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Challenges and current status of the TLEP lattice design

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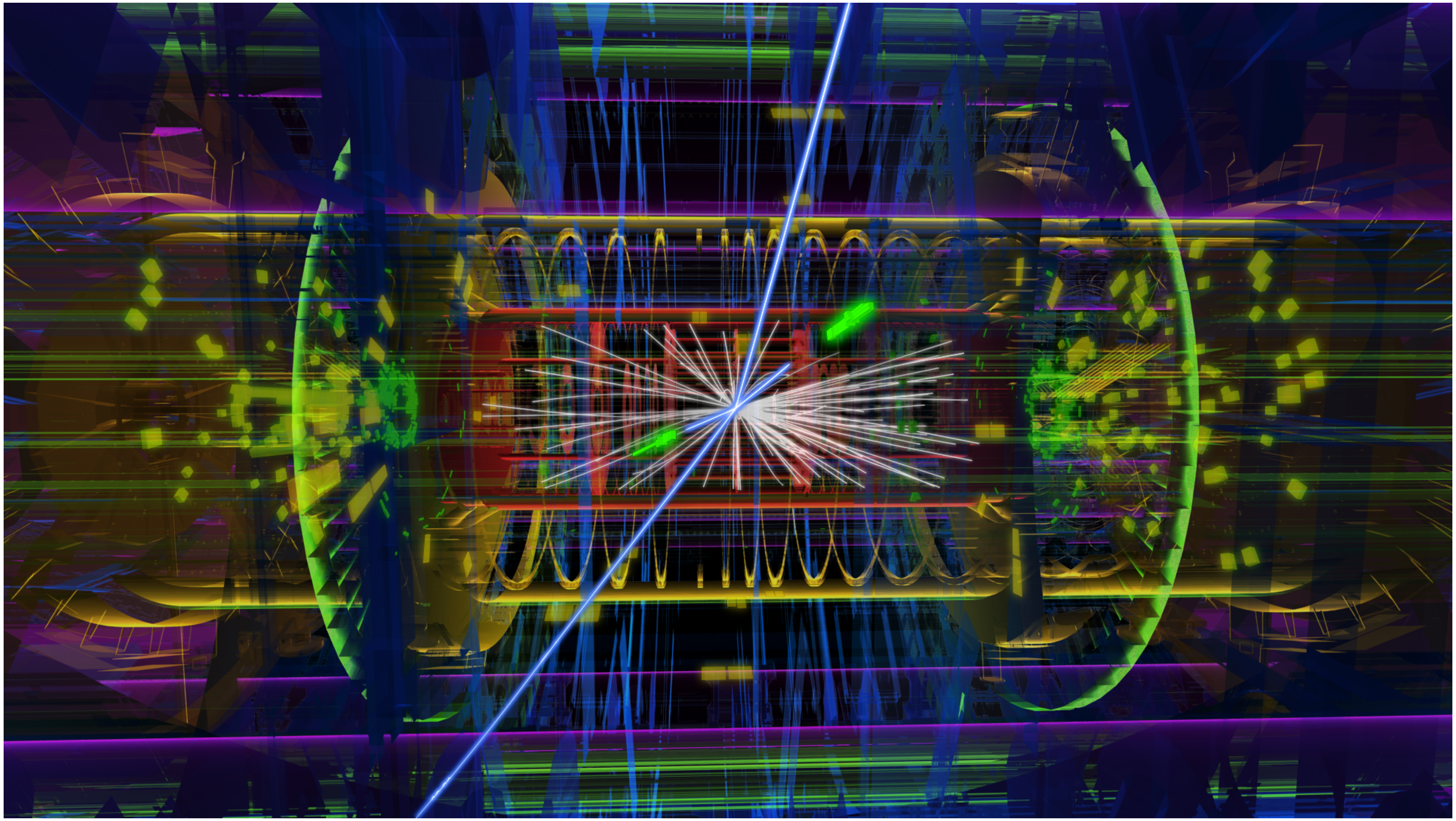
Outline

- Introduction
- 1) Lattice design for 175 GeV beam energy
- 2) Beam emittances
- 3) Lattice modifications for smaller energies
- 4) Interaction region lattice, mini-beta optics
- Résumé

What do we have now?



- ATLAS event display: $H \rightarrow e^+ + e^- + \mu^+ + \mu^-$

A bit of history

- In July 2011 a proposal was made to (re)install a 120 GeV / beam e^+e^- collider in the LEP-LHC tunnel – named LEP3. Work on LEP3 started in a series of workshops.

- The 80 km TLEP machine appeared in 2012 in parallel with the feasibility study for a 80 km ring for a future hadron collider around CERN. TLEP and LEP3 were presented in September 2012 at the European Strategy meeting in Krakow.

- In October 2013 TLEP was integrated into the FCC study and is now known as FCC-ee.

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Future Circular Collider Study (FCC)

- New 80-100 km storage ring
- **FCC-hh** (=long-term goal):

→ High-energy hadron collider
→ Push the energy frontier to 100 TeV

- **FCC-ee (TLEP):**

→ e^+/e^--collider as intermediate step

- **FCC-he**

→ Hadron-lepton collider option
→ Deep inelastic scattering

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Physics goals of TLEP

- 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

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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	1360	98
Bunch population [10^{11}]	1.8	0.7	0.46	1.4
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

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→ Challenging dynamic aperture

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- High synchrotron radiation losses include sophisticated absorber design in the lattice

Current TLEP Layout

- Layout compatible with hadron collider
- Circumference: 80 km
  (will be increased to 100 km)

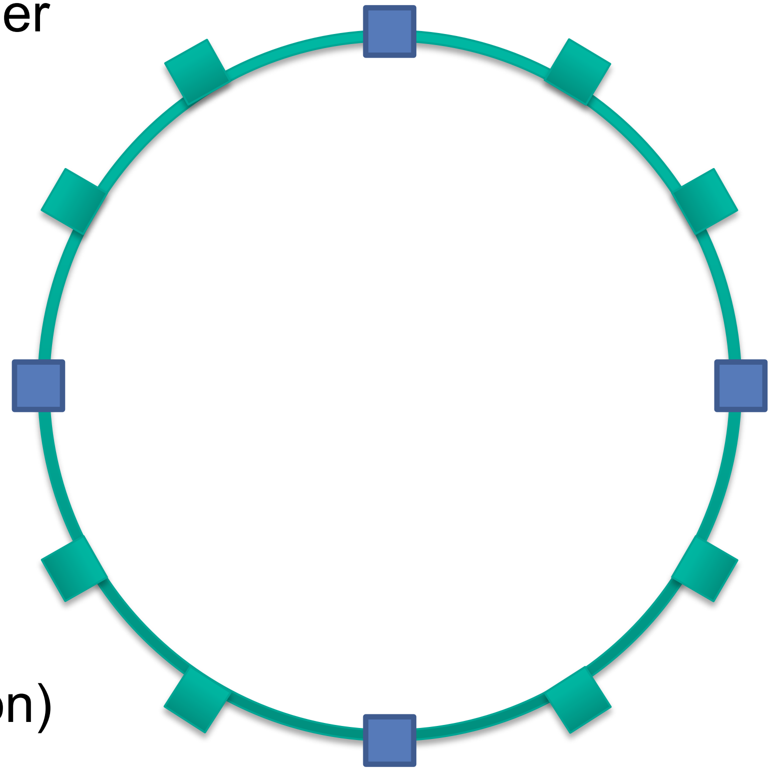
- 4 mini-beta insertions (blue)
- 8 long straight sections (green)
  (**1.5 km each**! for RF, injection, …)

→ 12 Arcs

- 12 RF sections (every straight section)

→ Limit sawtooth effect

- 2 rings, side-by-side (polarization, vertical emittance)



1) Lattice design for 175 GeV beam energy

- Textbook like approach: start with FODO cells

→ High dipole fill factor, easy to handle and optimize analytically

- Phase advance 90° / 60° (LEP experience, to be discussed)

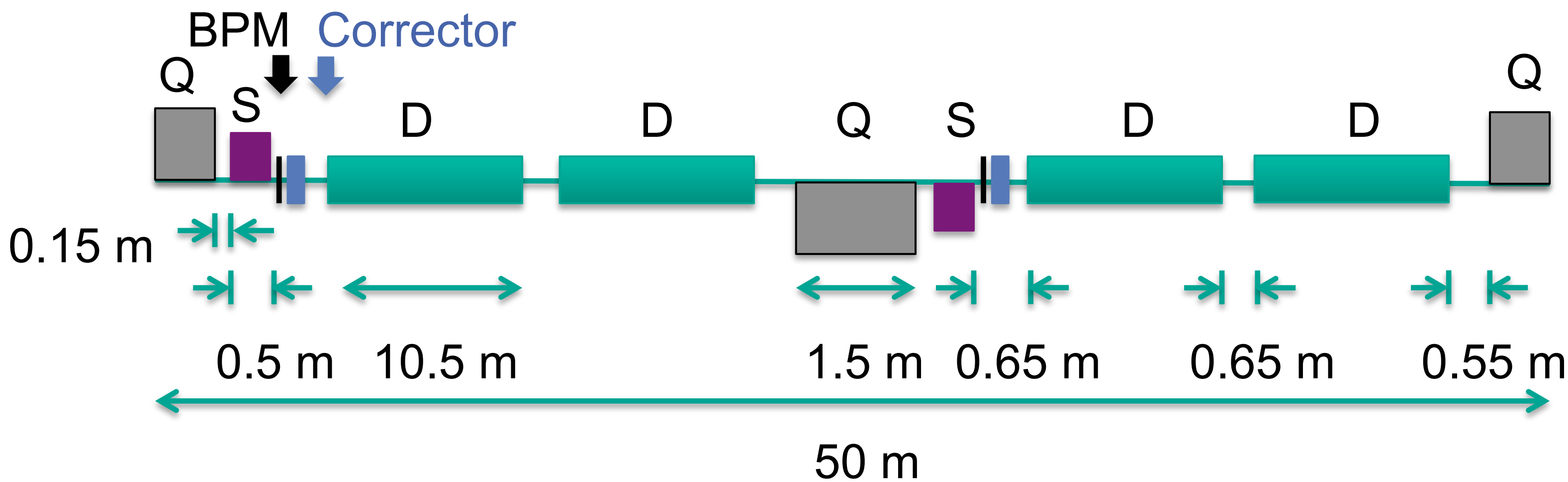
- Achieve horizontal emittance by selecting the cell length

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

- Use phase advance for fine tuning

1) TLEP FODO cell

- Cell length: $L_{cell} = 50$ m
- Layout already considers max. dipole length, drift spaces for absorbers, flanges etc.



D = dipole, Q = quadrupole, S = sextupole

$N_{dipoles}$ = 6048 (384 half bend) (LHC: 1232)

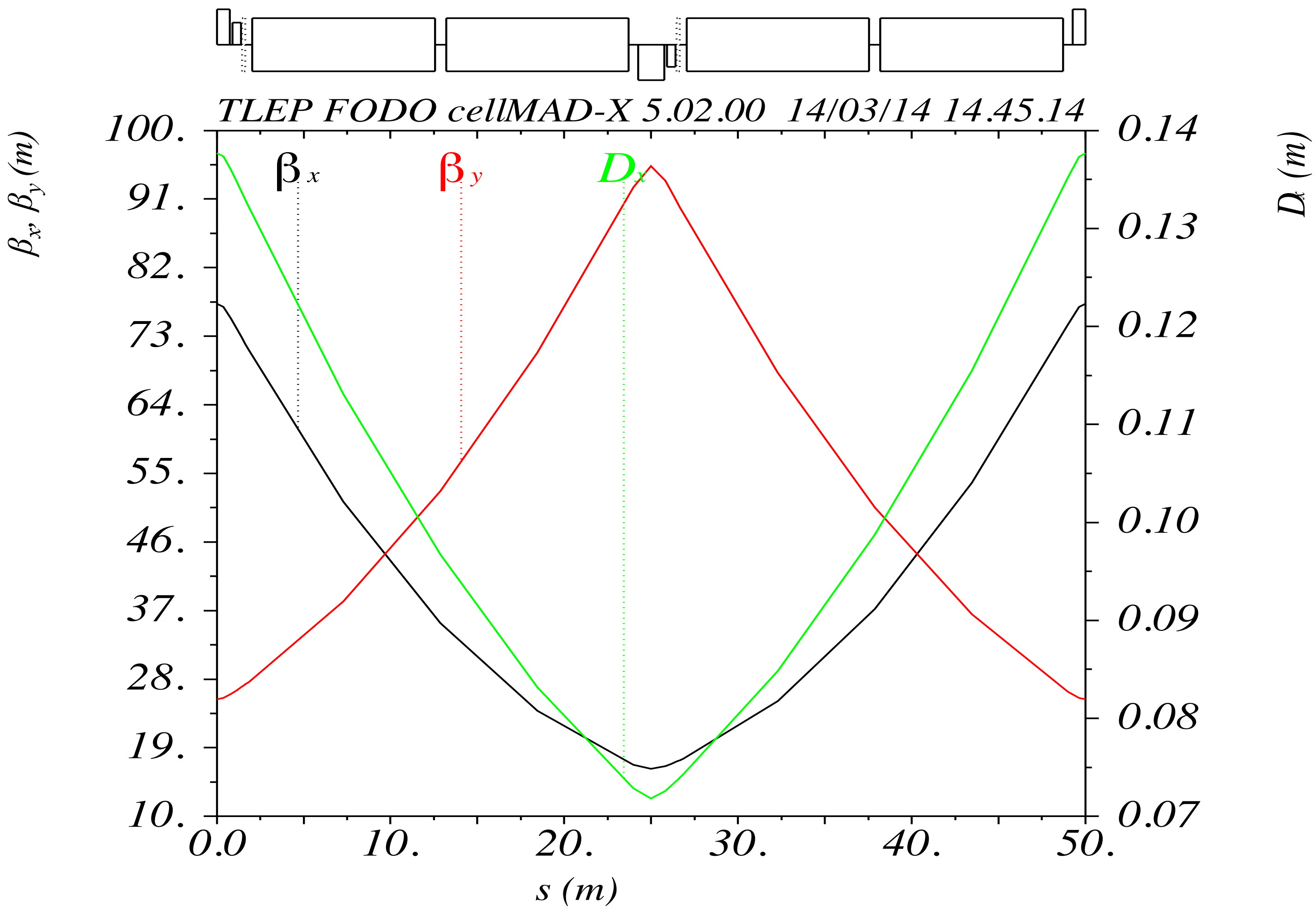
$N_{quadrupoles}$ = 3216 (LHC: 478)

$\rho \approx 9.8$ km

$\theta = 1.07$ mrad

$B\rho = 583.3$ Tm

1) TLEP FODO cell

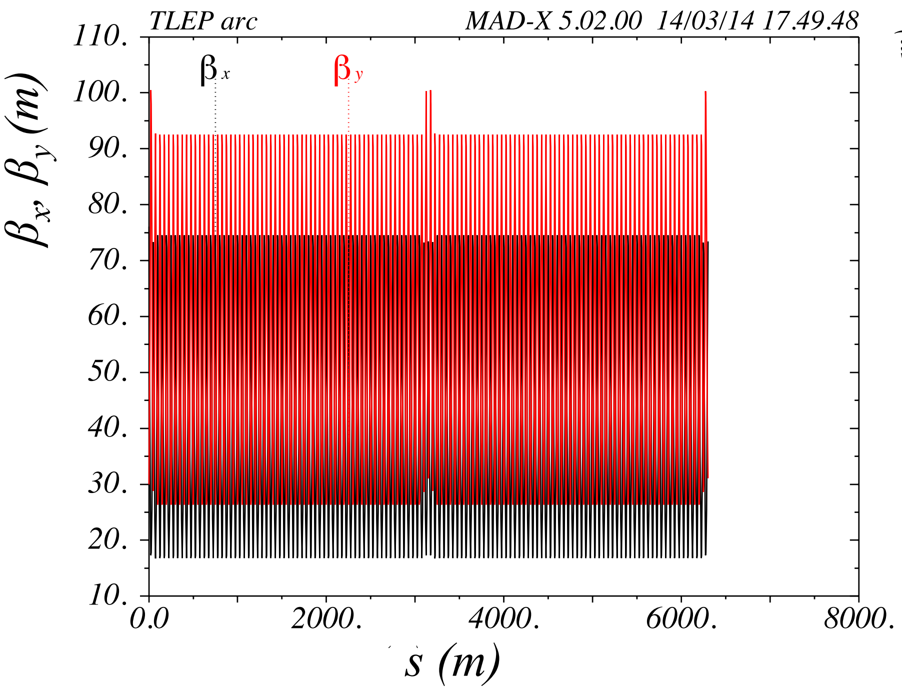


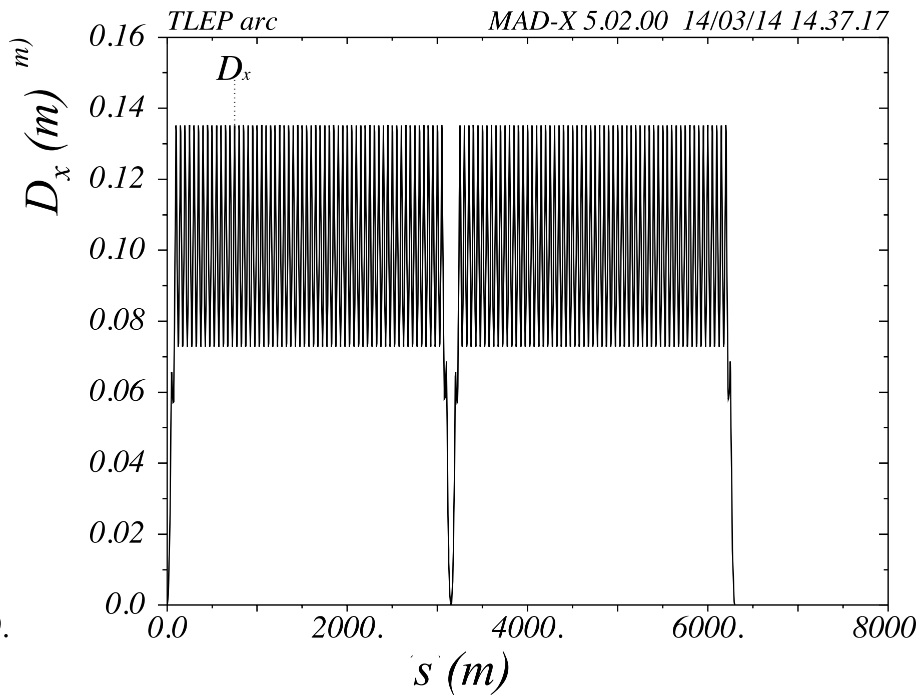
1) TLEP Arc

- 2*63 FODO cells
- Each arc is embedded in dispersion free region

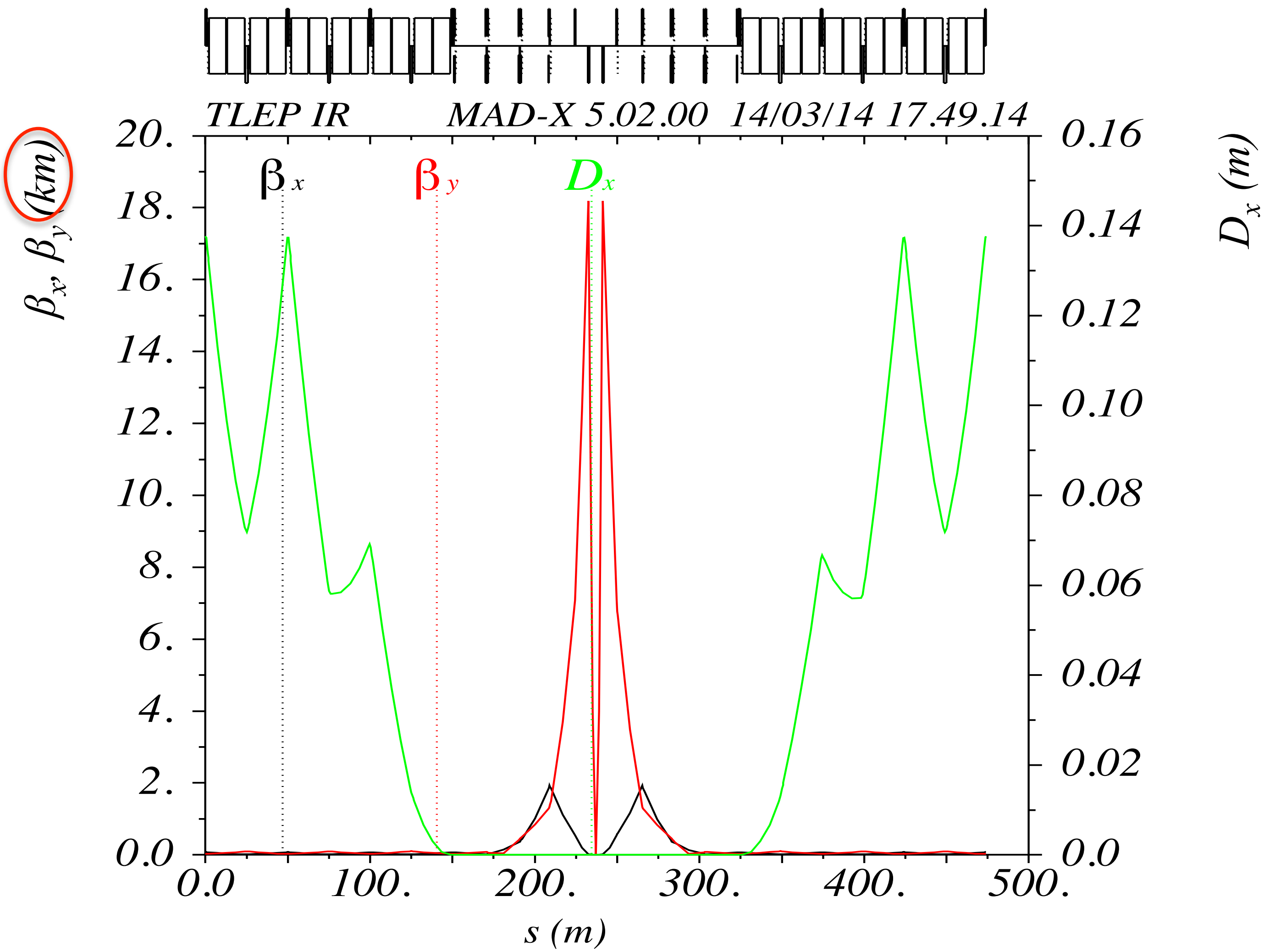
→ 2 half bend cells as dispersion suppressor at beginning and end

- Arc length: ≈ 6 km





1) TLEP Interaction region



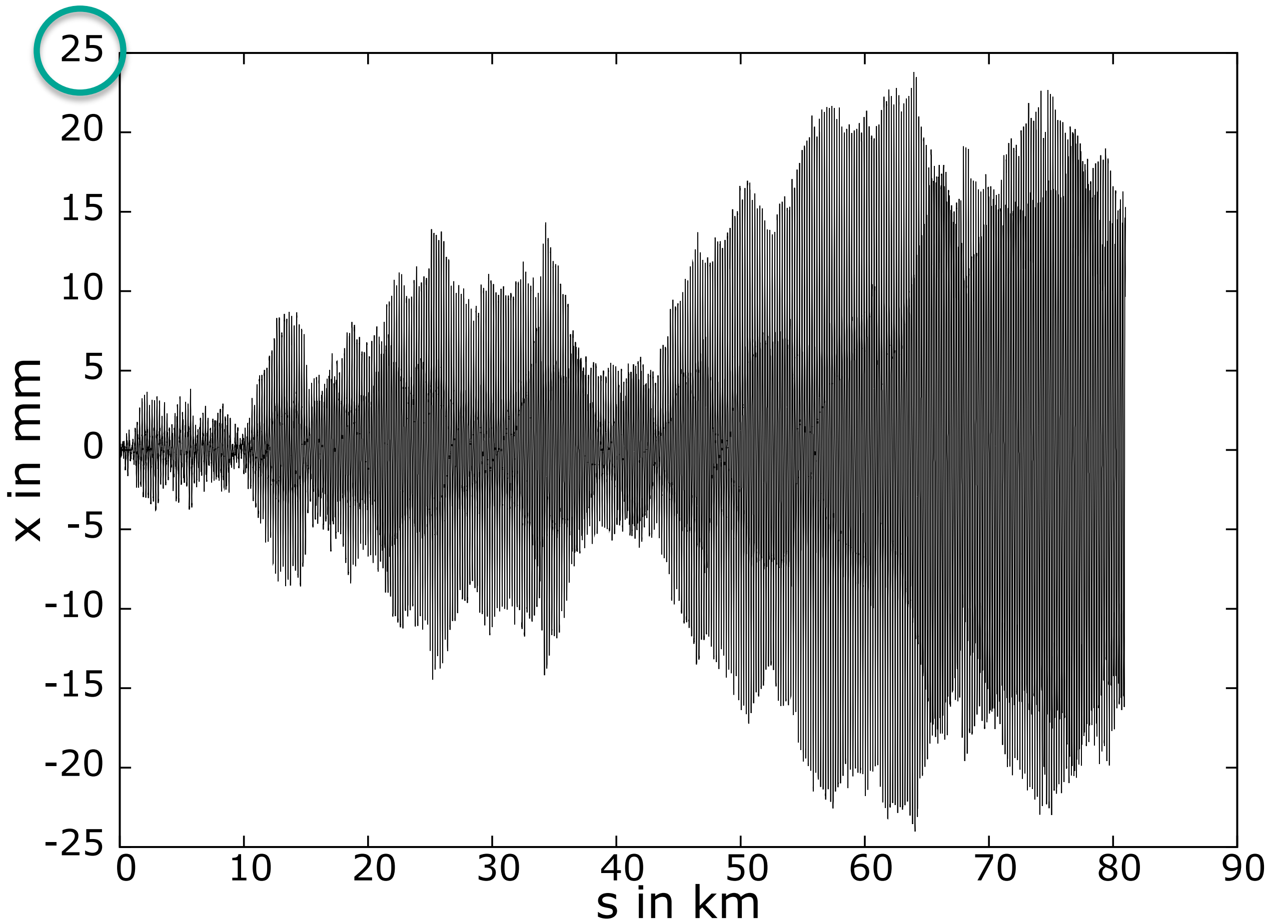
2) Beam emittances

- Required ratio: $\varepsilon_y/\varepsilon_x = 0.001$
- Horizontal emittance is defined by energy, cell length and focusing properties. ✔
- Vertical emittance is defined by orbit tolerances (misalignments & coupling).
- Assumed magnet alignment tolerance (D. Missiaen):

$$\Delta x = \Delta y = 150 \ \mu m$$

- Orbit tolerances add up to very large distortions and are amplified by the extreme minibeta concept.

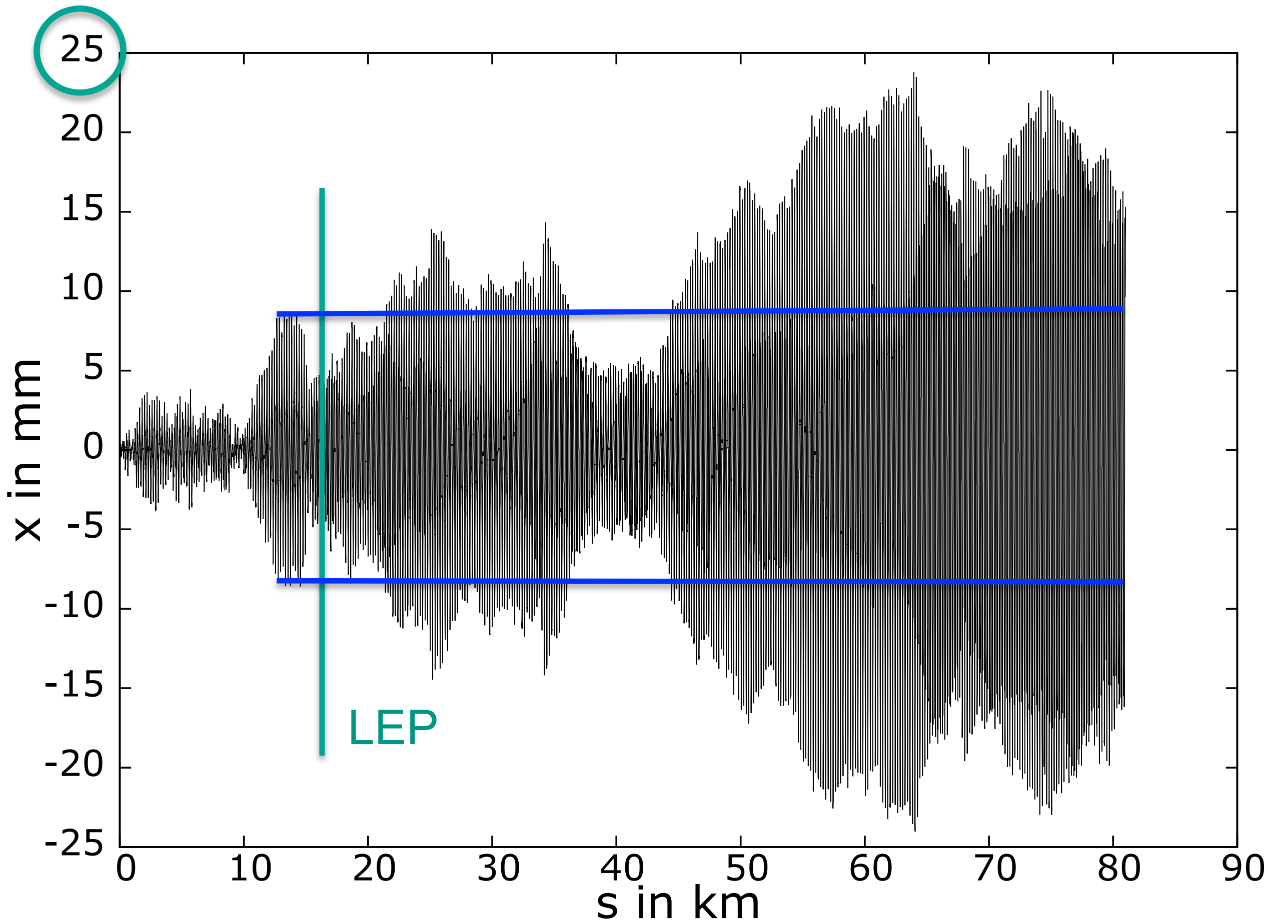
2) Horizontal distorted orbit



- Due to transversal misalignments of quadrupoles
- Calculated as transfer line

Without minibetas!

2) Horizontal distorted orbit



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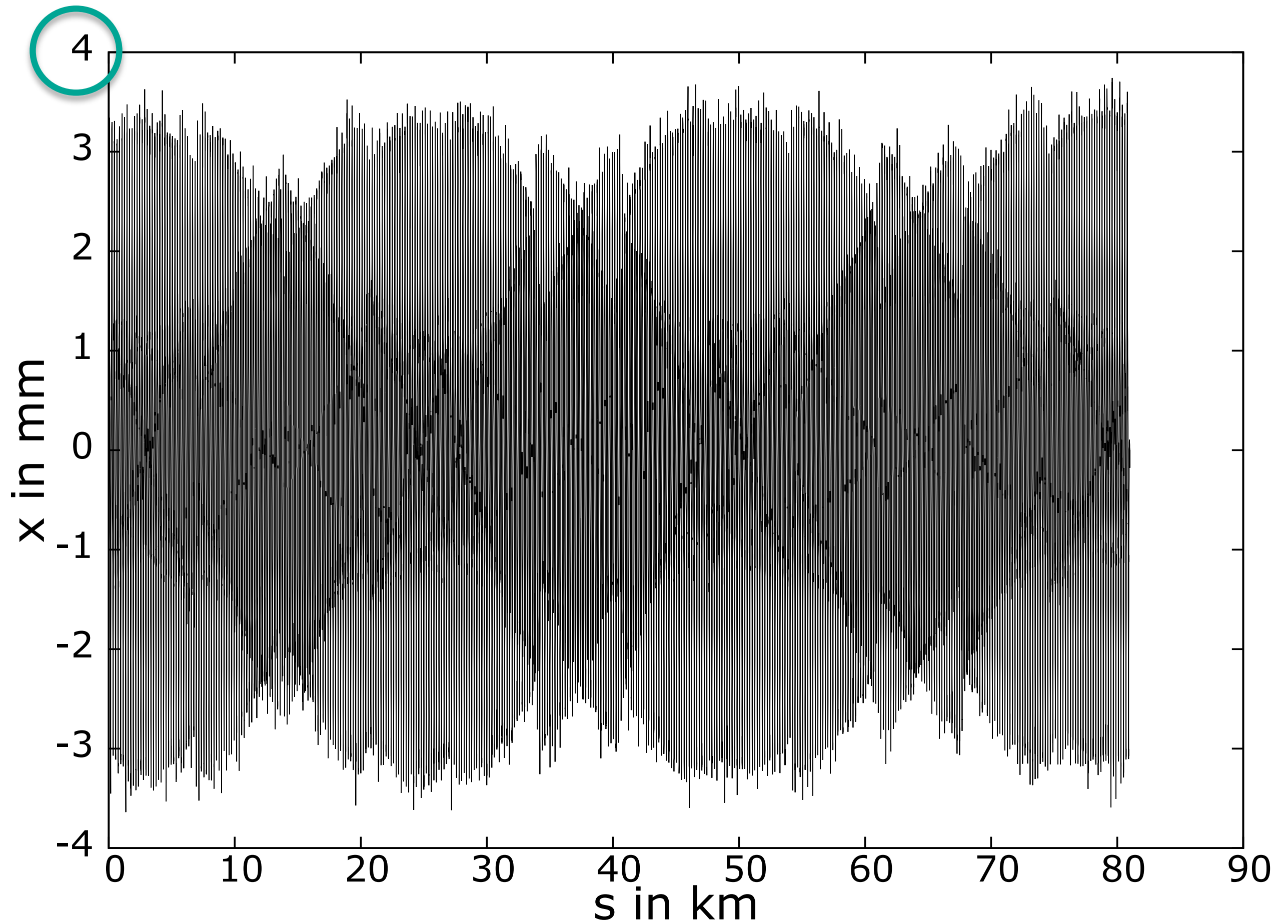
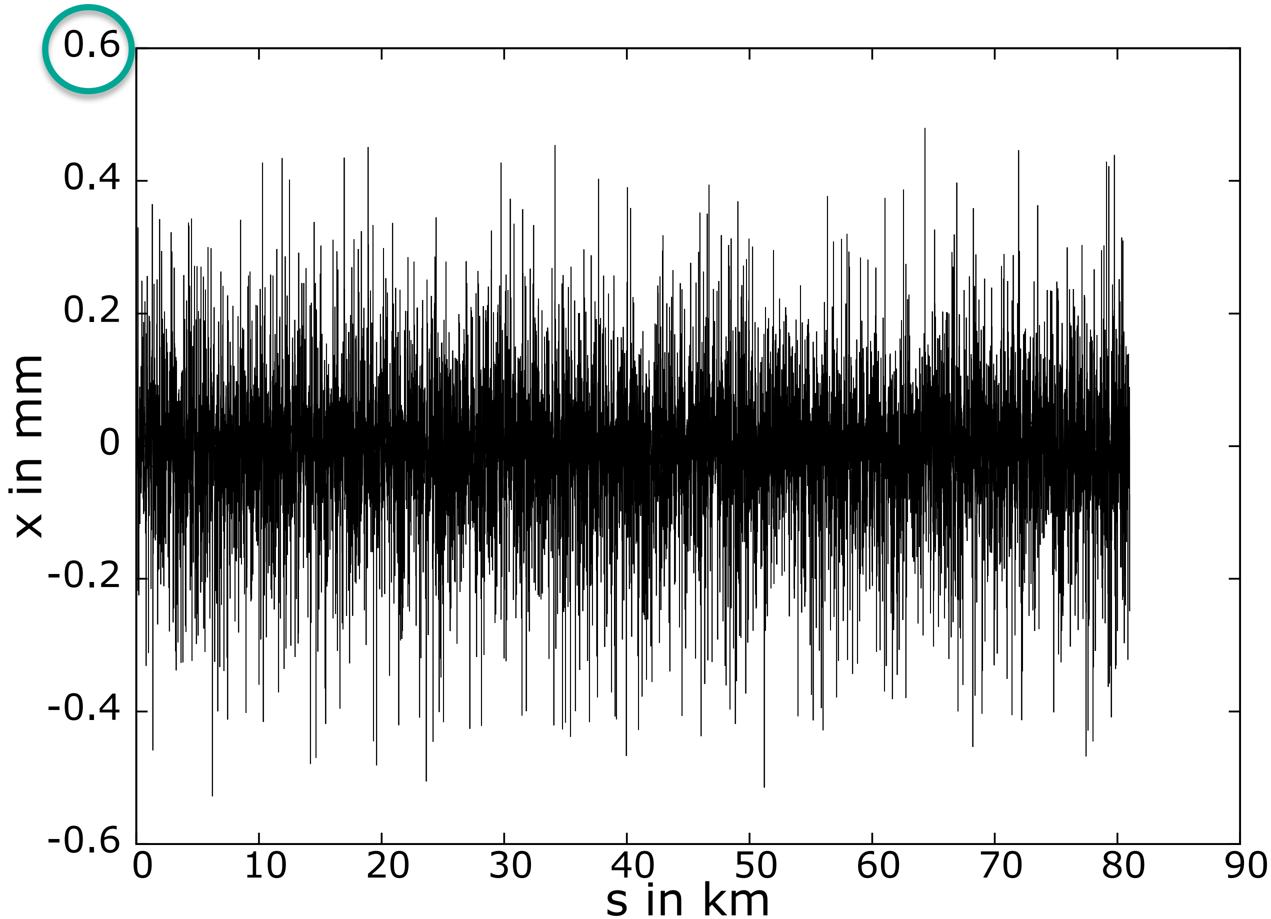


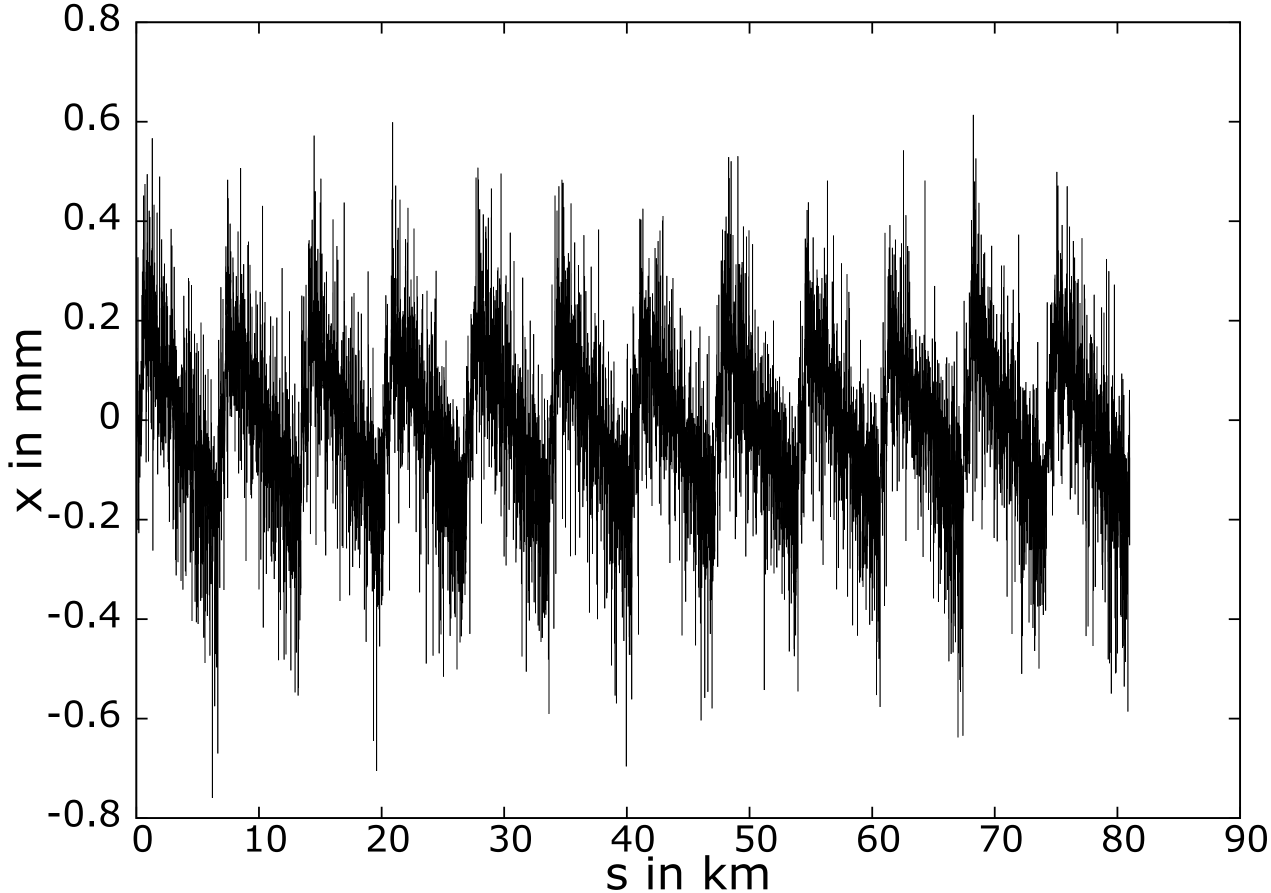
- … after 3 orbit correction iterations

2) Horizontal distorted orbit



- … after closing the ring, final correction and switching on sextupoles

2) Horizontal distorted orbit



$$x_D(s) = D(s) \cdot \frac{\Delta p}{p}$$

- … including synchrotron radiation and RF structures

2) Beam emittances

- Equilibrium emittances calculated by MAD-X:

$$\varepsilon_x = 1.23\ \text{nm},\ \boxed{\varepsilon_y = 1.05\ \text{pm}}\ ✔$$

Without minibetas!

- Can we maintain these values including coupling and beam-beam effects?

- How do we deal with the extreme sensitivity of the minibeta sections?

($\beta_y \approx 18$ km)

$$x_{rms}(s) \propto \sqrt{\beta(s)} \cdot \sqrt{\beta(s_0)}$$

→ Active alignment feature with piezos?

3) Lattice modifications for smaller energies

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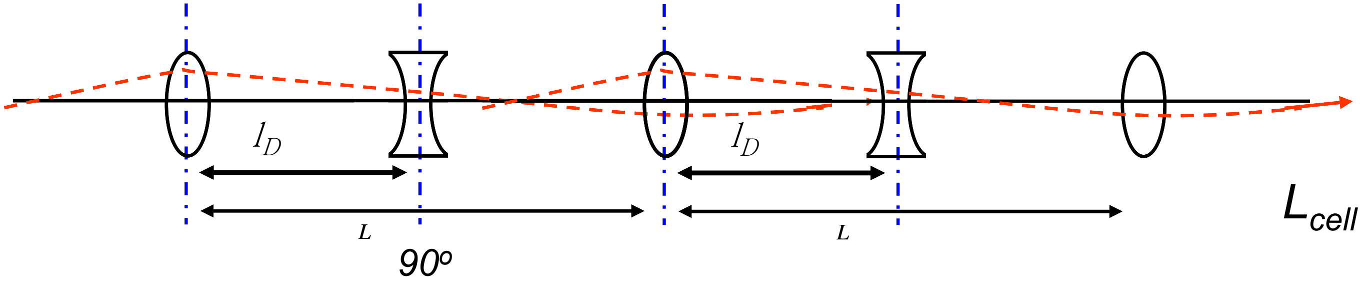
Beam energy [GeV]	45.5	80	120	175
Transverse emittance ε - Horizontal [nm] - Vertical [nm]	 29.2 0.060	 3.3 0.007	 0.94 0.0019	 2 0.002

- At 45.5 GeV the emittance is a factor 15 higher compared to 175 GeV!
- BUT: $\varepsilon_0 \propto \gamma^2$

→ How can we counteract the natural emittance shrinking for lower energies?

3) Lattice modifications for smaller energies

- Increase the FODO cell length to adjust the emittance!



$L_{cell} = 50m$

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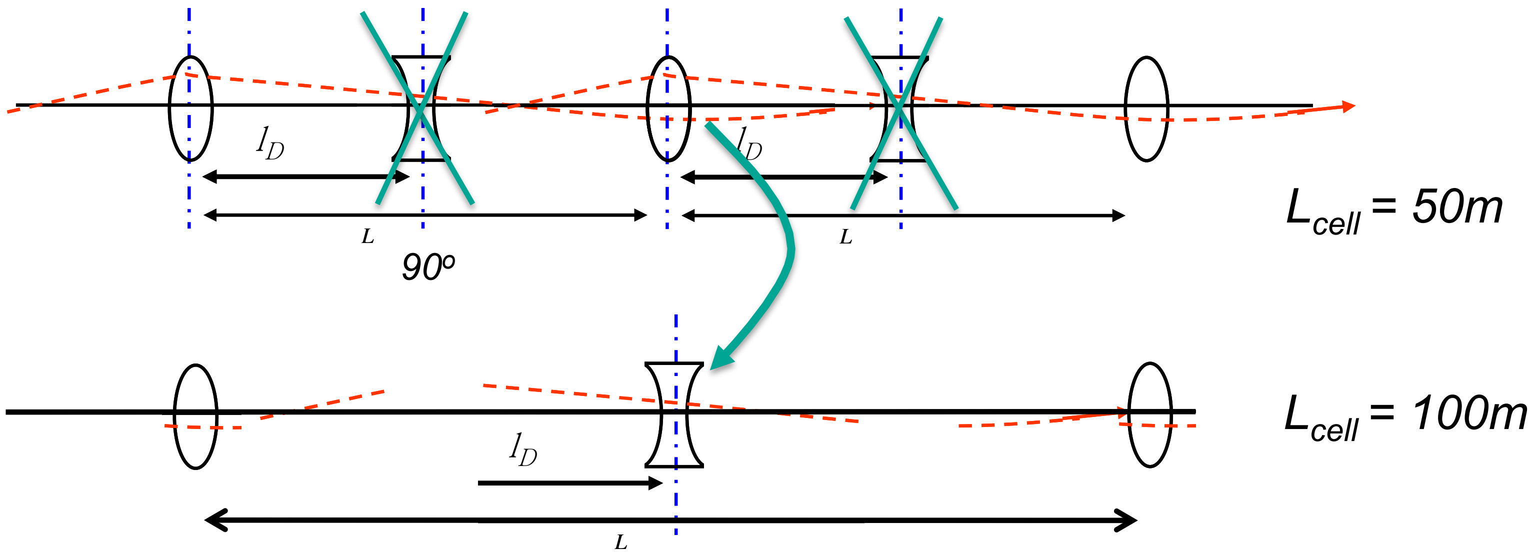

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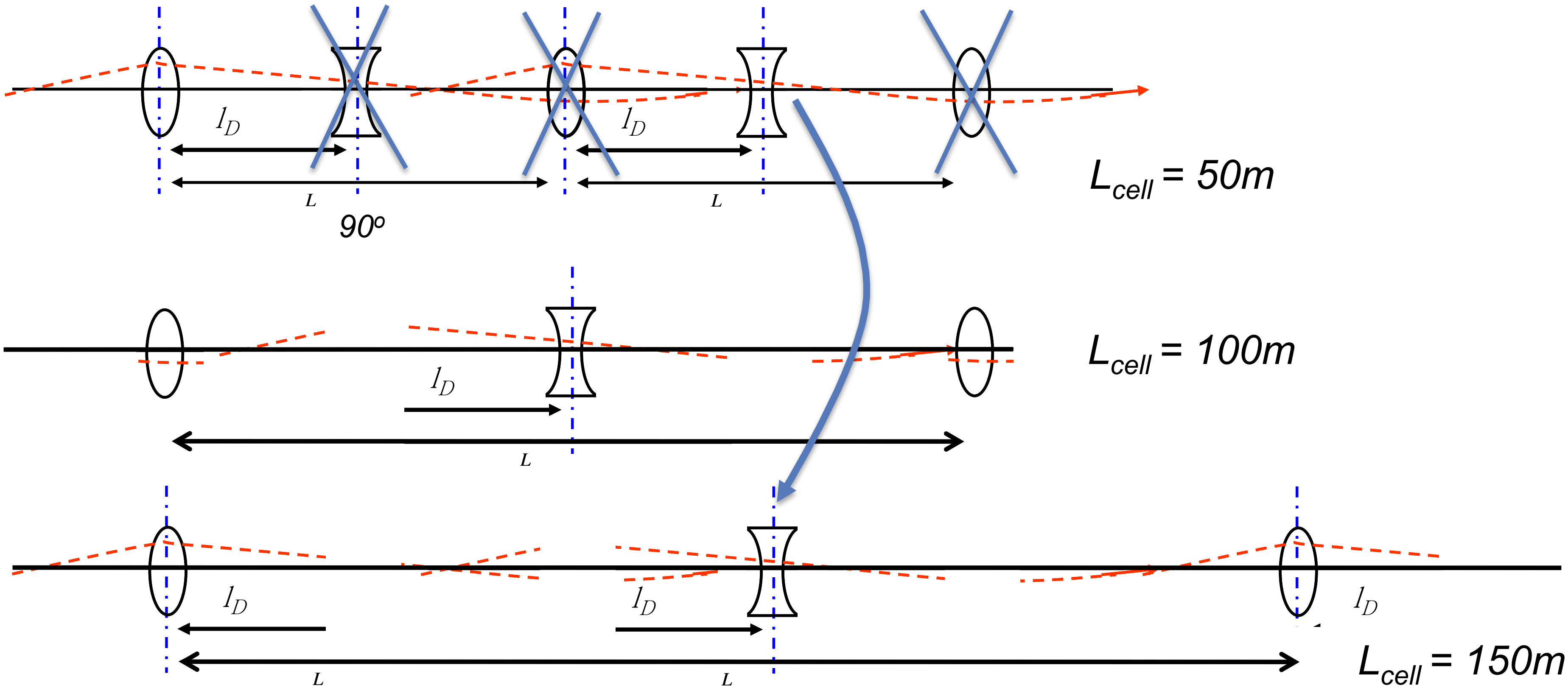

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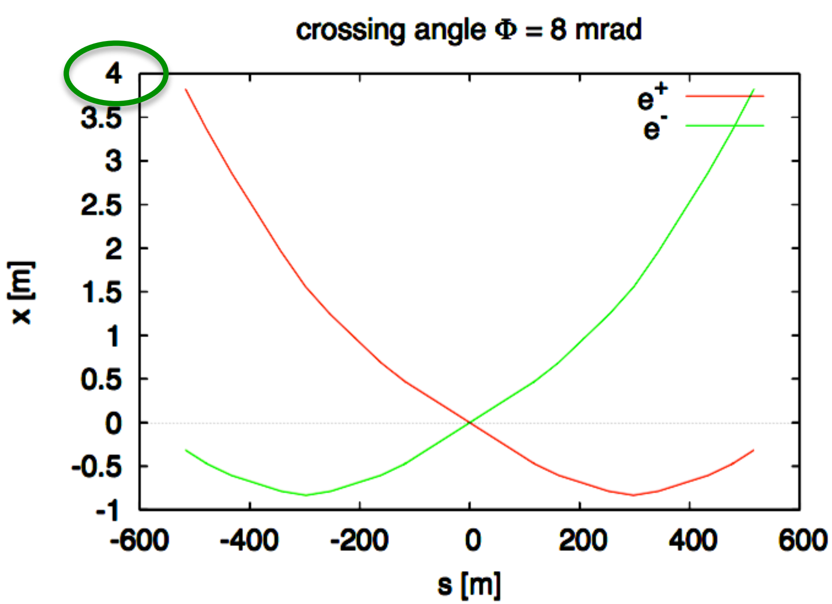
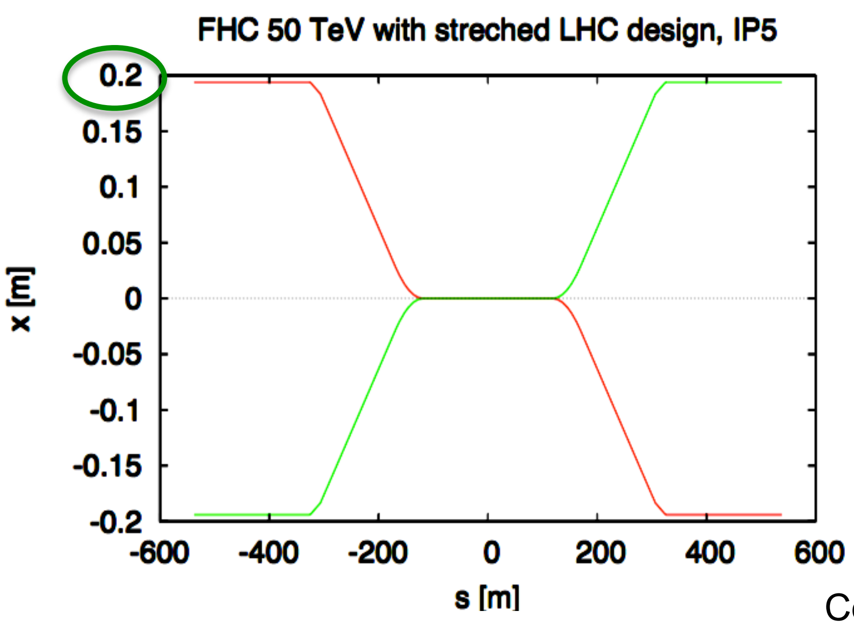
4) Interaction region lattice

- Large number of bunches: → 2 rings and crossing angles

→ How do we get sufficient separation to avoid beam-beam-effect?

→ How do we separate the beams without large synchrotron radiation background?





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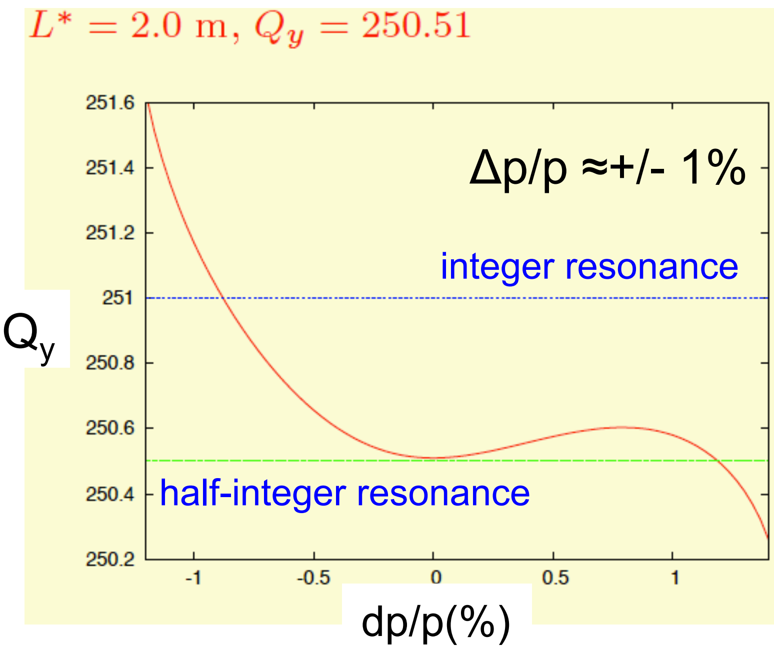
- How do we get a proton and an electron geometry together?

4) Mini-beta optics

- Extreme small β_y^* = 1 mm drives chromaticity to extreme values

without mini-beta: $Q'_x = -399$, $Q'_y = -332$ with mini-beta: $Q'_x = -483$, $Q'_y = -3066$

- Tune shift drives off-momentum particles to strong resonances



→ Linear Collider like interaction region with quasi local chromaticity control?

→ How to distribute the correction load in IR and arc?

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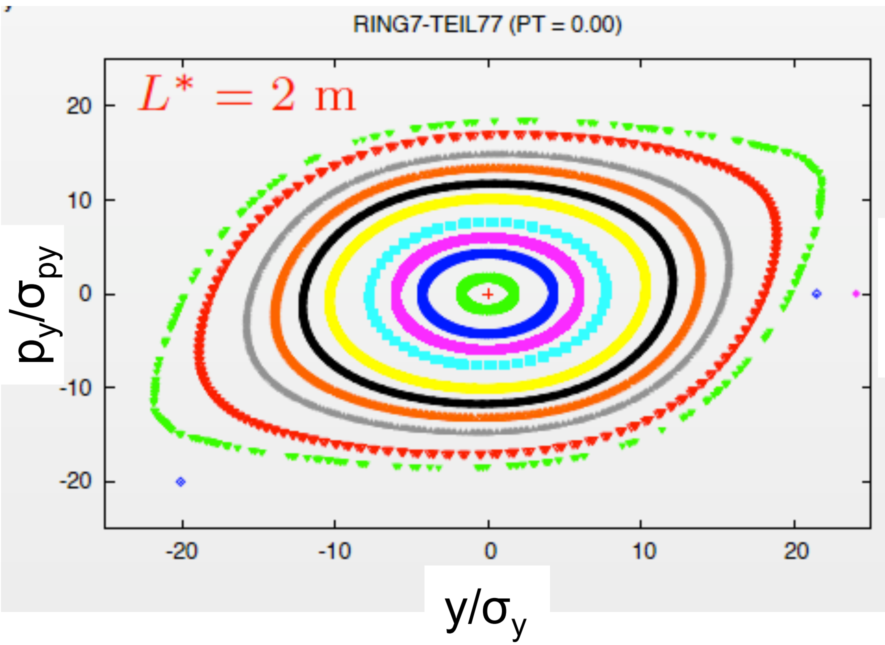
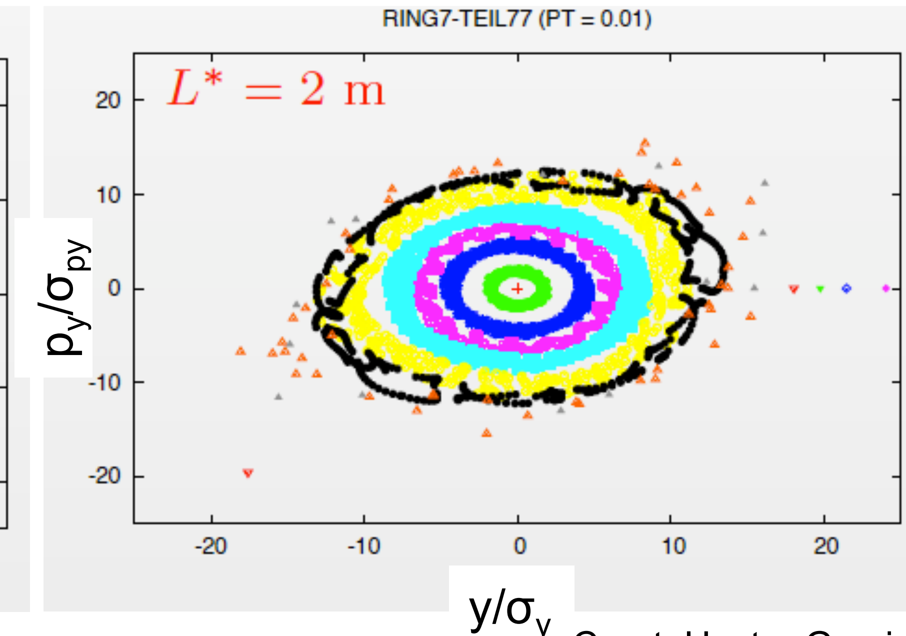
4) Dynamic aperture

- Very first dynamic aperture calculations

Ideal momentum Δp/p = 0



Off momentum Δp/p = ± 1 %



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- How do we improve the dynamic aperture for Δp/p = ±2 %?

Résumé

- We need a lattice design with highest flexibility.
  → Is a FODO cell the best solution? Light source lattices?

- We have to determine different beam optics to obtain the required emittances for all 4 energies.

- We have many challenges for the design of the interaction region:
  → Separation scheme with tolerable amount of synchrotron radiation
  → Large number of bunches
  → Minibeta insertions with $\beta_y^* = 1$ mm

- And still control and compensate the chromaticity.

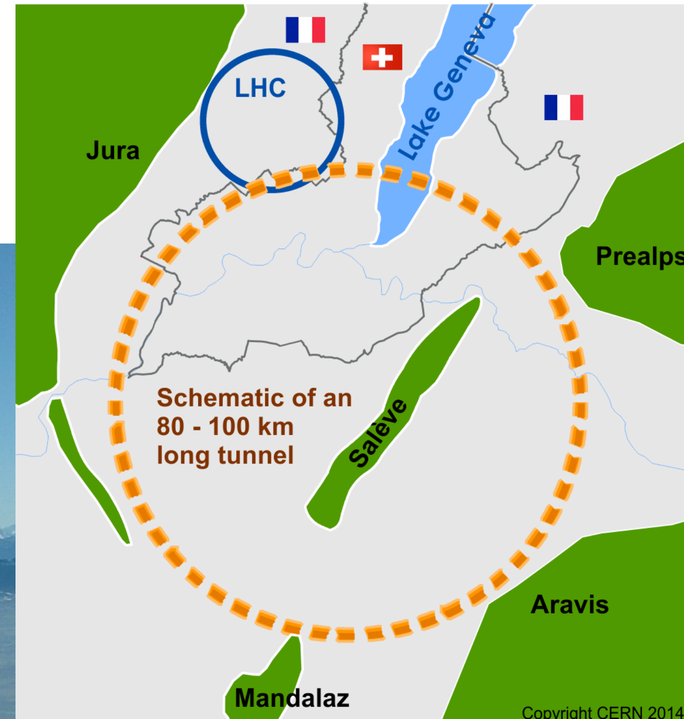
- We have to obtain a momentum acceptance of $\Delta p/p = \pm 2$ %.

FCC hh ee he

CERN

KIT Karlsruhe Institute of Technology

Thank you for your attention!



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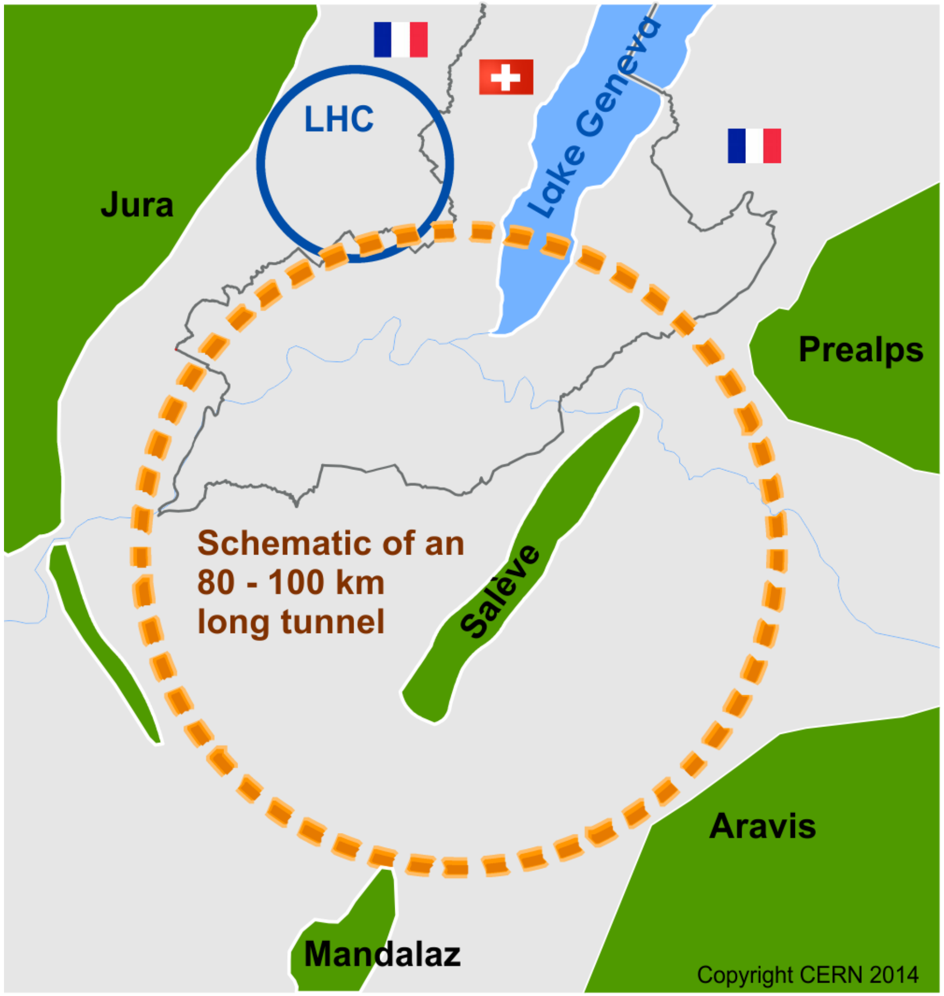
Potential location for TLEP/FCC-hh



court. Michael Benedikt

FCC motivation: pushing energy frontier

High-energy hadron collider *FCC-hh* as long-term goal

- **Seems only approach to get to 100 TeV range** in the coming decades
- High energy and luminosity at affordable power consumption
- **Lead time design & construction > 20 years** (LHC study started 1983!)

  → **Must start studying now to be ready for 2035/2040**

Lepton collider *FCC-ee* as potential intermediate step

- Would provide/share **part of infrastructure**
- Important **precision measurements** indicating the energy scale at which new physics is expected
- Search for **new physics in rare decays of *Z, W, H, t*** and rare processes

Lepton-hadron collider *FCC-he* as option

- High precision **deep inelastic scattering and Higgs physics**

Most aspects of collider designs and R&D non-site specific.
Tunnel and site study in Geneva area as ESU requests.

(court. Michael Benedikt)

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Momentum comp. [10^{-5}]	18	2	0.5	0.5
Betatron function at IP b* - Horizontal [m] - Vertical [mm]	 0.5 1	 0.5 1	 0.5 1	 1 1
Beam size at IP s* [mm] - Horizontal - Vertical	 121 0.25	 26 0.13	 22 0.044	 45 0.045
Bunch length [mm] - Synchrotron radiation - Total	 1.64 2.56	 1.01 1.49	 0.81 1.17	 1.16 1.49
Energy loss / turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	2.5	4	5.5	11

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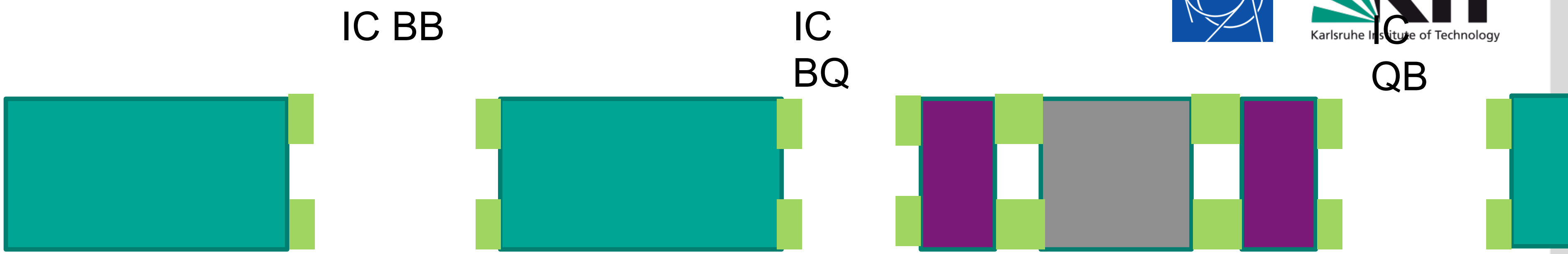
- Interaction region layout for a large number of bunches
- Horizontal emittance is increasing with reduced energy
- Extremely small vert. beta* (β_y* = 1 mm)
  → High chromaticity
  → Challenging dynamic aperture
- High synchrotron radiation losses include sophisticated absorber design in the lattice

Interconnection types and naming convention



Assumptions:
Quadrupoles and sextupoles with the same chamber and on same girder (two halfs?)

Interconnection BB

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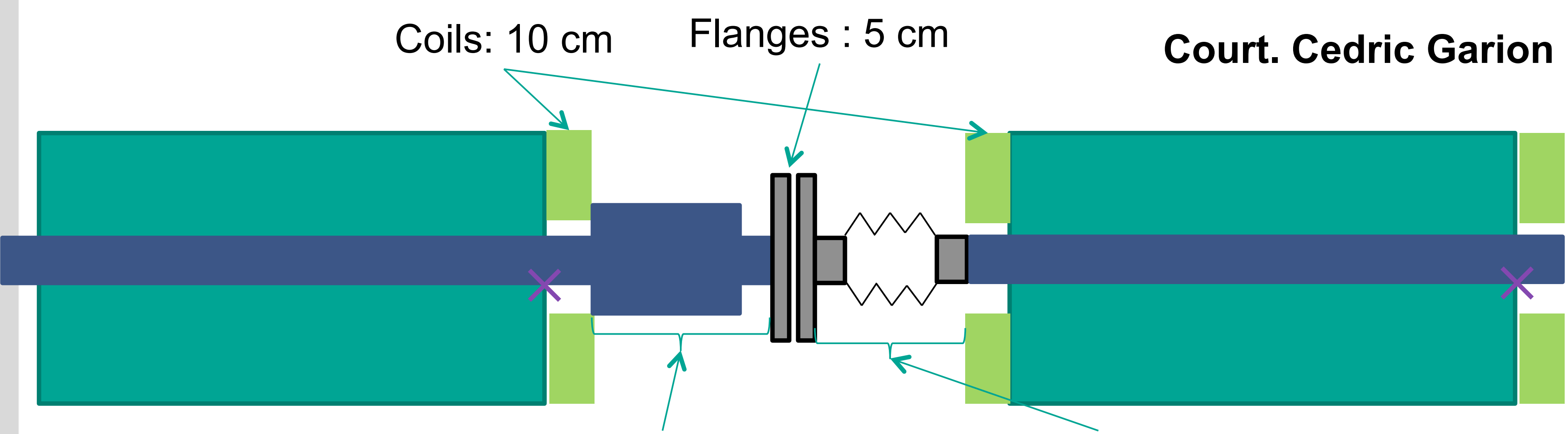
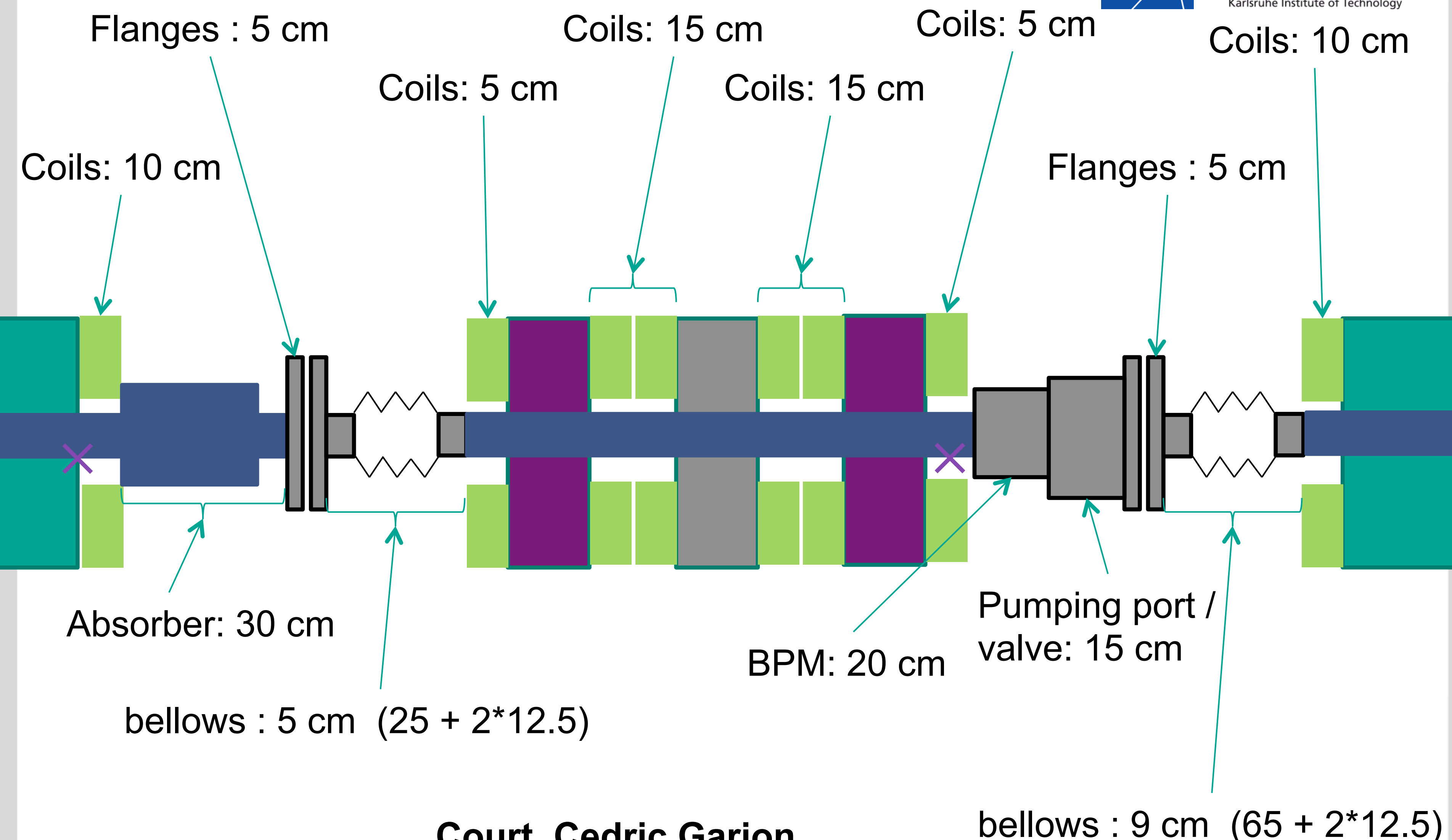


→ IC BB: ~ 65 cm (65 + 2*12.5)

Interconnections BQ and QB



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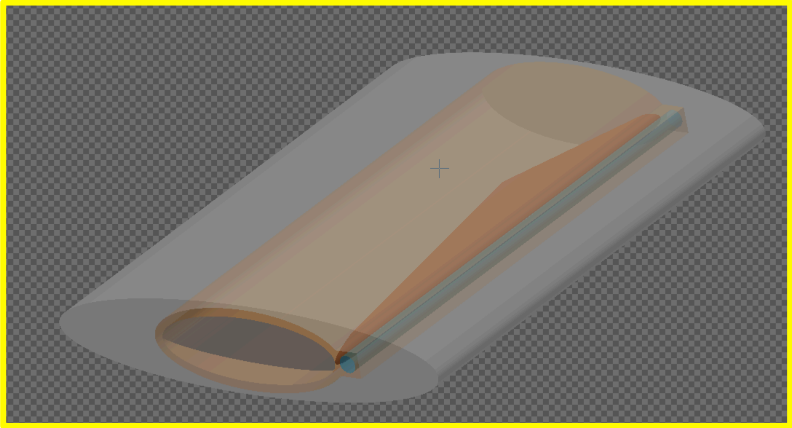
→ IC BQ: ~ 55 cm

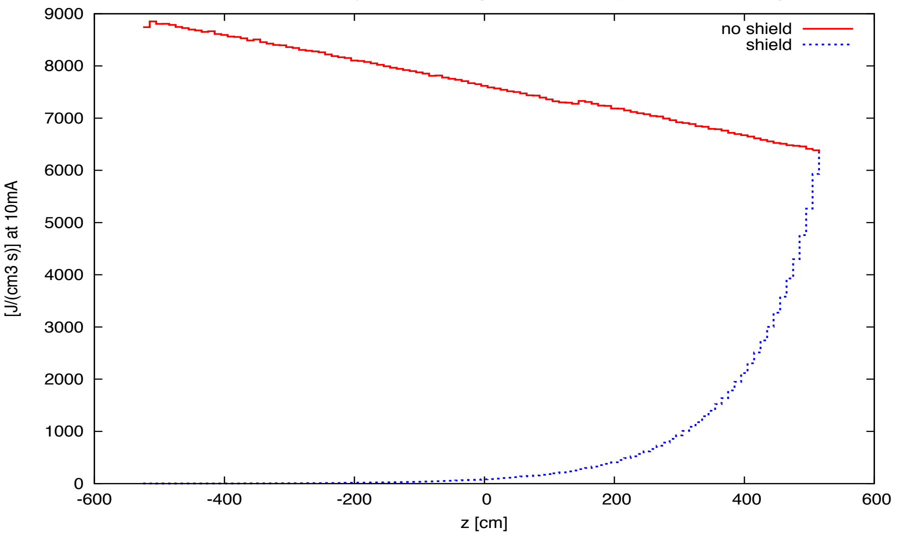
→ IC BQ: ~ 65 cm

Challenge 2: Lattice Design ... Layout of the Magnets

Achieve highest possible fill factor
to limit synchrotron radiation losses
Include Absorber Design in the lattice layout
Distribute RF straights to limit saw tooth effect
(dispersion suppressor layout)



power density along the dipole magnet



Dipole length defined by synchrotron radiation load
$L_{dipole} < 11m$

court. Luisella Lari et al

2) Beam emittances

- Equilibrium emittances calculated by MAD-X:

  ε_x = 1.23 nm, ε_y = 1.05 pm ✔

  Without minibetas!

- Can we maintain these values including coupling and beam-beam effects?

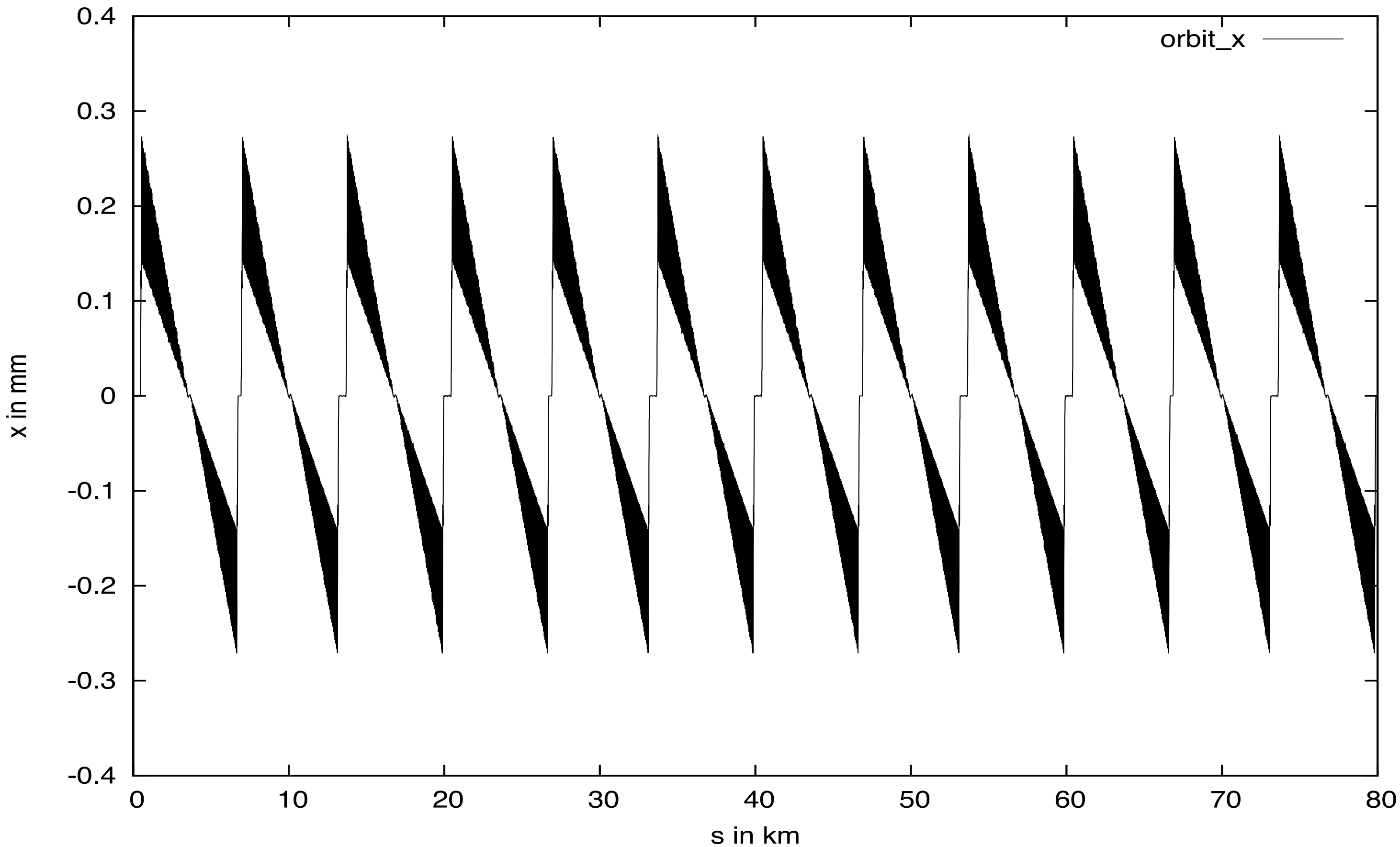
- How do we deal with the extreme sensitivity of the minibeta sections?

  ($\beta_y \approx$ 18 km)

$$x_{rms}(s) = \frac{\sqrt{\beta(s)}}{2\sin Q\pi}\Delta x'\sqrt{\beta(s_0)}\cos\left[\psi(s)-\psi(s_0)-Q\pi\right]$$

→ Active alignment feature with piezos?

Sawtooth effect (no misalignments)



- RF equally distributed among minibetas and straight sections

3) Lattice modifications for smaller energies

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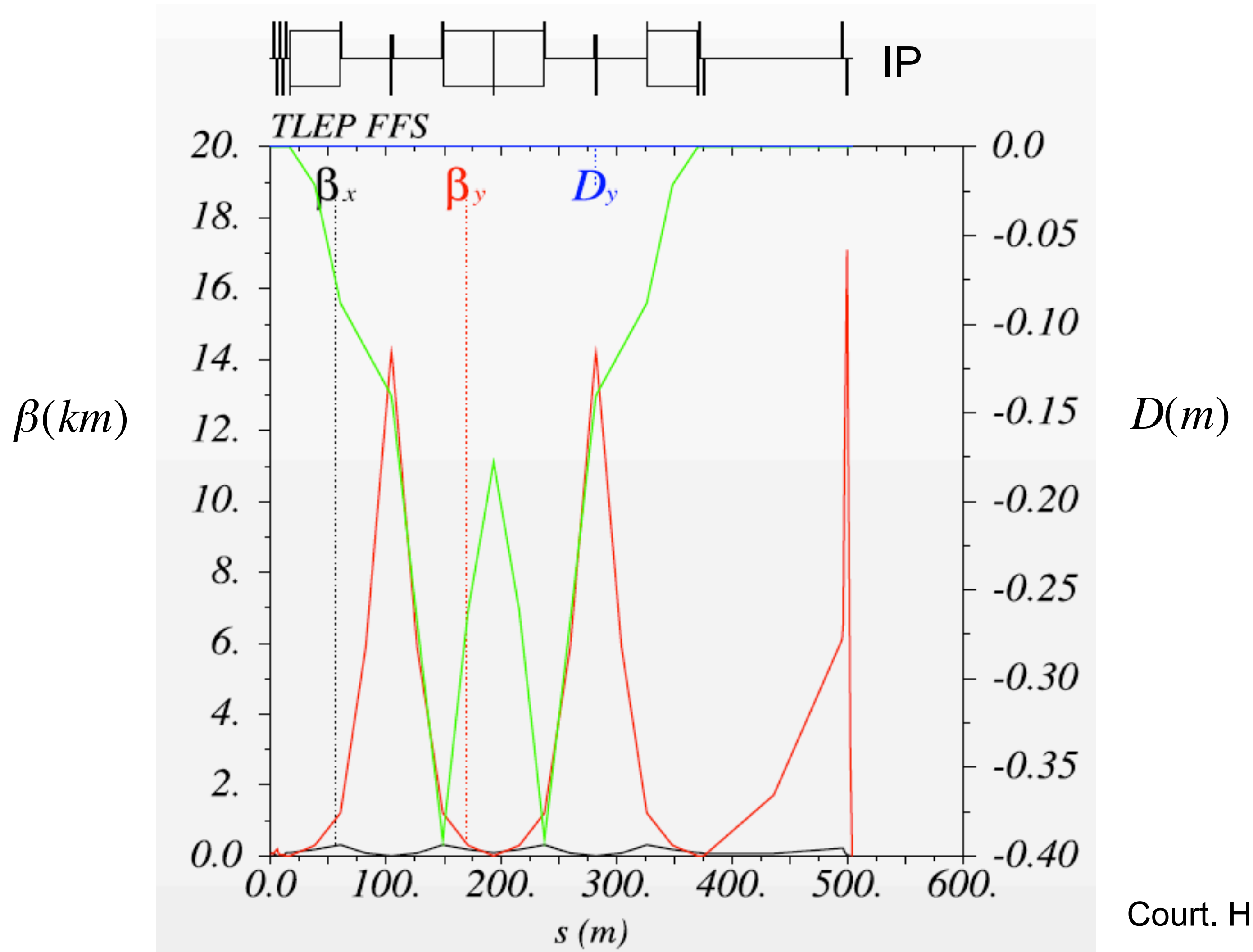
Beam energy [GeV]	45.5	80	120	175
Transverse emittance e - Horizontal [nm] - Vertical [pm]	 29.2 60	 3.3 7	 0.94 1.9	 2 2

- At 45.5 GeV the emittance is a factor 15 higher compared to 175 GeV!
- BUT: $\varepsilon_0 = C_q \gamma^2 \frac{I_5}{J_x I_2},$ $\quad I_2 = \oint \frac{1}{\rho^2} ds$

$$I_5 = \oint \frac{\mathcal{H}_x}{|\rho|^3} ds, \qquad \mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2$$

→ How can we counteract the natural emittance shrinking for lower energies?

Minibeta with quasi-local correction scheme



Court. Hector Garcia