Challenges and status of the FCC-ee lattice design

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INTRODUCTION

Following the recommendations of the European Strategy Group for High Energy Physics CERN launched a design study to investigate the feasibility of circular colliders in future high energy physics research (Future Circular Collider Study, FCC) . One part of this study is the investigation of an e+/e- collider with the circumference of 100 km called FCC-ee (TLEP). It is supposed to provide highest possible luminosity in the beam energy range from 45 GeV to 175 GeV. The main physics programs include scans around the central values:

- Z (45.5 GeV): Z pole, high precision of M_Z and Γ_Z,
- W (80 GeV): W pair production threshold,
- H (120 GeV): H production,
- t (175 GeV): tt threshold.

CHALLENGES FOR THE LATTICE DESIGN

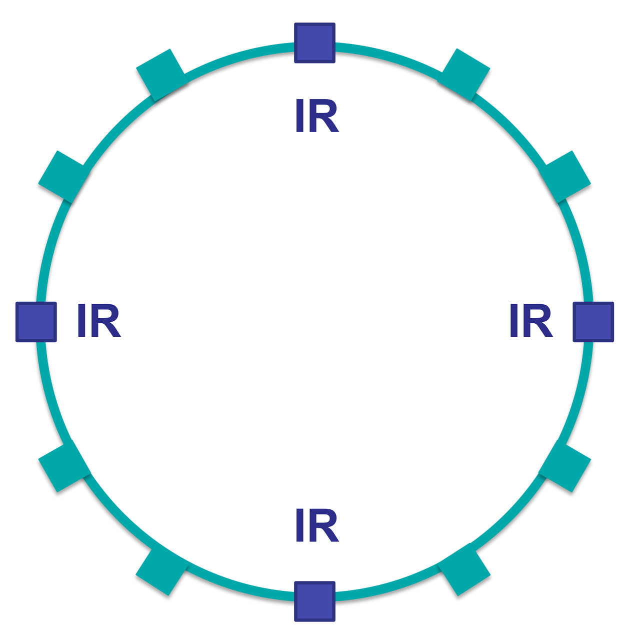
- Lattice must be designed and optimized for 4 different beam energies
- Challenging interaction region design for a large number of bunches (up to 16700) and an extremely small vertical beta* ($\beta_y^* = 1$ mm)
  - → High chromaticity & challenging dynamic aperture
  - → High beamstrahlung effects at 175 GeV beam energy
- Increasing horizontal emittance with reduced energy (but $\varepsilon_x \propto \gamma^2$)
- Very small vertical emittance: $\varepsilon_y = 0.001 \times \varepsilon_x$
- High synchrotron radiation losses (7.55 GeV/turn) require sophisticated absorber design

MACHINE LAYOUT

The circumference is 100km.
(defined by the maximum energy and magnetic field of the hadron machine)

12 long straight sections (**1.5 km each**!)
→ 4 interaction regions (experiments) (blue)
→ 8 for injection, beam dump, etc. (green)

RF will be distributed in every straight section to narrow the sawtooth effect.



Right: Sketch of the machine layout of FCC-ee

HIGH ENERGY LATTICE (175 GeV,120 GeV)

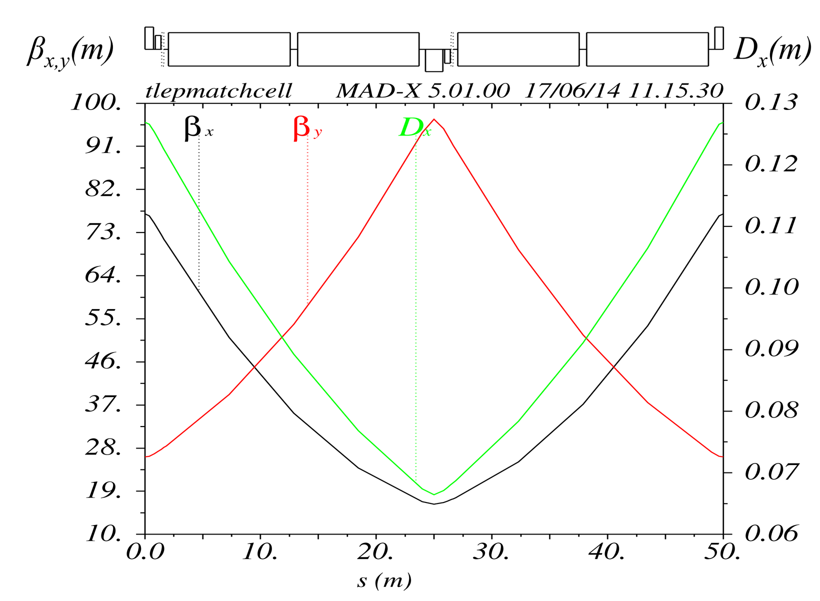
FODO cell lattice
→ High dipole fill factor
→ Easy to handle and optimize analytically

Phase advance 90°/60° (good experience with LEP)
Cell length 50 m to achieve horizontal emittance

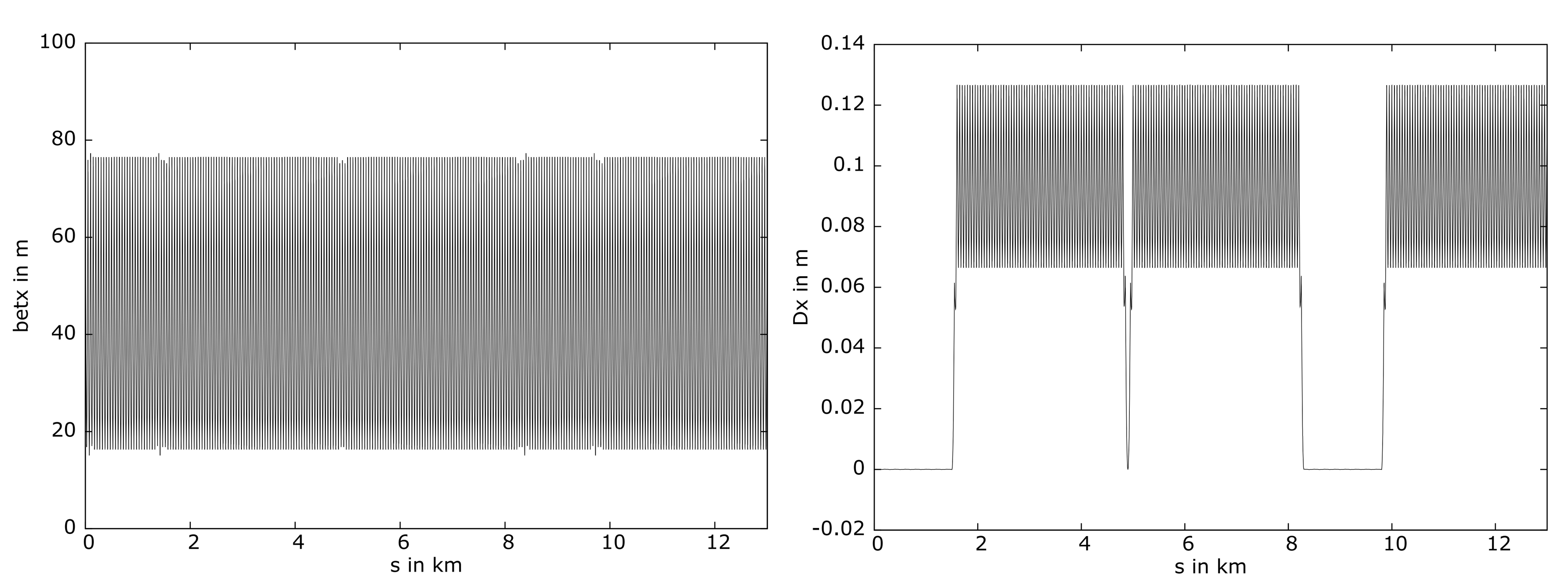
Current design already takes space for flanges, bellows and absorbers into account!

Half-bend dispersion suppressors (2 cells each)

Number of bends per ring: 6048
Number of quadrupoles per ring: 3216



Optical functions of a FODO cell designed for FCC-ee (calculated with MAD-X)



Optical functions of the first 13 km of the FCC-ee lattice beginning with a straight section calculated with MAD-X: the left plot shows the beta function in horizontal plane, the right plot shows the horizontal dispersion.

The transversal beam emittance and dispersion function in a FODO cell can be described by following equations [1]:

$$\varepsilon = \left(\frac{\delta p}{p}\right)^2 \left(\gamma D^2 + 2\alpha D D' + \beta D'^2\right) \qquad \hat{D} = \frac{L_{cell}^2}{\rho} \cdot \left(1 + \frac{1}{2}\sin\left(\frac{\psi_{cell}}{2}\right)\right) \Big/ \sin^2\left(\frac{\psi_{cell}}{2}\right) \qquad (1)$$

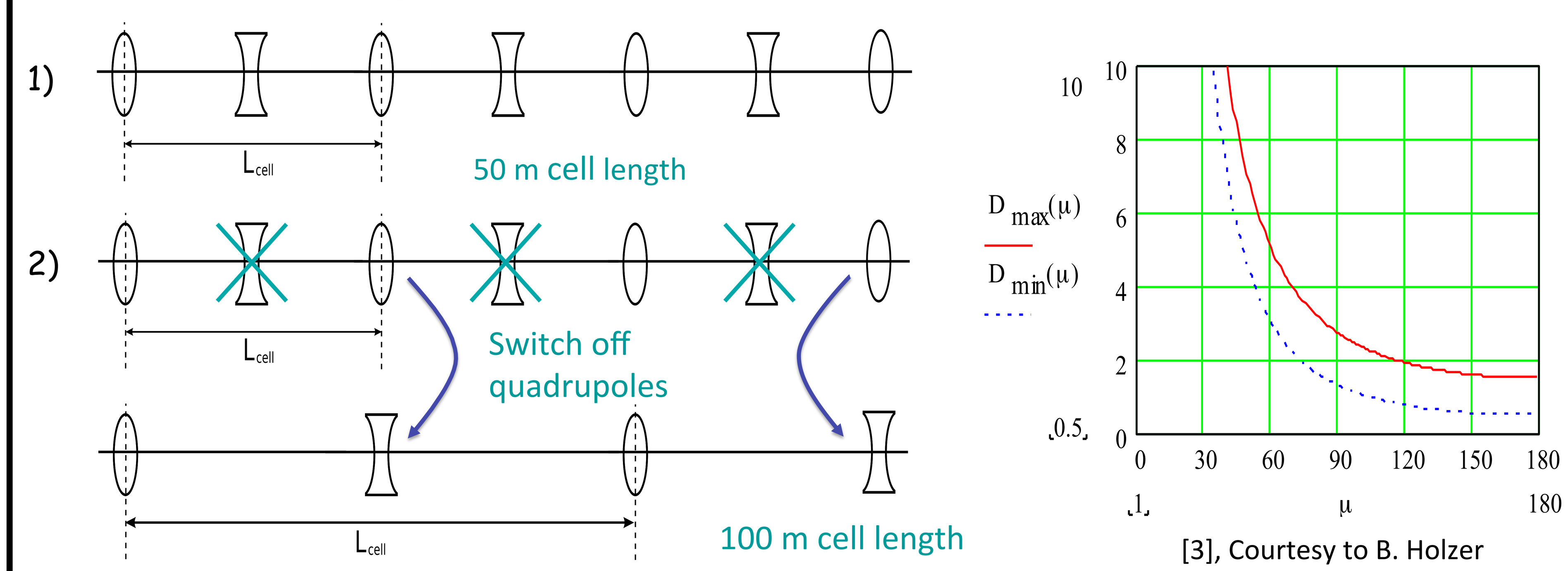
The horizontal emittances in the high energy lattice calculated with the MAD-X EMIT module are

$\varepsilon_x = 1.00$ nm for an 175 GeV beam and
$\varepsilon_x = 0.47$ nm for an 120 GeV beam.

These values are exactly half of the requested baseline parameters. This factor of 2 serves as margin until the emittance increase due to coupling and misalignments is taken into account.

EMITTANCE TUNING

Given that the emittance is proportional to the beam energy squared [2], the lattice has to be changed to increase the emittance for smaller energies.
As a consequence of equations (1) a larger dispersion in the arcs is required. This can be reached by a extension of the cell length or a smaller the phase advance Ψ of the cell.



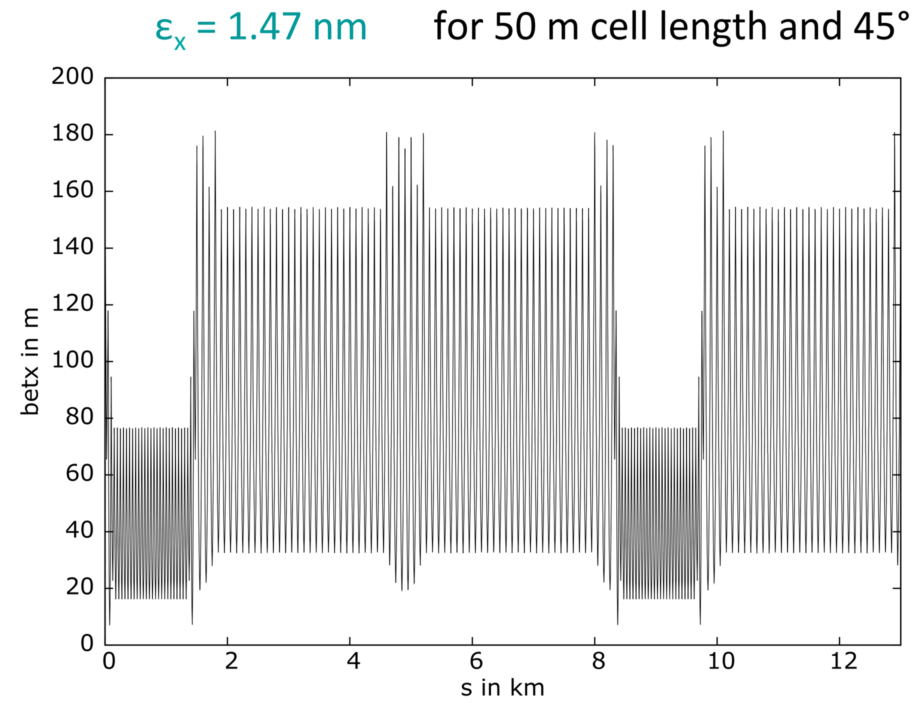
Illustrations of increasing the dispersion without changing the hardware: the left side shows how to chang the cell length by switching off quadrupoles, the plot on the right side shows the dispersion as a function of the phase advance.

LATTICES FOR 80 GeV

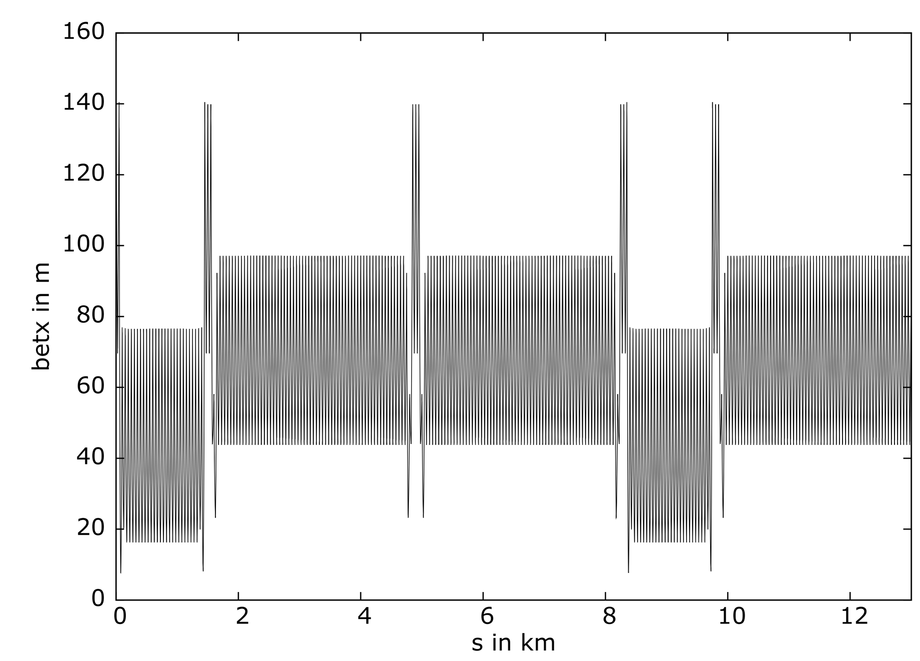
To achieve the requested horizontal emittance for 80 GeV beam energy analytical calculations according to [2] have shown that either the cell length has to be doubled or the phase advance has to be reduced to 45°. In both cases the dispersion suppressors have to be supported by quadrupoles of the arcs. The lattice design for the straight sections can stay the same.

Simulation with MAD-X EMIT give following results for the horizontal beam emittance:

$\varepsilon_x = 1.70$ nm for 100 m cell length and 90° phase advance
$\varepsilon_x = 1.47$ nm for 50 m cell length and 45° phase advance



Horizontal beta function of the first 13 km's with 100 m FODO cell length and constant phase advance of 90°

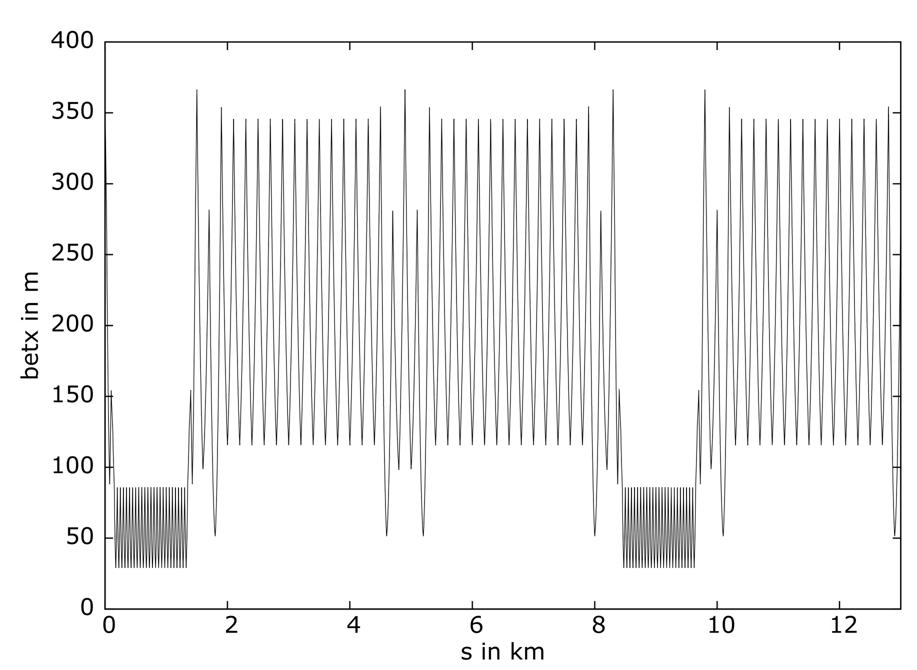


Horizontal beta function with 45° phase advance and constant FODO cell length of 50 m

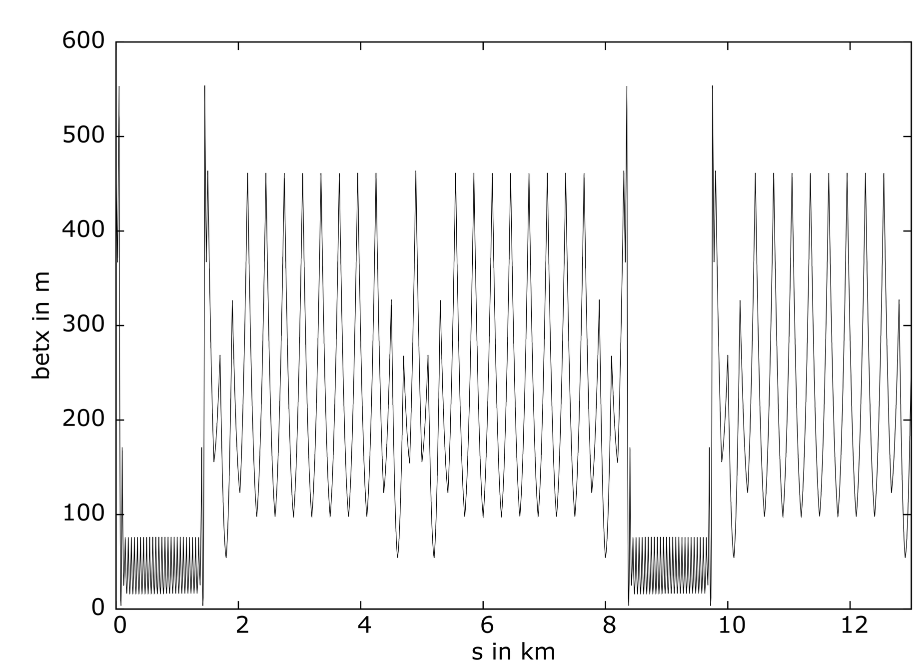
LATTICES FOR 45.5 GeV

For 45.5 GeV beam energy several combinations of changing cell length and phase advance are possible. Three of them with reasonable phase advances were simulated with MAD-X:

200 m cell length and 60° phase advance: $\varepsilon_x = 12.5$ nm
250 m cell length and 72° phase advance: $\varepsilon_x = 14.5$ nm
300 m cell length and 90° phase advance: $\varepsilon_x = 14.2$ nm



Horizontal beta function of the first 13 km's with 200 m FODO cell length and 60° phase advance



Horizontal beta function with 300 m cell length and 90° phase advance

NEXT STEPS

- Both misaligned elements and coupling are required to the correct vertical beam emittance
- Stability of the beam with misaligned elements will be one criterion to choose the final lattices
- Sextupole scheme in the arcs needs to be combined with quasi-local chromaticity correction in the interaction regions to achieve 2 % dynamic aperture
- Compatibility with hadron machine requires investigation of other designs: racetrack, kink, …
- Comparison of the FODO lattice with light source lattices

REFERENCES

[1] CERN Accelerator School, Fifth General Accelerator Physics Course, Proceedings, 1994
[2] L. C. Teng, Minimizing the Emittance in Designing the Lattice of an Electron Storage Ring, 1984
[3] B. Holzer, Lattice Design, CERN Accelerator School 2013, Lecture Slides