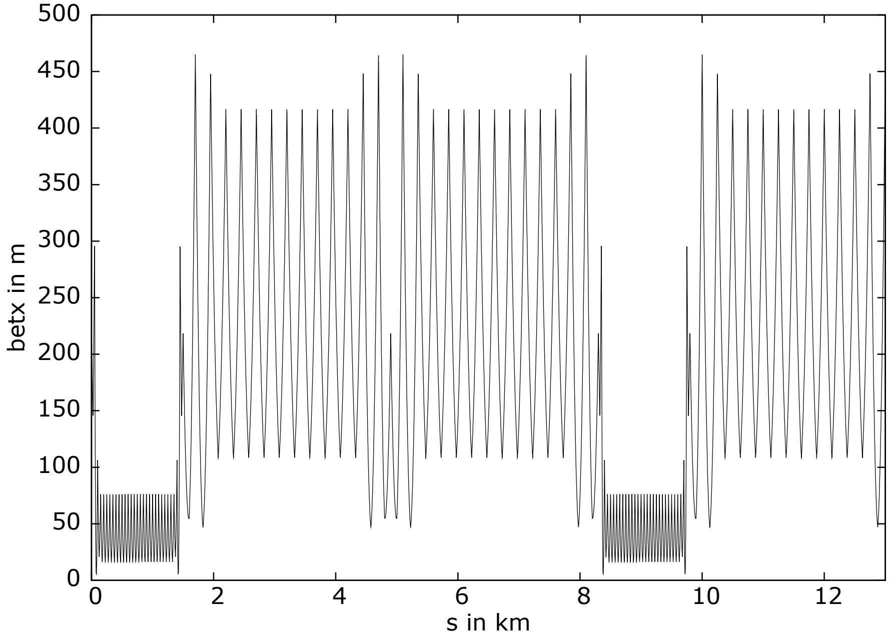


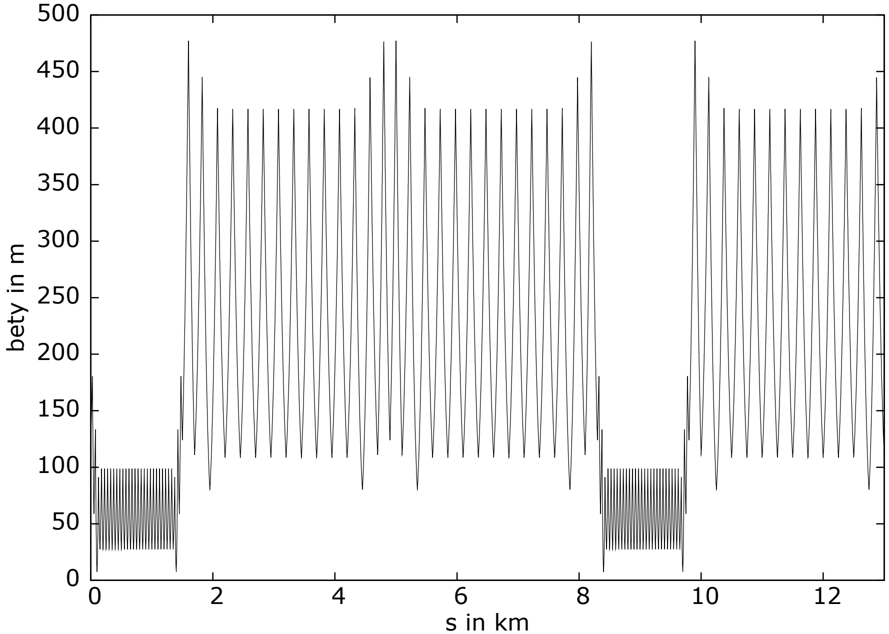
FCC-ee baseline parameter: **$0.5 \times \varepsilon_x = 14.6$ nm**

Analytical calculation: **$\varepsilon_x = 13.6$ nm**

MADX Emit: **$\varepsilon_x = 12.5$ nm**

45.5 GeV: 250 m cell length



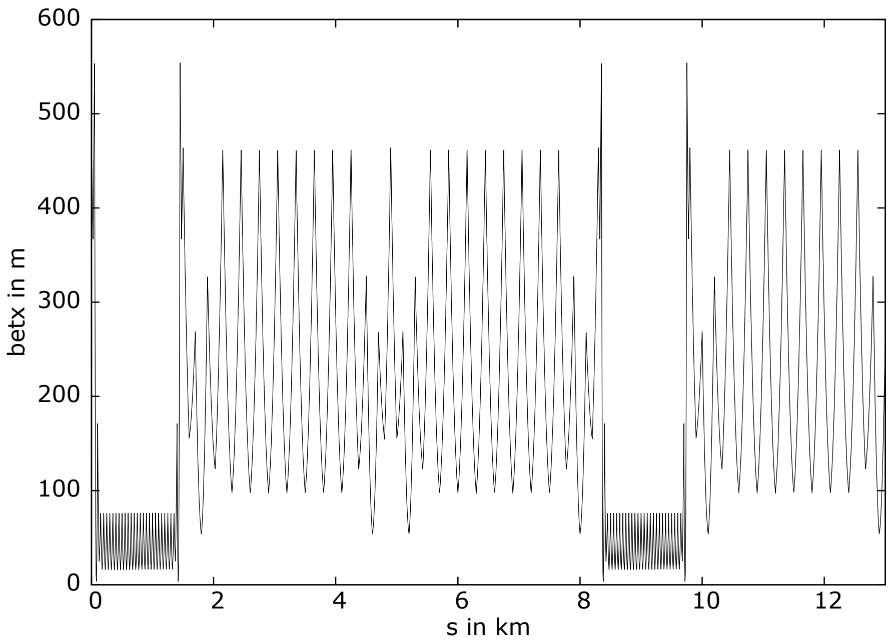


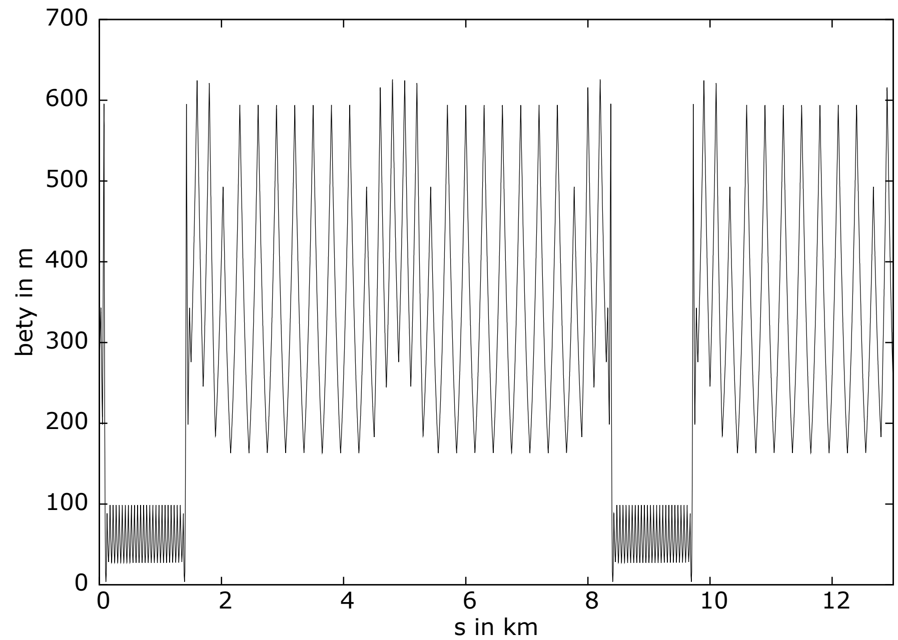
FCC-ee baseline parameter: **$0.5 \times \varepsilon_x = 14.6$ nm**

Analytical calculation: **$\varepsilon_x = 15.9$ nm**

MADX Emit: **$\varepsilon_x = 14.5$ nm**

45.5 GeV: 300 m cell length





FCC-ee baseline parameter: **$0.5 \times \varepsilon_x = 14.6$ nm**

Analytical calculation: **$\varepsilon_x = 15.2$ nm**

MADX Emit: **$\varepsilon_x = 14.2$ nm**

Résumé I

- The baseline parameter provide a variety of challenges for the lattice design

  → A lattice with highest flexibility is needed

- To achieve the emittance baseline parameters the lattice has to be modified

- Two possible alternatives:

  → Changing of the cell length

  → Changing of the phase advance

Résumé II

- Different beam optics were determined to obtain the required emittances for all 4 energies.

- For 175 GeV and 120 GeV beam energy the same lattice can be used
- For 80 GeV and 45.5 GeV several lattices with different cell length and phase advance were implemented

- This is just the very first design!

  → Misalignment studies, chromaticity correction scheme

Next steps

1. Introduction of misalignments and coupling
   → Which lattice is most stable?
   → How much does horizontal emittance increase?
   → Calculation of the distorted orbit and vertical emittance

Sandra Aumon

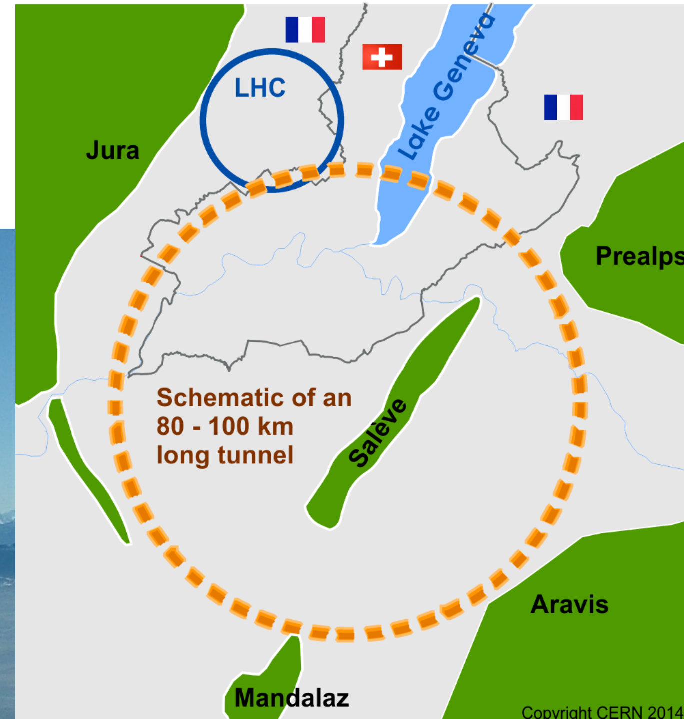
2. Which software is reliable for those calculations?

Andreas Doblhammer

3. State-of-the-art chromaticity correction scheme

4. Investigate light source lattices for colliders

Thank you for your attention!



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80 GeV: important parameters

Cell length in arc (m) Phase advance in arc cell	50 45°/45°	100 90°/60°	Baseline parameter
Horizontal emittance (nm)	1.47	1.70	2 x 1.65
Energy loss per turn (MeV)	337.03	337.03	330
Momentum compaction (10^{-5})	1.99	2.22	2
Max. hor. beta function in arc (m)	141.47	181.54	-
Max. vert. beta function in arc (m)	141.68	211.05	-
Max. dispersion in arc (m)	0.41	0.58	-

45.5 GeV: important parameters

Cell length in arc (m) **Phase advance in arc cell**	**200** **60°/60°**	**250** **72°/72°**	**300** **90°/60°**	**Baseline** **parameter**
Horizontal emittance (nm)	12.5	14.5	14.2	2 x 14.6
Energy loss per turn (MeV)	35.3	35.3	35.3	30
Momentum compaction (10^{-4})	1.69	1.86	1.81	1.8
Max. hor. beta function in arc (m)	366.51	465.71	554.00	-
Max. vert. beta function in arc (m)	407.92	477.70	626.43	-
Max. dispersion in arc (m)	4.02	4.87	4.56	-
RMS beam size σ_x in arc* (mm)	2.1	2.6	2.8	-

* $\sigma_x = \sqrt{\varepsilon_x \beta_x}$