Lattice design for FCC-ee

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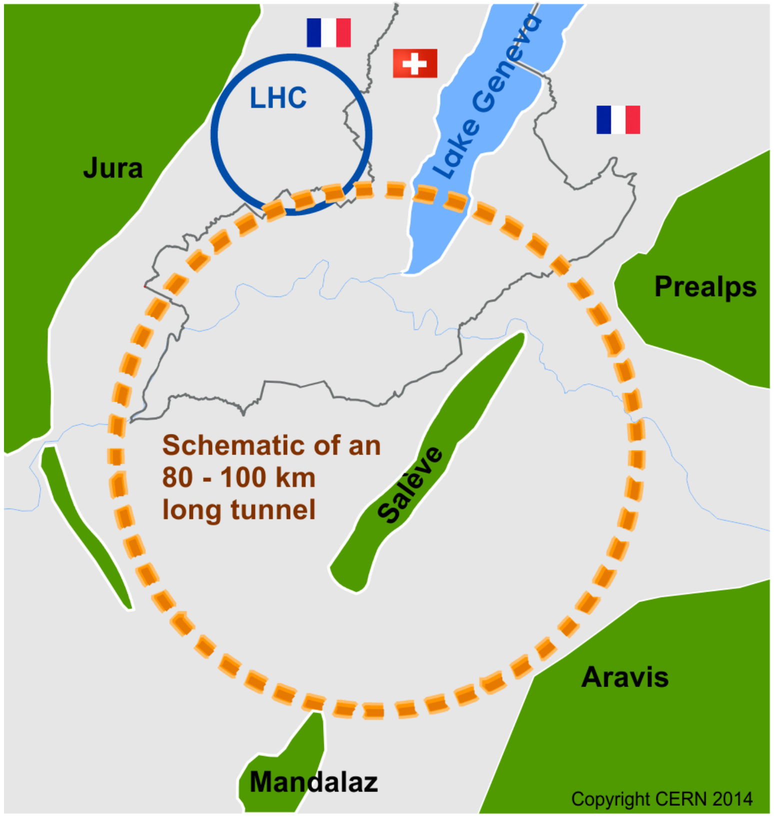
Future Circular Collider Study

- 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



Physics goals of FCC-ee

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

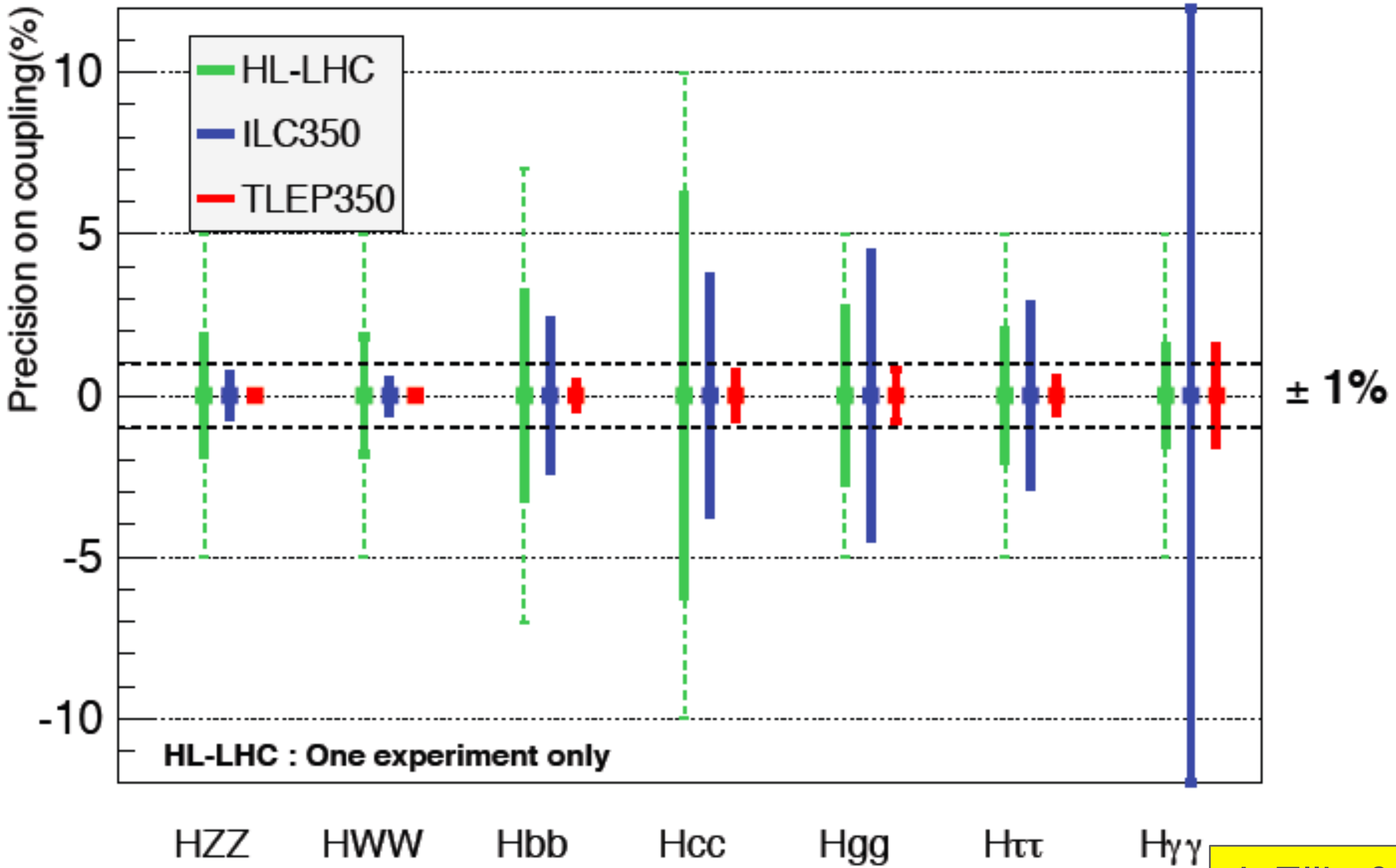
- Beam energy range from 45 GeV to 175 GeV

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

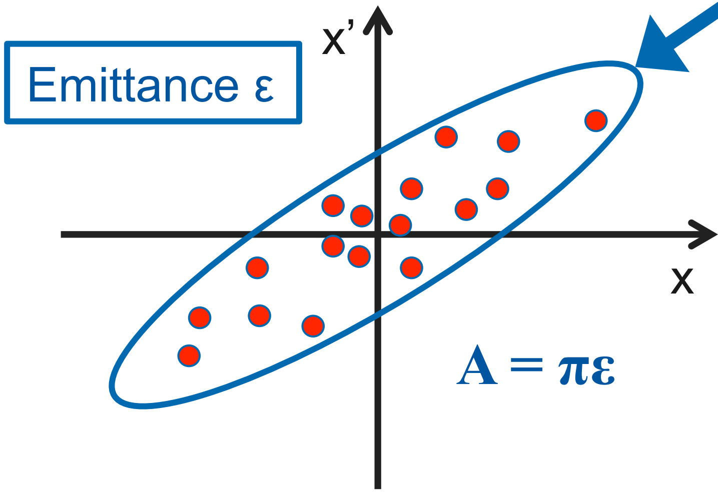
Coupling precision

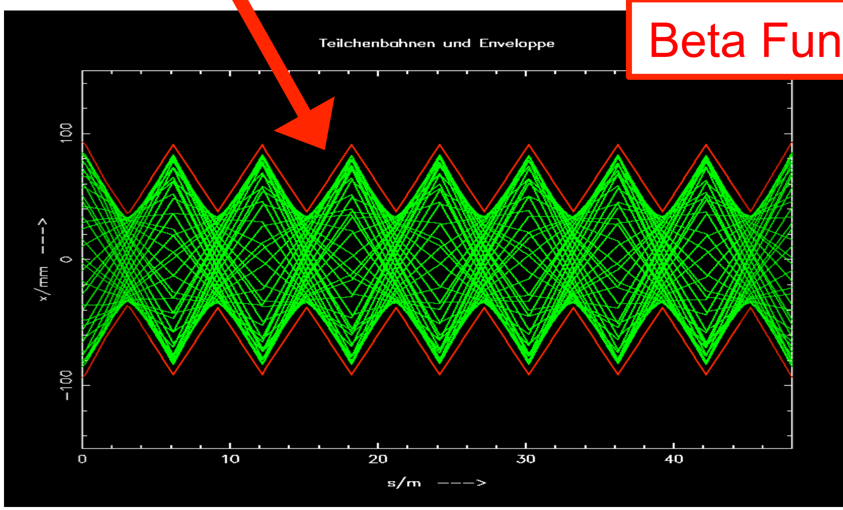


J. Ellis & P. Janot

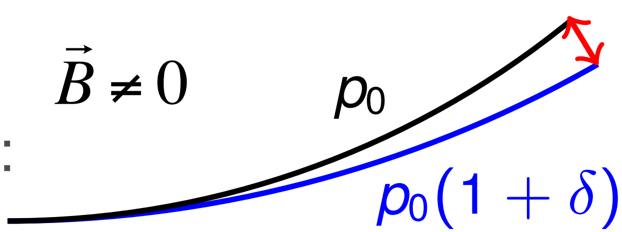
Linear Beam Dynamics

- Particle trajectory: $x(s) = \sqrt{\varepsilon}\,\sqrt{\beta(s)}\,\cos(\psi(s)+\phi)$





- Particles with energy deviation: $\vec{B} \neq 0$



$\Delta x = \delta D$

$\delta = \Delta p/p$

Dispersion function D

Challenges: 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]**	29.2	3.3	0.94	2
- **Vertical [nm]**	0.06	0.007	0.0019	0.002
Momentum comp. [10^{-5}]	18	2	0.5	0.5
Betatron function at IP β*				
- **Horizontal [mm]**	500	500	500	1000
- **Vertical [mm]**	1	1	1	1
Energy loss / turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	2.5	4	5.5	11

- Design & optimize a lattice for 4 different energies
- 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

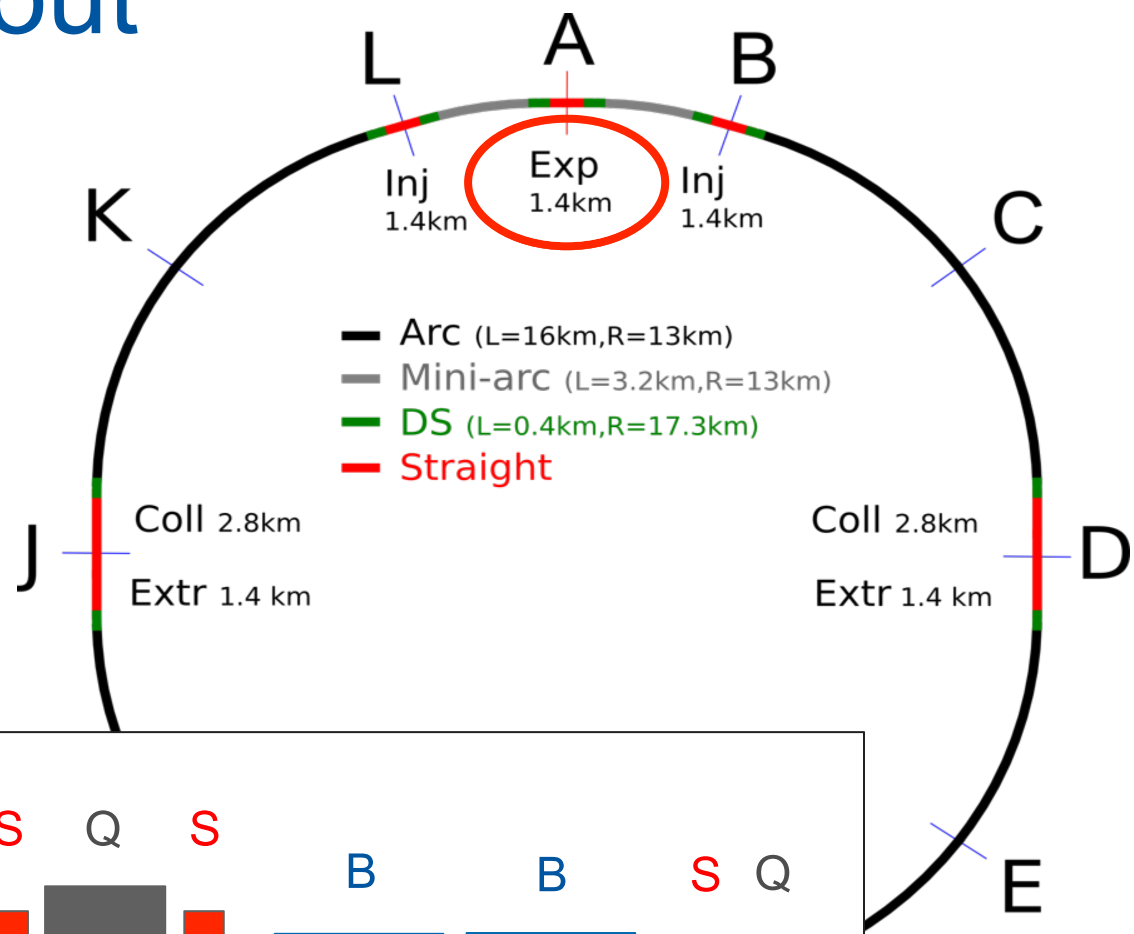
→ Challenging dynamic aperture

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

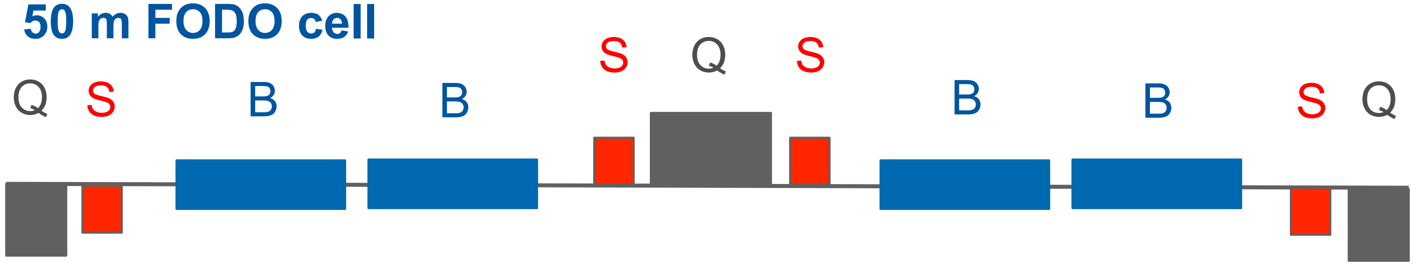
FCC-ee Layout

100 km circumference

2 experiments



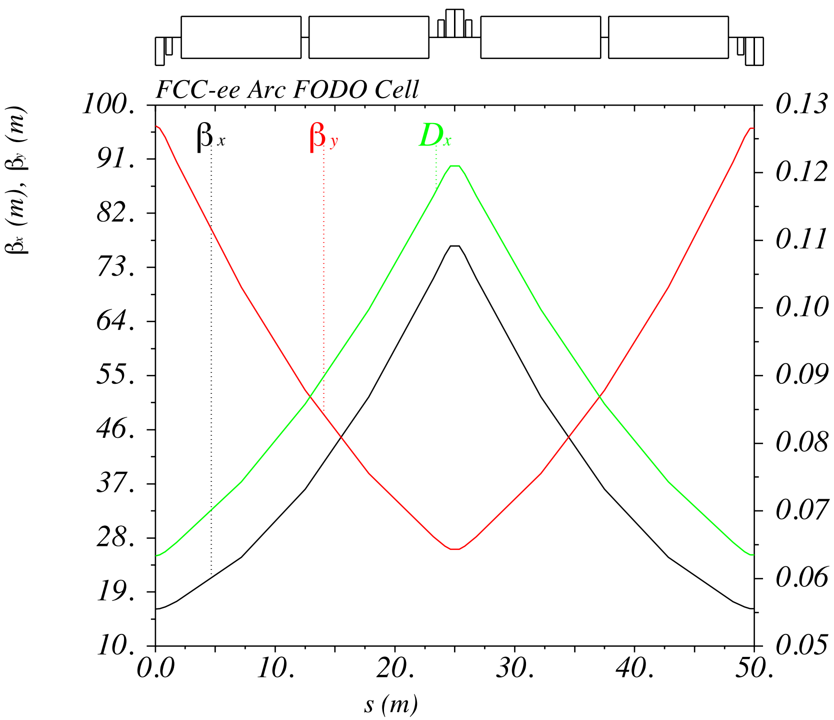
50 m FODO cell



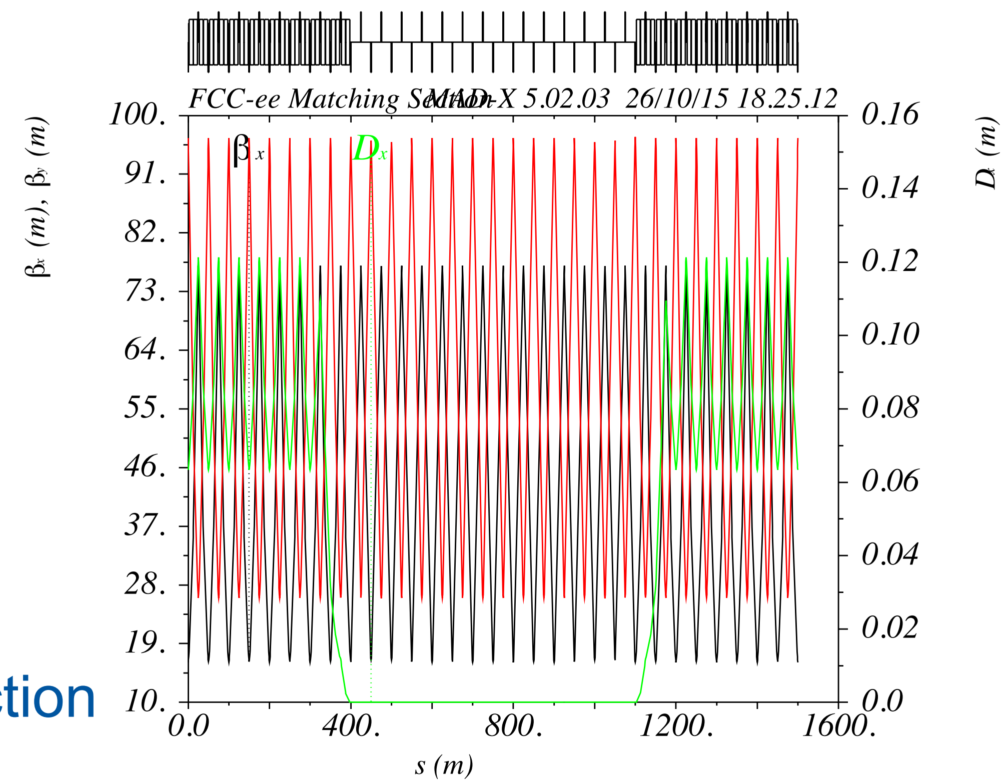
B = bending magnet, Q = quadrupole, S = sextupole

Optical functions (175 GeV)

Arc FODO cell



Mini straight section



My PhD thesis so far:

- Maintain the lattice for FCC-ee (Arcs)
- Horizontal emittance tuning
- Chromaticity correction using the arcs

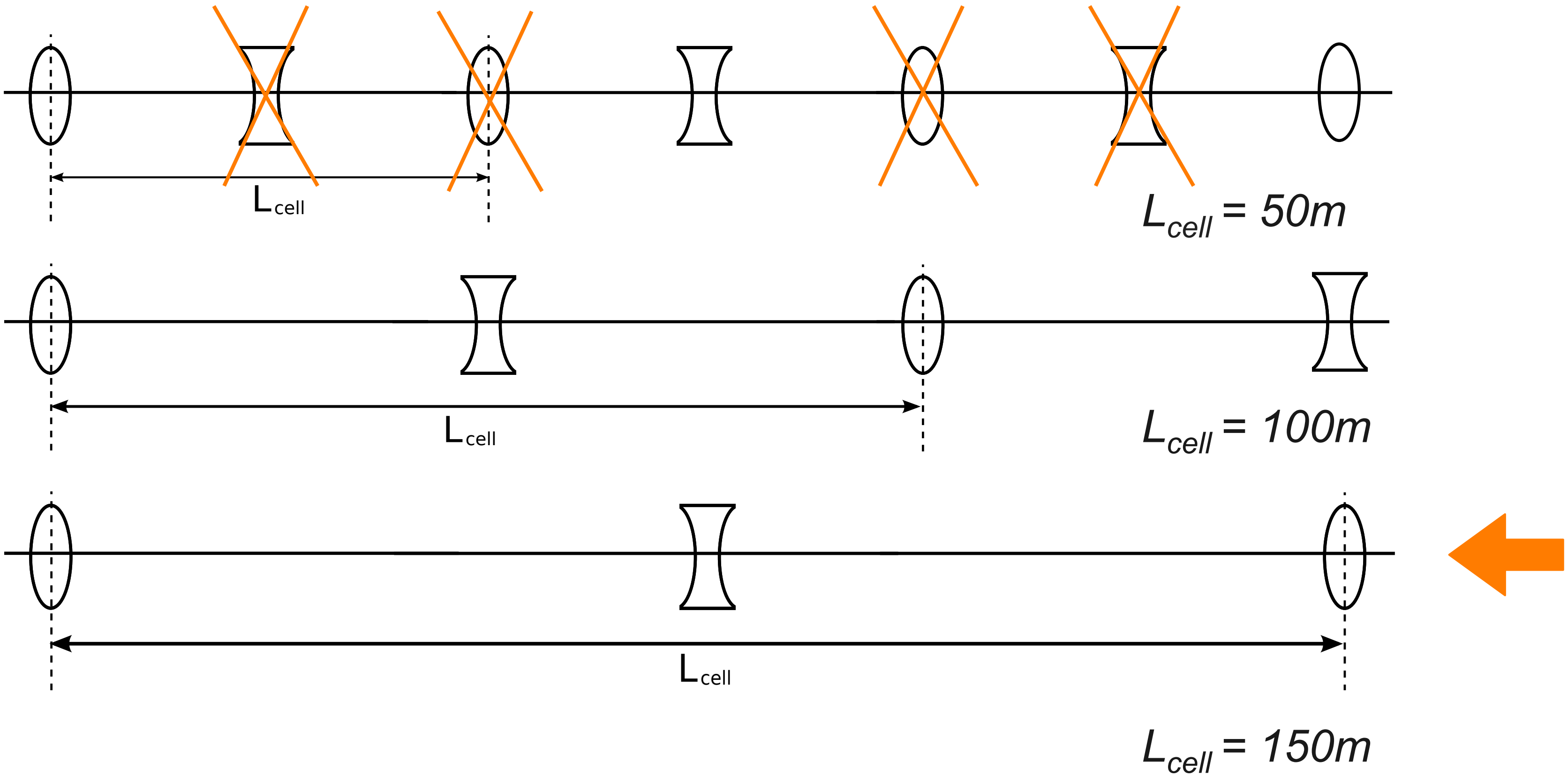
Baseline parameter list:

Beam energy [GeV]	45.5	80	120	175
Horizontal emittance ε [nm]	29.2	3.3	0.94	2

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

1) Emittance tuning

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

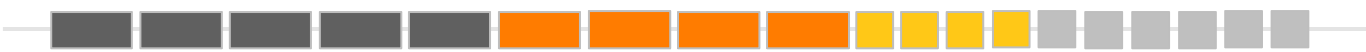


Lattices for 80 and 45.5 GeV

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

Half-bend dispersion suppressor

80 GeV: L_{cell} = 100 m, Ψ = 90°/60°

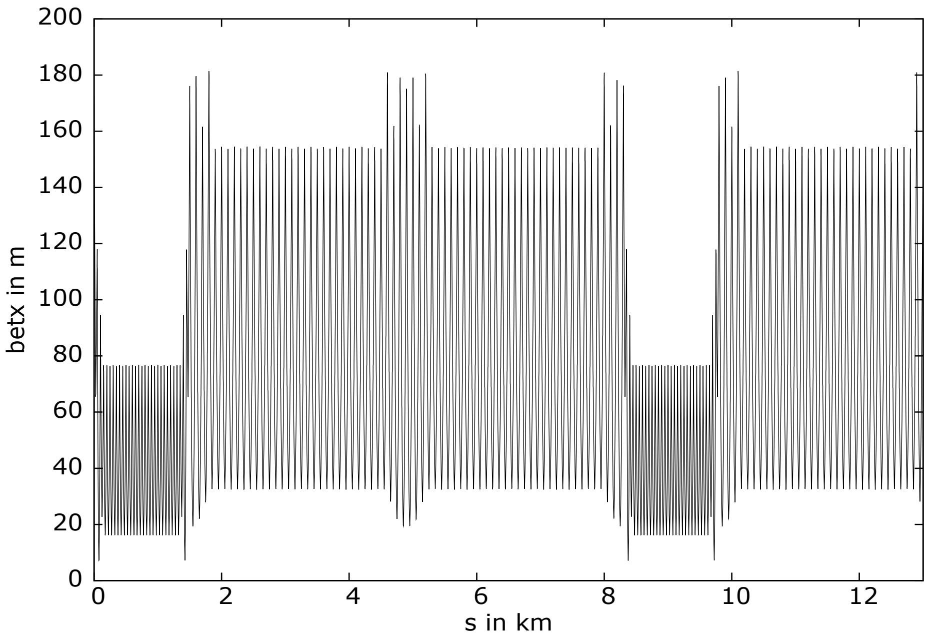


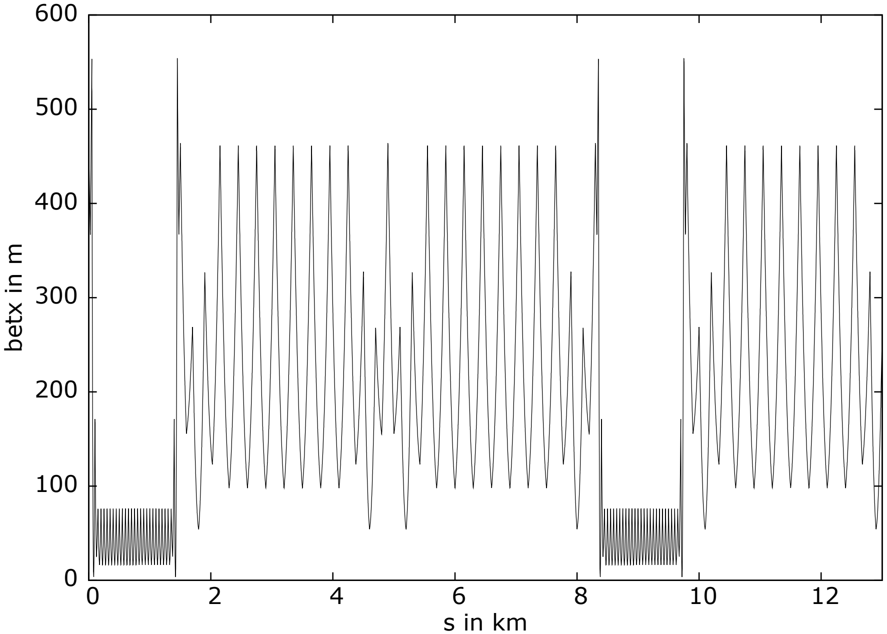
Dispersion suppressor based on quadrupoles

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

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

Optics with larger cell lengths





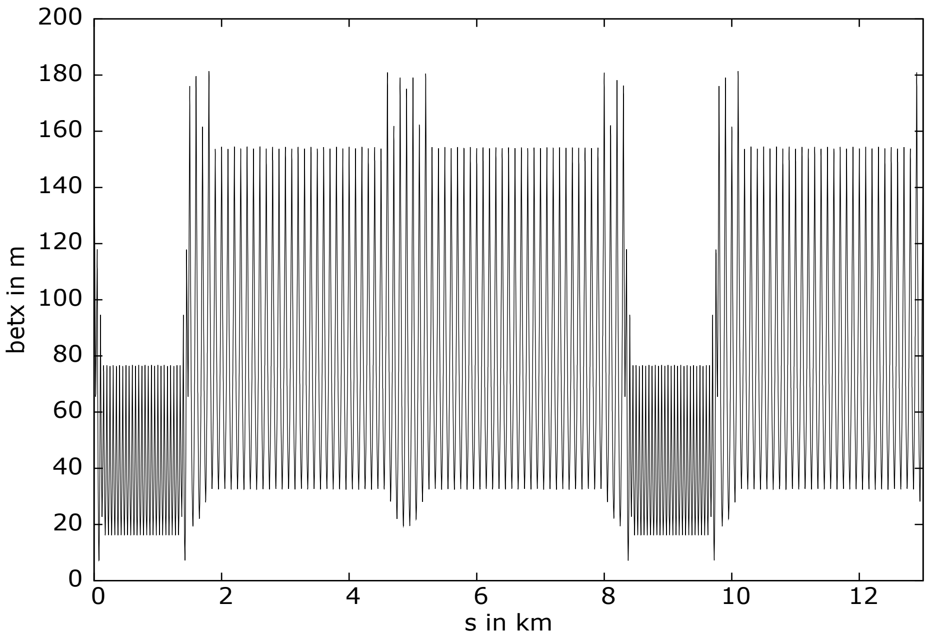
80 GeV beam energy

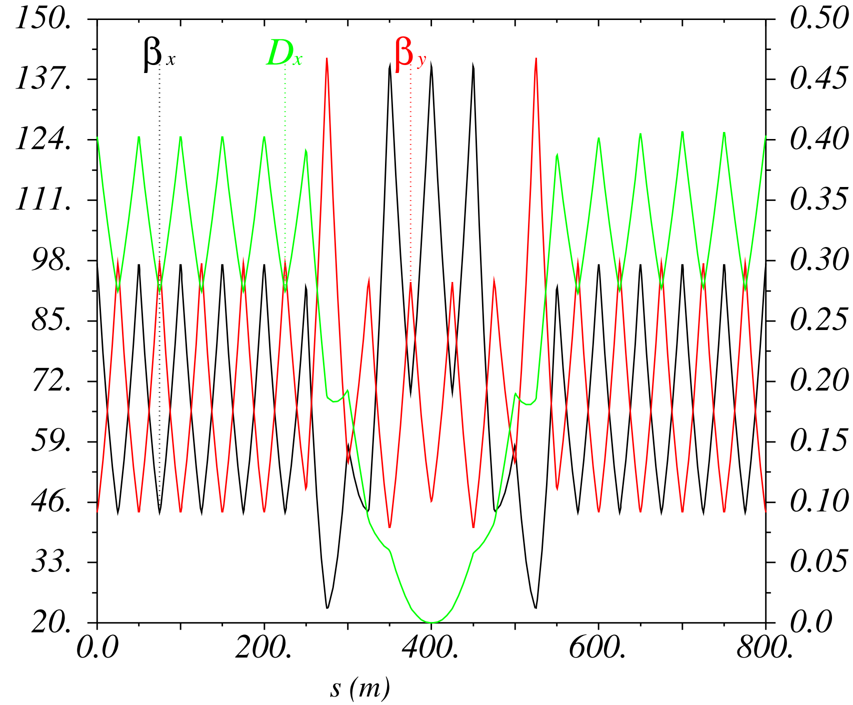
MADX Emit: ε_x = 1.70 nm

45.5 GeV beam energy

MADX Emit: ε_x = 14.2 nm

Optics with larger cell lengths





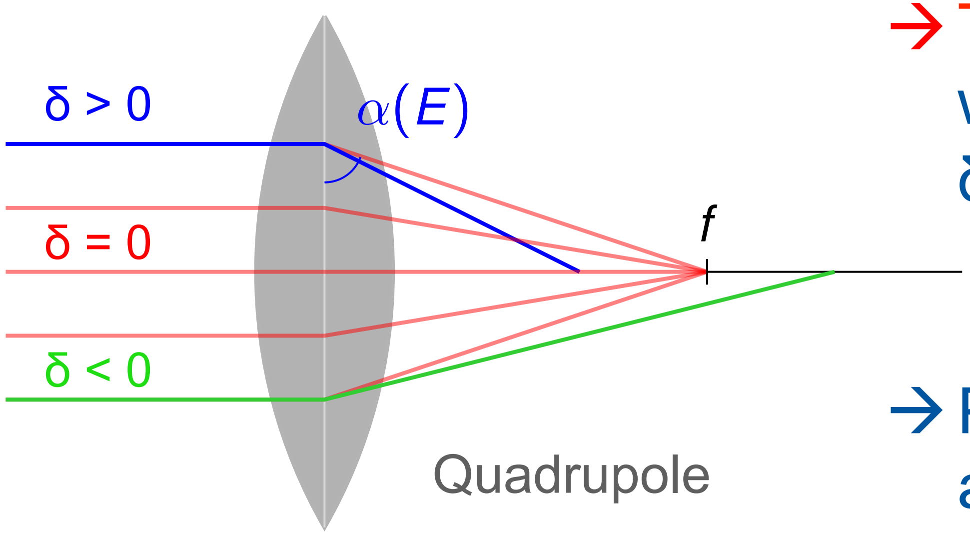
80 GeV beam energy

MADX Emit: ε_x = 1.70 nm

Re-matched Dispersion Suppressor

2) Chromaticity

Dispersion in the quadrupoles modifies focusing strength



→ Tune shift for particles with energy deviation δ = Δp/p

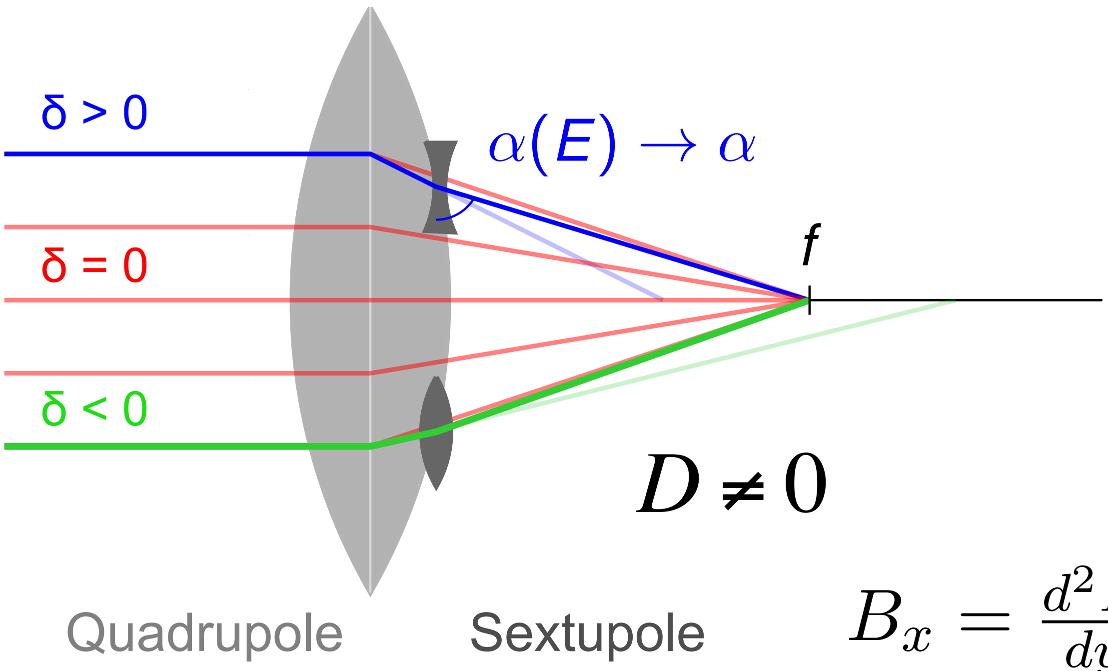
→ Particles hit resonances and get lost

$$Q(\delta) = Q_0 + \frac{\partial Q}{\partial \delta}\delta + \frac{1}{2}\frac{\partial^2 Q}{\partial \delta^2}\delta^2 + \frac{1}{6}\frac{\partial^3 Q}{\partial \delta^3}\delta^3 + \dots$$

Tune | 1st order | 2nd order | 3rd order chromaticity

Chromaticity correction

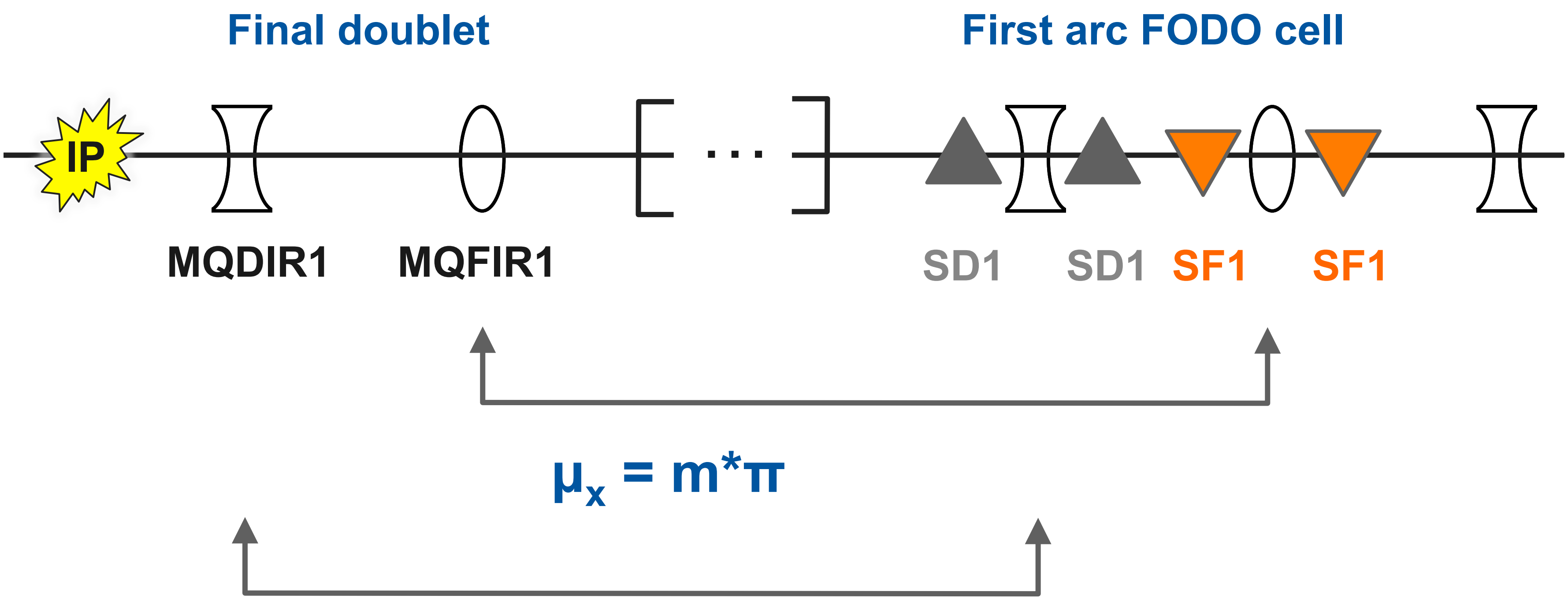
Correction with sextupole magnets in non-dispersive regions



$$B_x = \frac{d^2 B_x}{dy^2}\, x\, y$$

$$B_y = \frac{1}{2}\frac{d^2 B_y}{dx^2}(x^2 - y^2)$$

Phase advance FD – 1^{st} Sext.

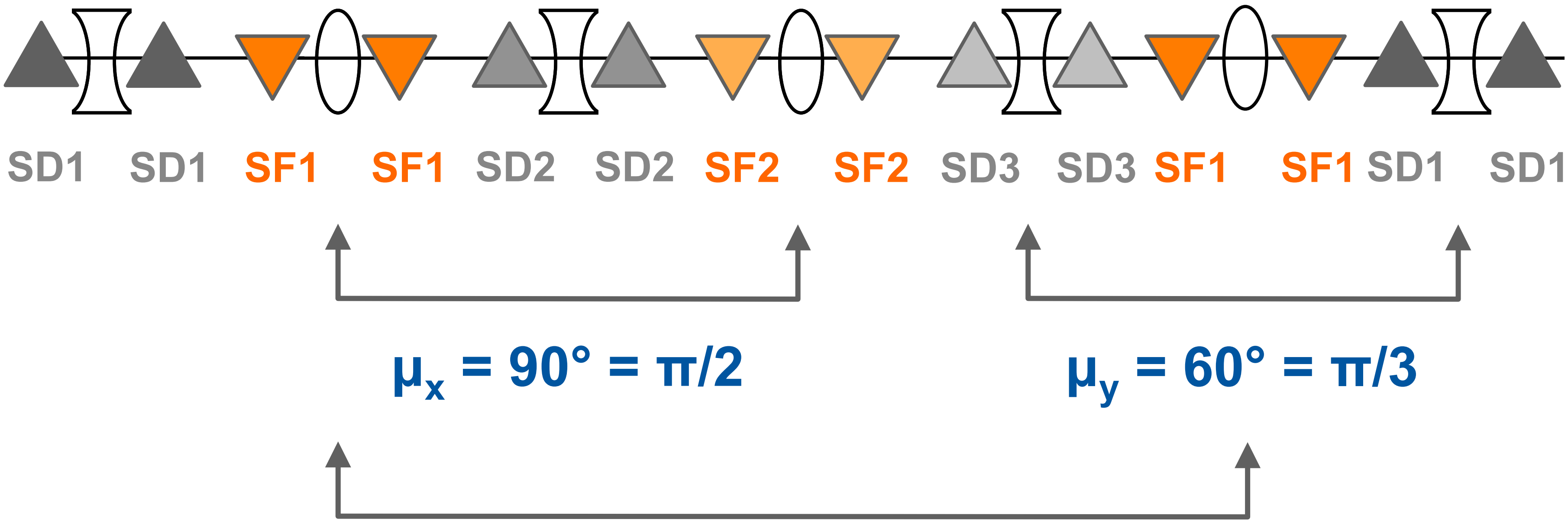


$\mu_x = m*\pi$

$\mu_y = n*\pi$

(m,n integer)

FCC-ee sextupole scheme



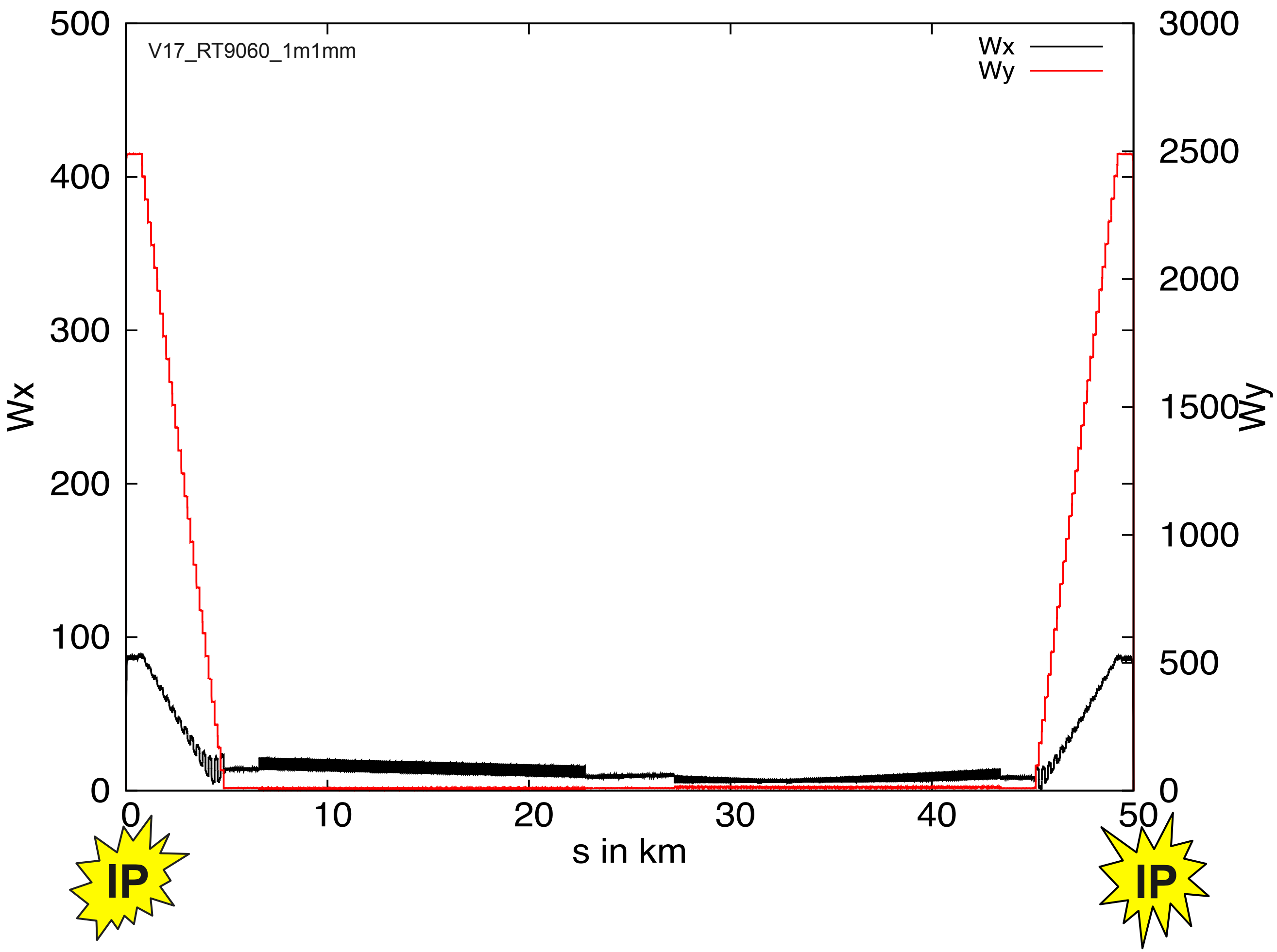
$\mu_x = 90° = \pi/2$

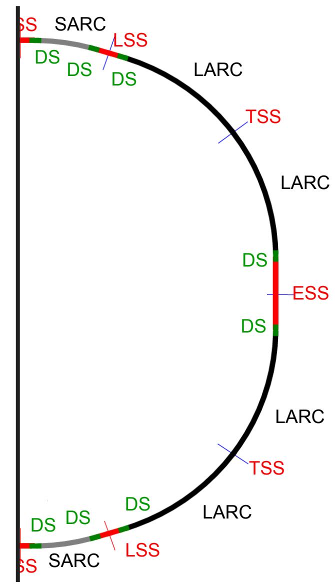
$\mu_y = 60° = \pi/3$

$\mu_x = 180° = \pi$ (→ -I transformation)

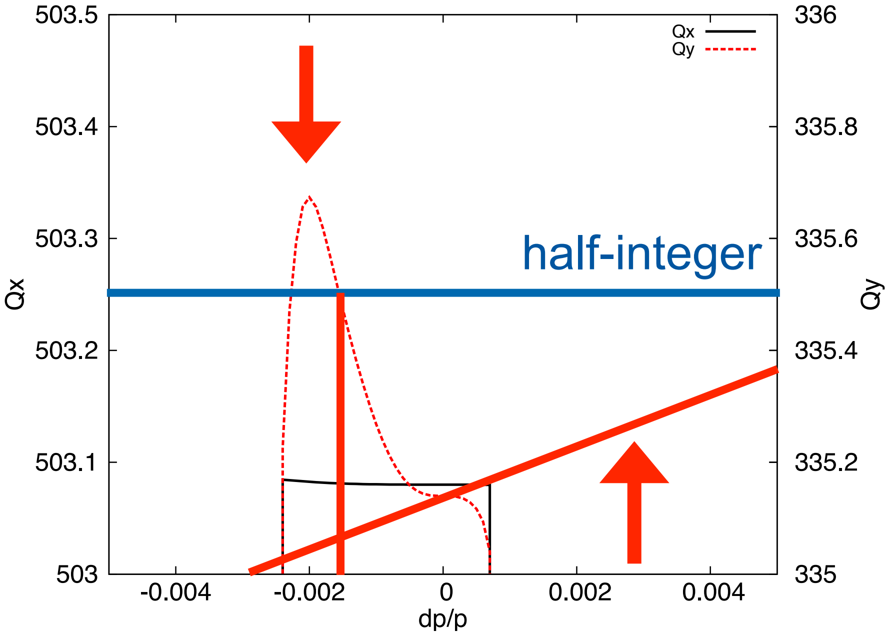
Even number of sextupoles per family!

W functions in the half-ring



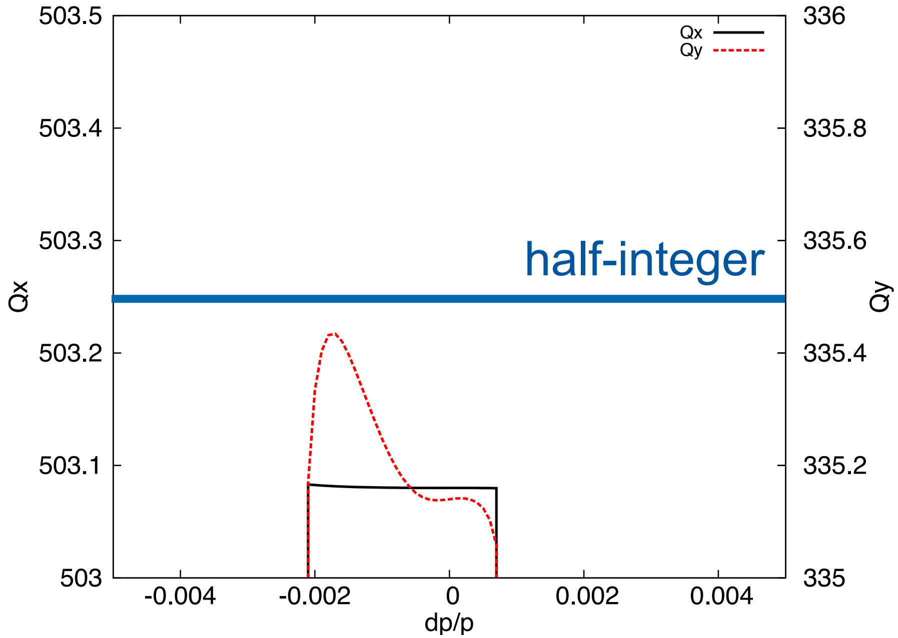


Optimising the momentum acceptance



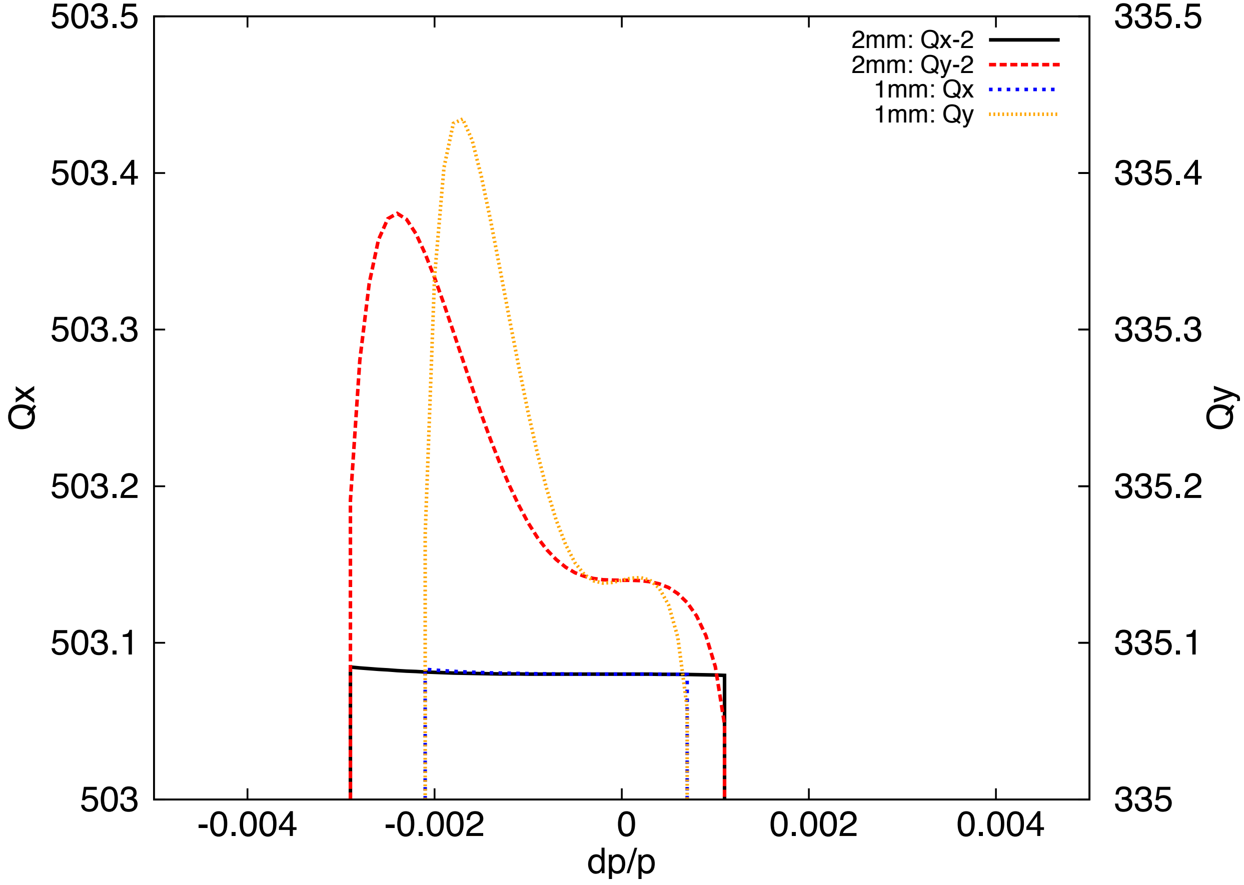
add linear chromaticity

$Q'_y = 0$ **[-0.15%, 0.07%]**



[-0.21%, 0.07%] $Q'_y = 15$

Mom. acceptance for different β*



β^*_y = 1 mm:

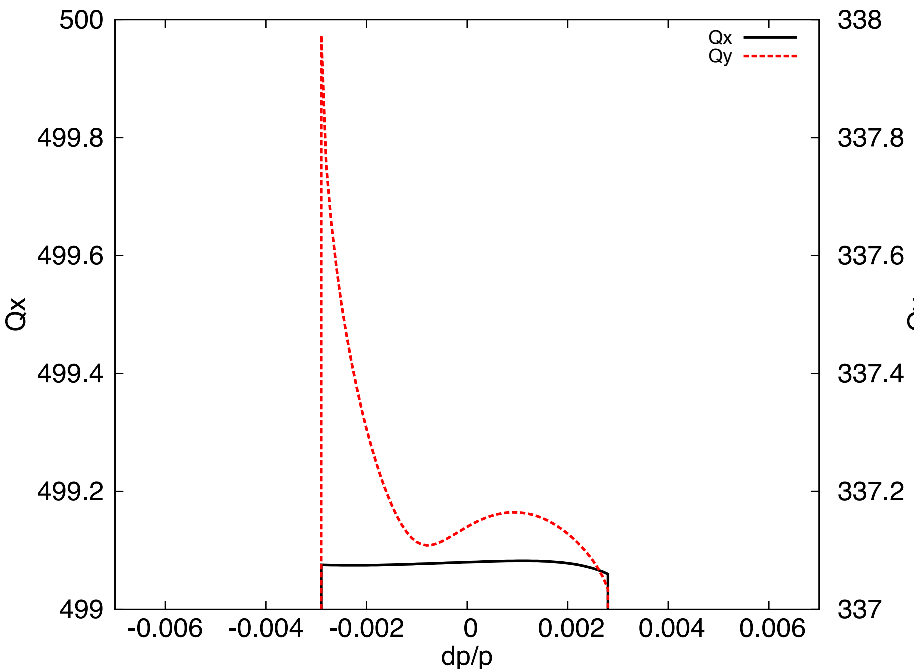
[-0.21%, 0.07%]

β^*_y = 2 mm:

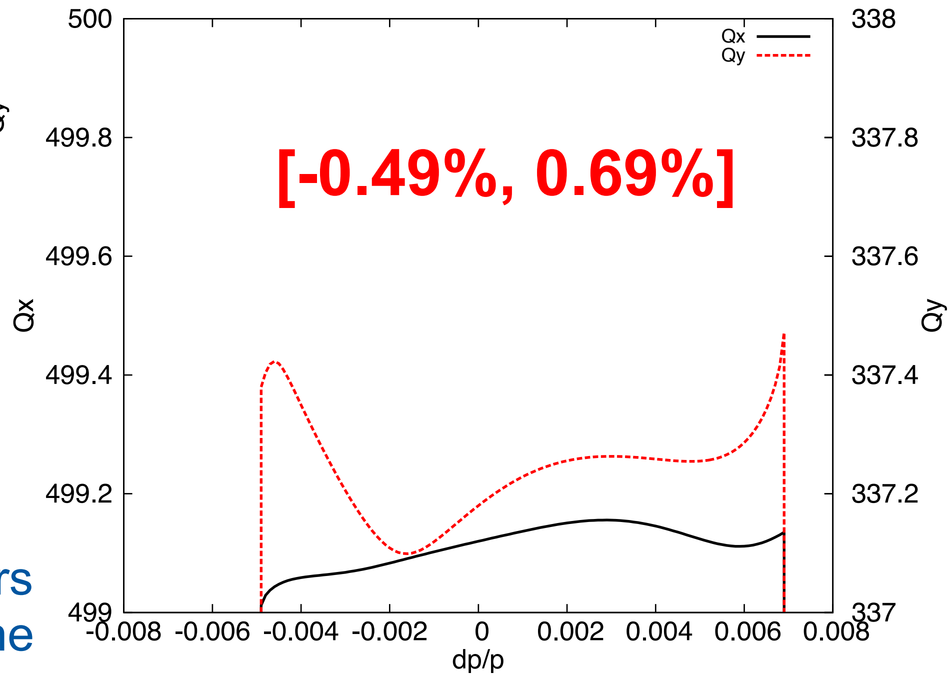
[-0.29%, 0.11%]

Different sextupole scheme

Vary individual sextupole pairs to flatten Q(Δp/p)



6 sextupole families per arc per plane



6 sextupole families + 12 free sextupole pairs per arc per plane

Summary

Lattice design for a future e+/e- collider

Linear lattice design

→ Horizontal emittance tuning

Non-linear dynamics

→ Higher order chromaticity correction

→ Momentum acceptance optimisation

Thank you for your attention!