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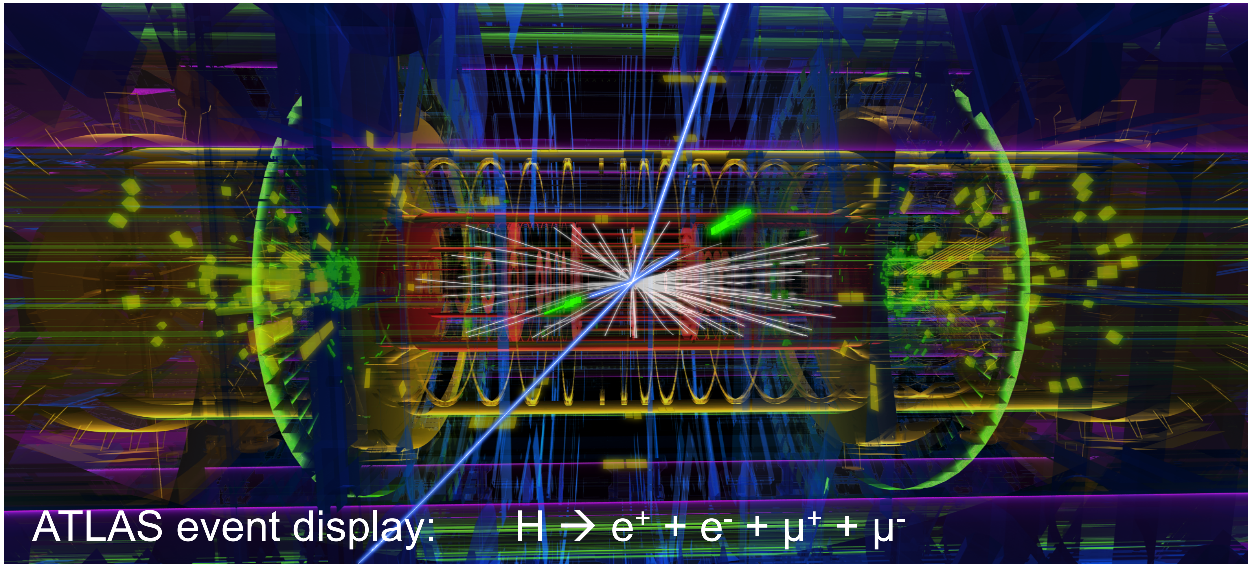
Karlsruhe Institute of Technology

FCC-ee: Lattice optimization and emittance tuning

Bastian Haerer (CERN, Geneva; KIT, Karlsruhe) for the FCC-ee lattice design team

Physics goals of FCC-ee



Main physics programs / energies (+ scan around 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.

All energies quoted refer to BEAM energies

Challenges: the parameter list

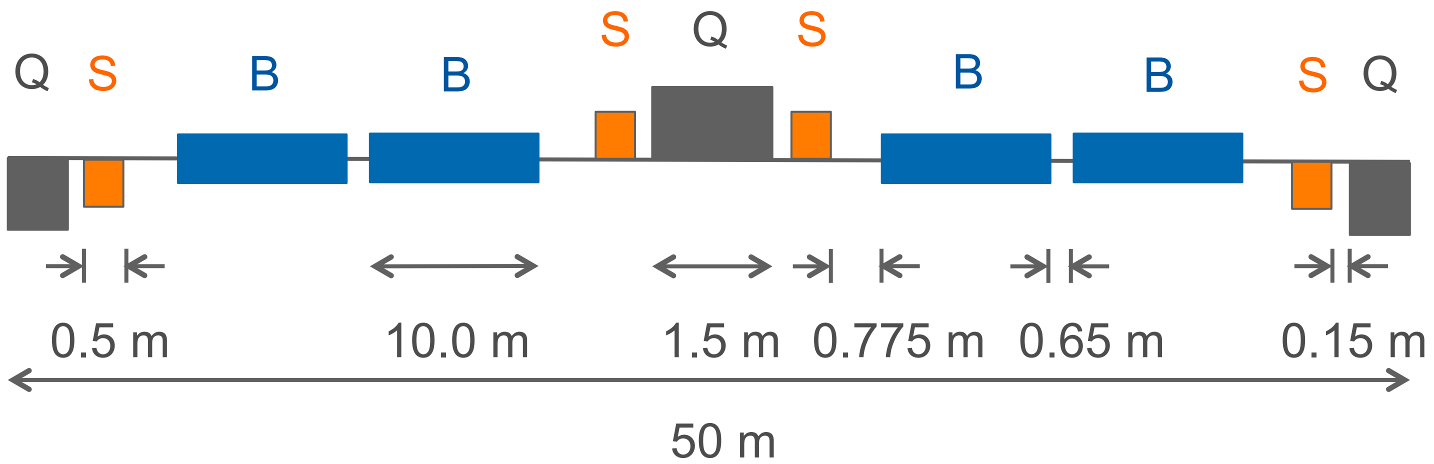
	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
Beam current [mA]	1450	152	30	6.6
Bunches / beam	16700	4490	1330	160
Bunch population [10^{11}]	1.8	0.7	0.46	0.83
Transverse emittance ε				
- **Horizontal [nm]**	29.2	3.3	0.94	2
- **Vertical [nm]**	0.06	0.007	0.0019	0.002
Momentum comp. [10^{-5}]	18	2	0.5	0.5
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 & optimise a lattice for 4 different energies
- 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

175 GeV: Arc FODO cell

Completely symmetric!

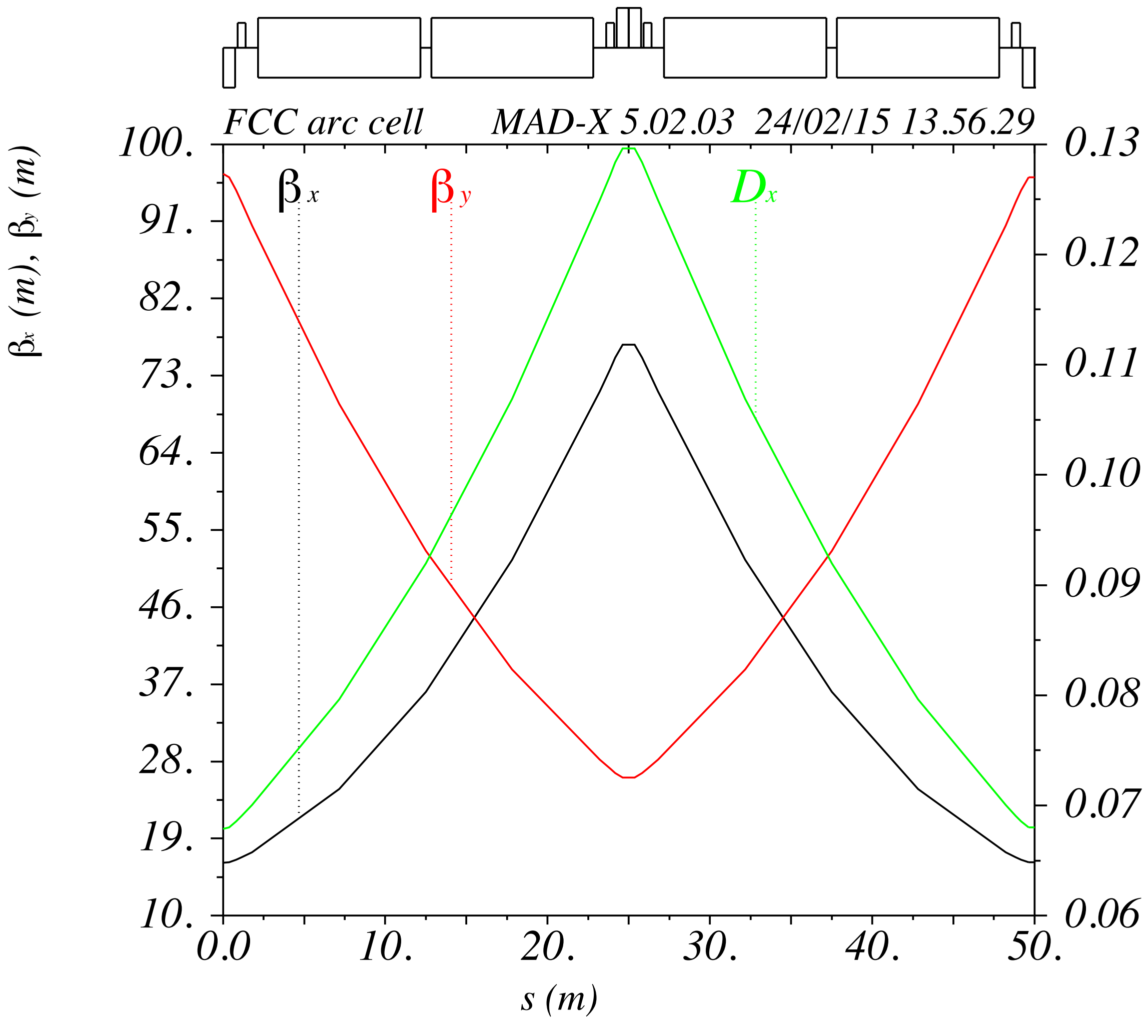
Layout already considers space for absorbers, flanges etc.



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

$N_{dipoles}$ = 6152 (192 half bend)
($\rho \approx$ 9.79 km, θ = 1.02 mrad, B = 60 mT)

Arc FODO cell: Optics

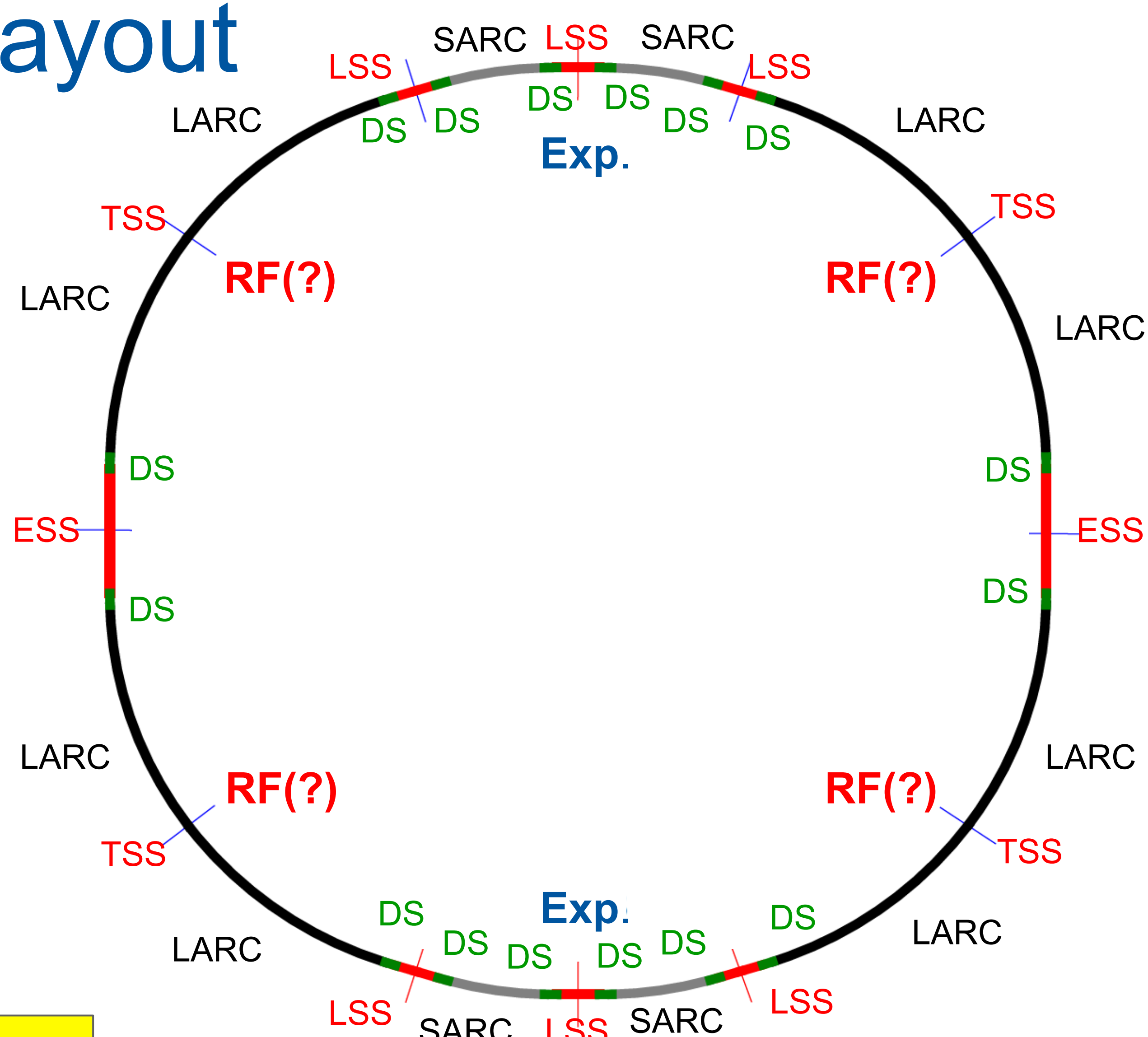


- $L = 50$ m
- $\Psi = 90°/60°$
- $\beta_{x,max} = 77.0$ m
- $\beta_{y,max} = 96.5$ m
- $D_{x,max} = 13.0$ cm

LEP: $D_{x,max} = 2.2$ m*

* LEP Design Report Vol. II

FCC Layout



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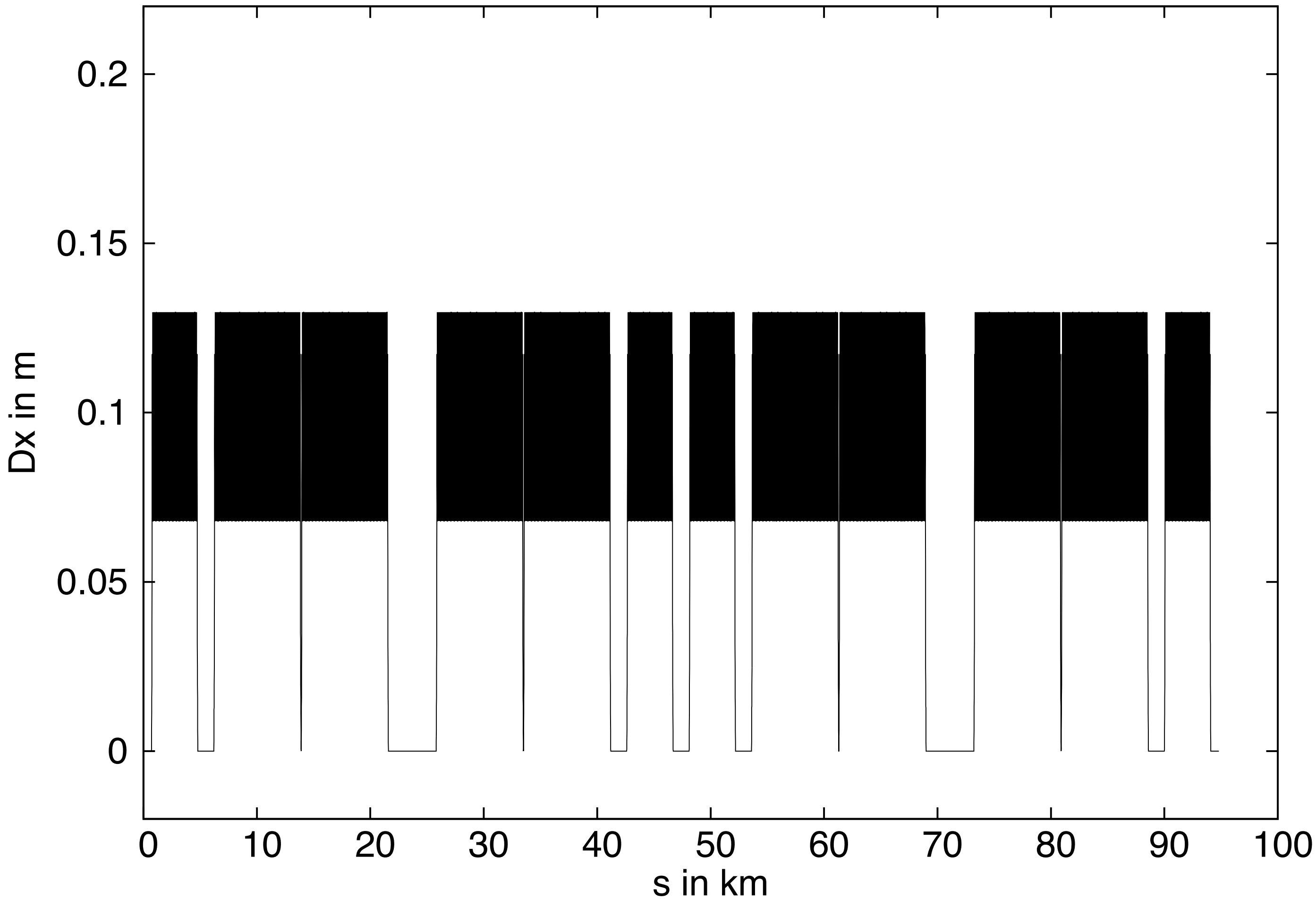
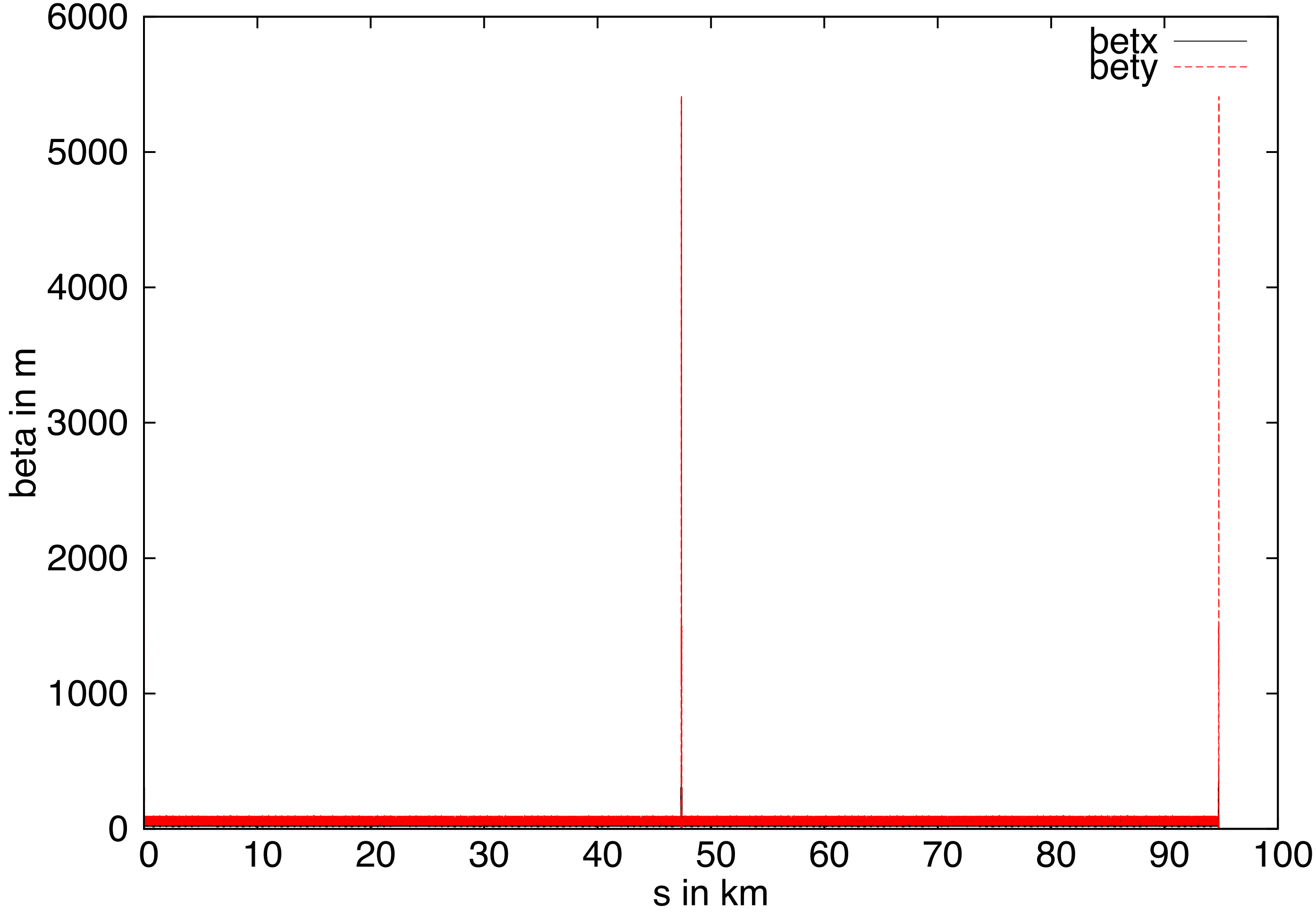
Horizontal Dispersion

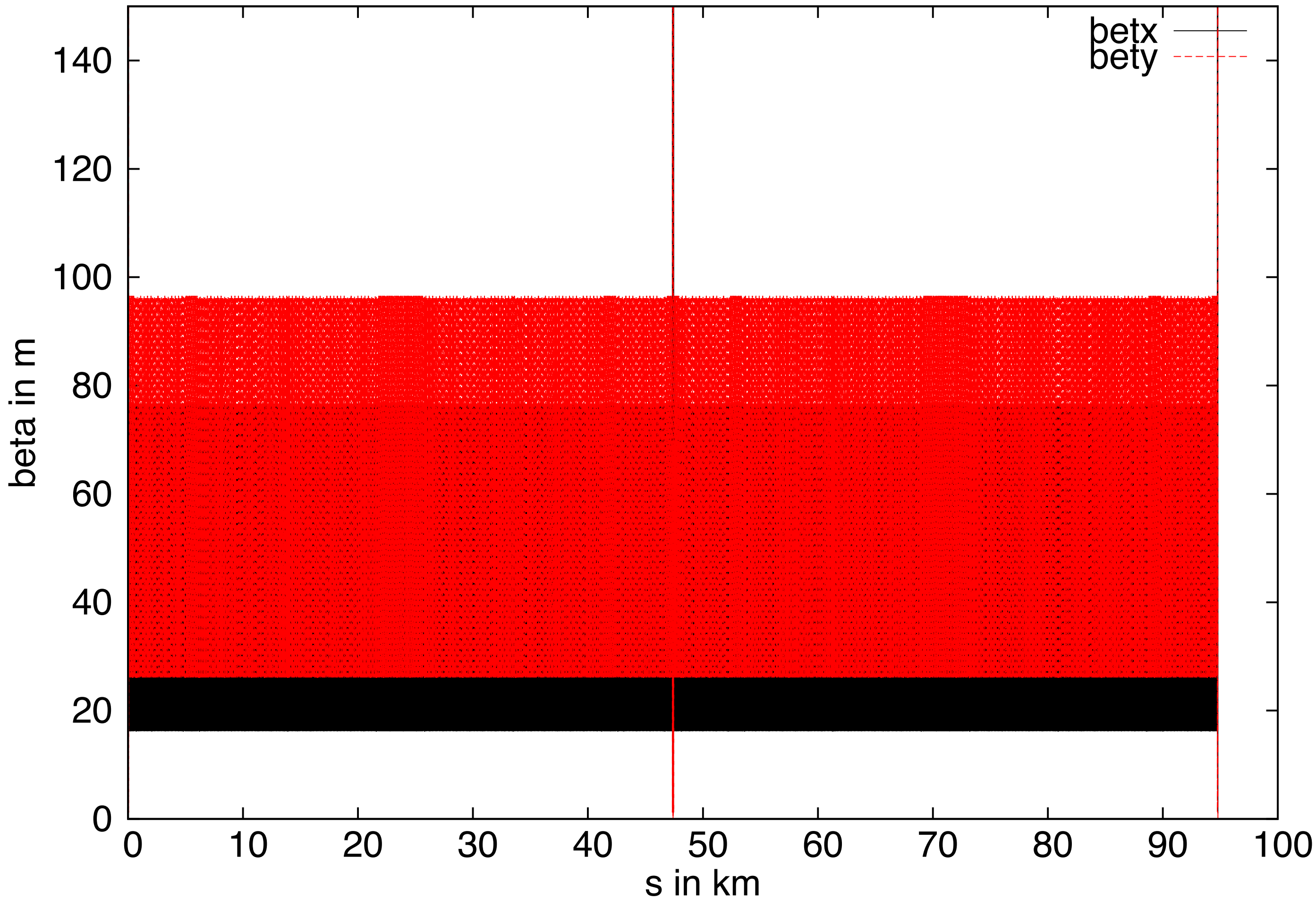


β functions



betx
bety
6000
5000
4000
3000
2000
1000
0
beta in m
0
10
20
30
40
50
60
70
80
90
100
s in km

β functions II



Emittance tuning for lower beam energies

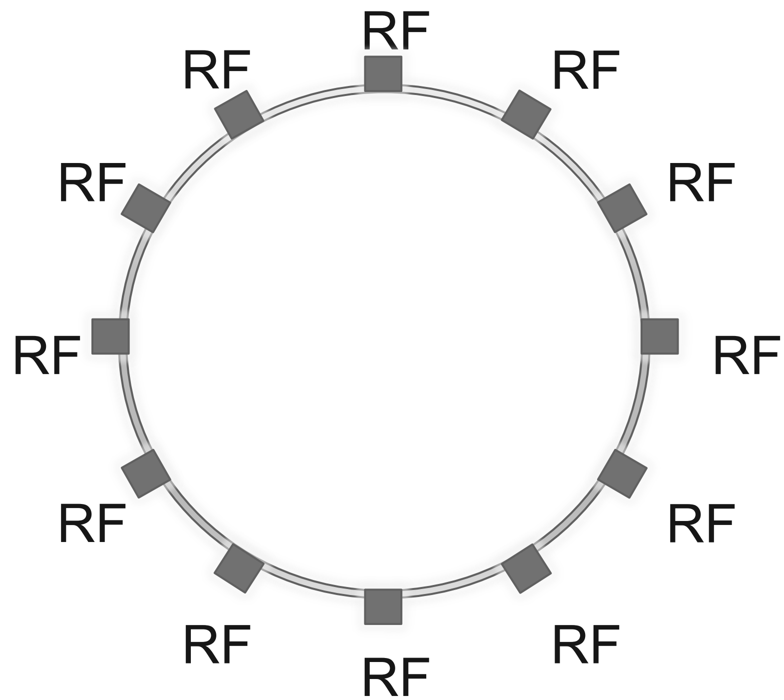
Motivation

Beam energy (in GeV)	Horizontal emittance (50 m cell lattice) (in nm rad)	Horizontal emittance (baseline) (in nm rad)
175.0	1.00	2.00
120.0	0.49	0.94
80.0	0.22	3.30
45.5	0.07	29.20

$$\varepsilon_x \propto \gamma^2$$

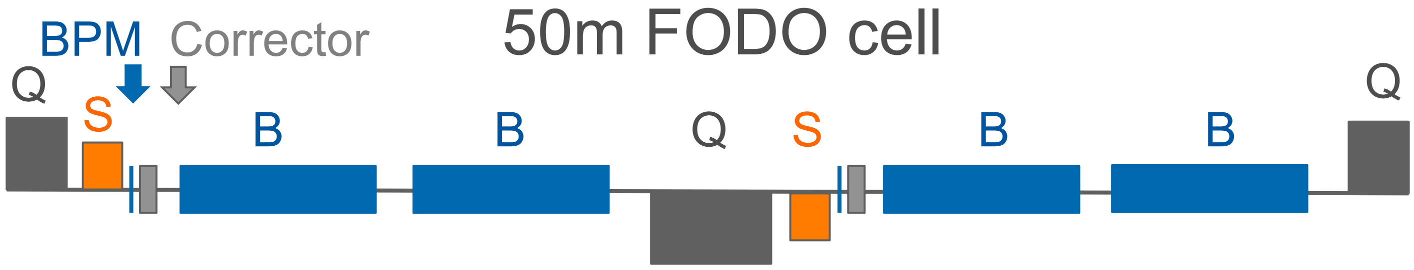
(γ = Lorentz factor)

Idealized Lattice



Symmetric layout:

Circumference:	100 km
Arc length:	2 x 3.4 km
Straight section length:	1.5 km

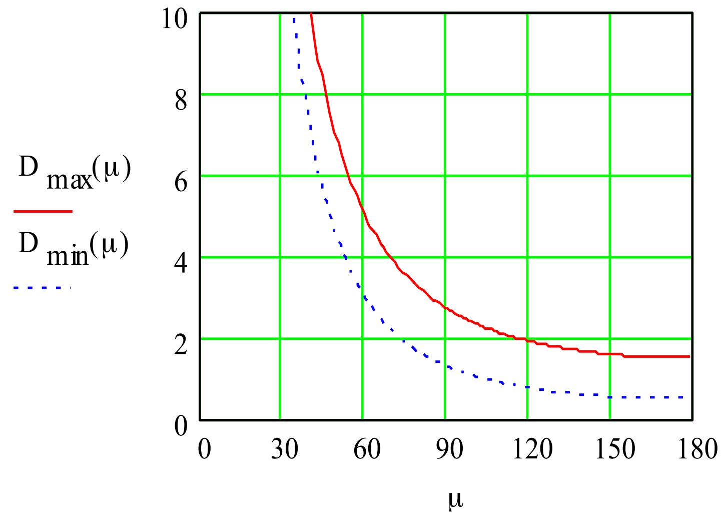


B = bending magnet, Q = quadrupole, S = sextupole

Changing the horizontal emittance for lower energies

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

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

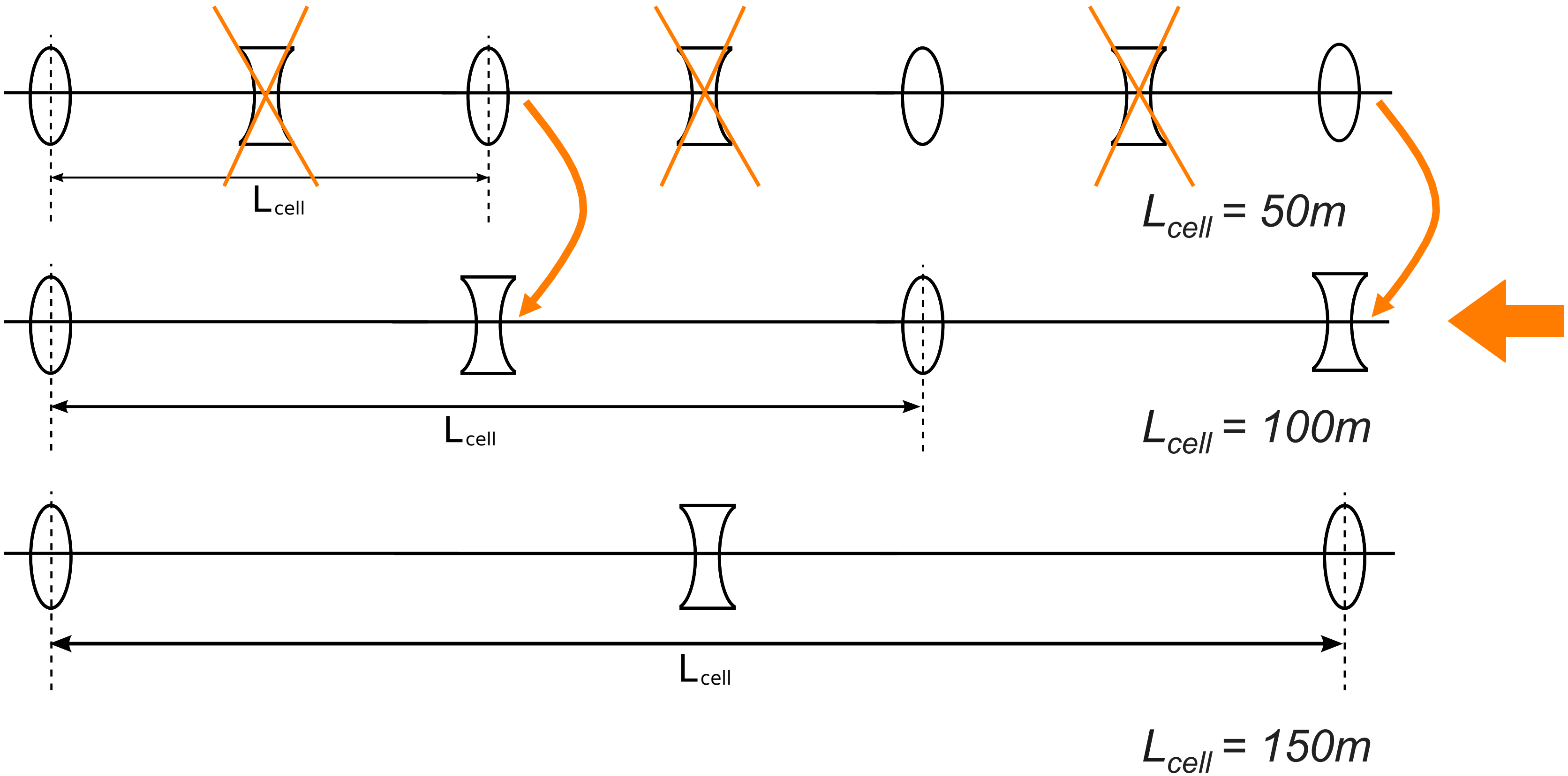


Court. B. Holzer

There are two different possibilities:

1) Change the phase advance Ψ of the FODO cell
   → Larger emittance: smaller phase advance
2) Change the cell length
   → Larger emittance: increase cell length

Changing the cell length



Feasible Lattice Changes

80 GeV beam energy:

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

45.5 GeV beam energy:

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

Examples: Different cell lengths

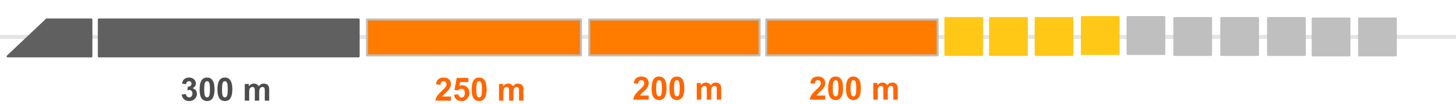
175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

Half-bend dispersion suppressor

80 GeV: L_{cell} = 100 m, Ψ = 90°/60°

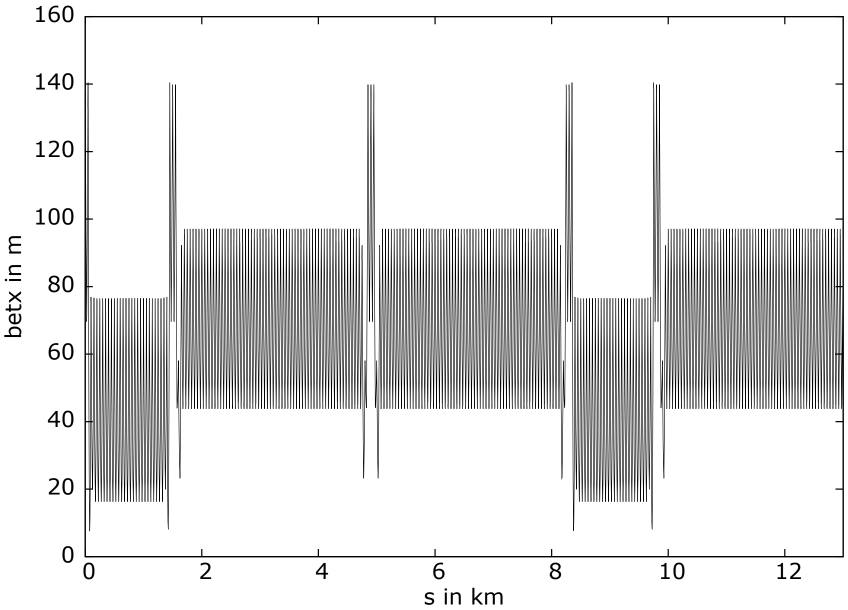
Dispersion suppressor based on quadrupoles

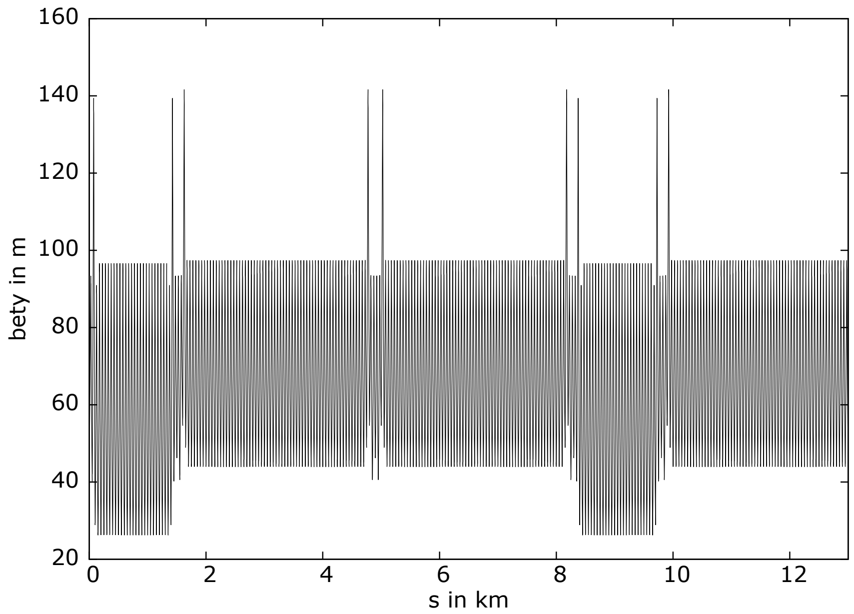
45.5 GeV: L_{cell} = 300 m, Ψ = 90°/60°



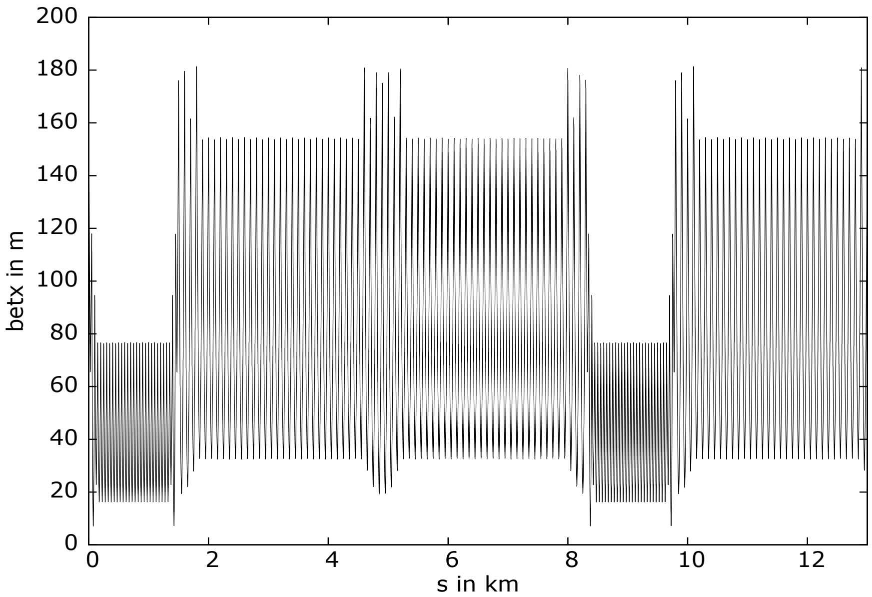
- **Arc cells**
- **Dispersion Suppressor**
- **Straight matching section (with RF)**
- **Straight cells (with RF)**

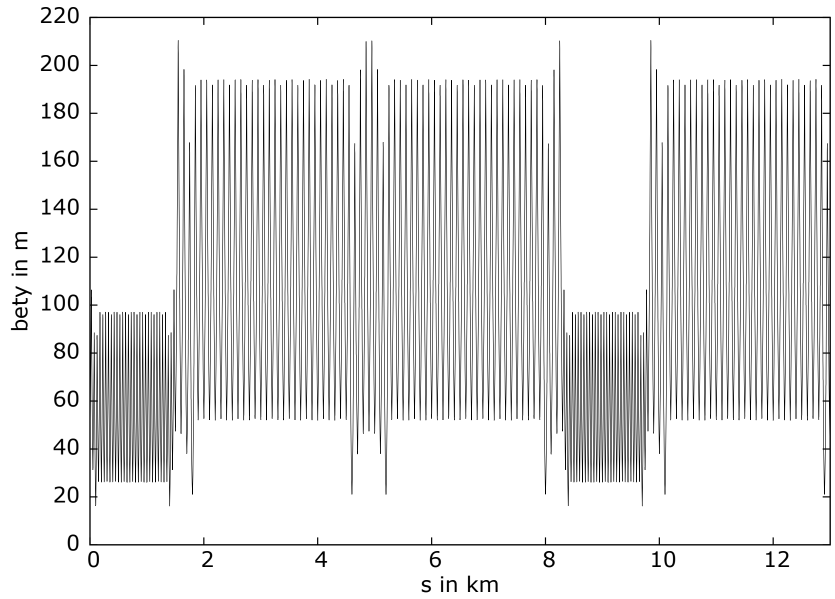
80 GeV: L_{cell}=50 m, $\Psi_{x,y}$=45°



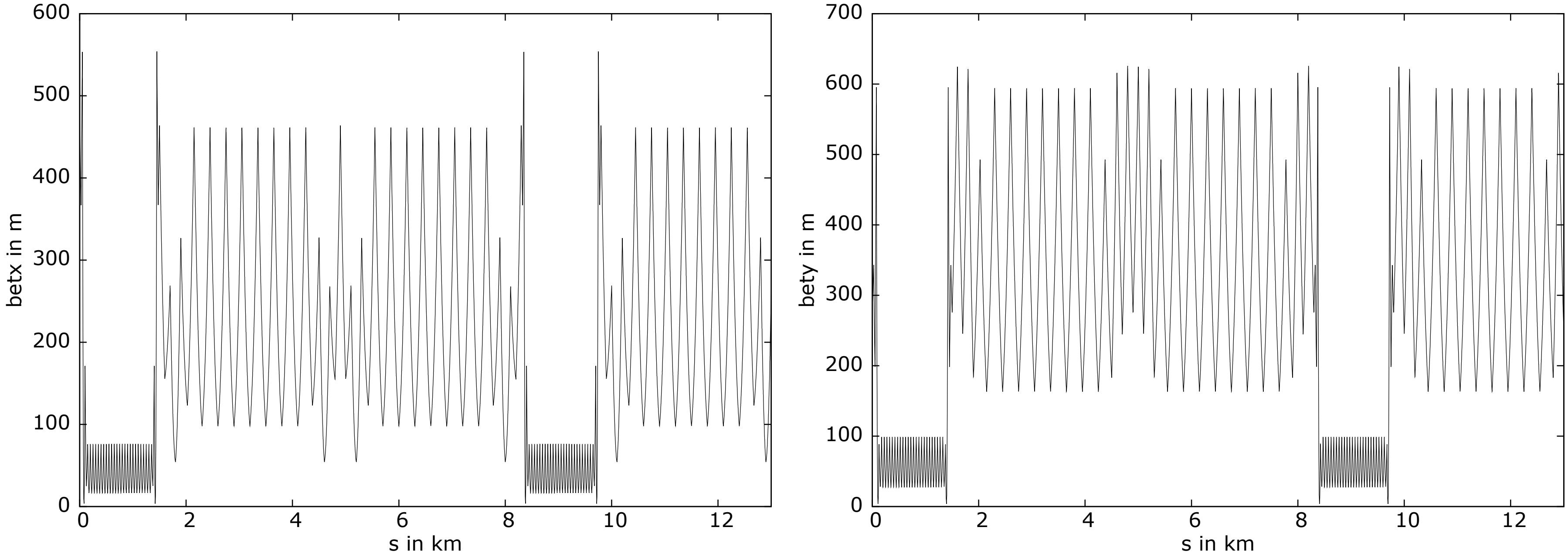


80 GeV: L_{cell}=100 m, Ψ_x=90°





45.5 GeV: L_{cell}=300 m, Ψ_x=90°



Emittance tuning: Results

80 GeV beam energy

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

45.5 GeV beam energy

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

Status

- Several lattices with different cell length and phase advance were proposed

- Final choice requires further investigation

  → Misalignment studies, coupling

  → How much does horizontal emittance increase?

  → Calculation of the distorted orbit and vertical emittance

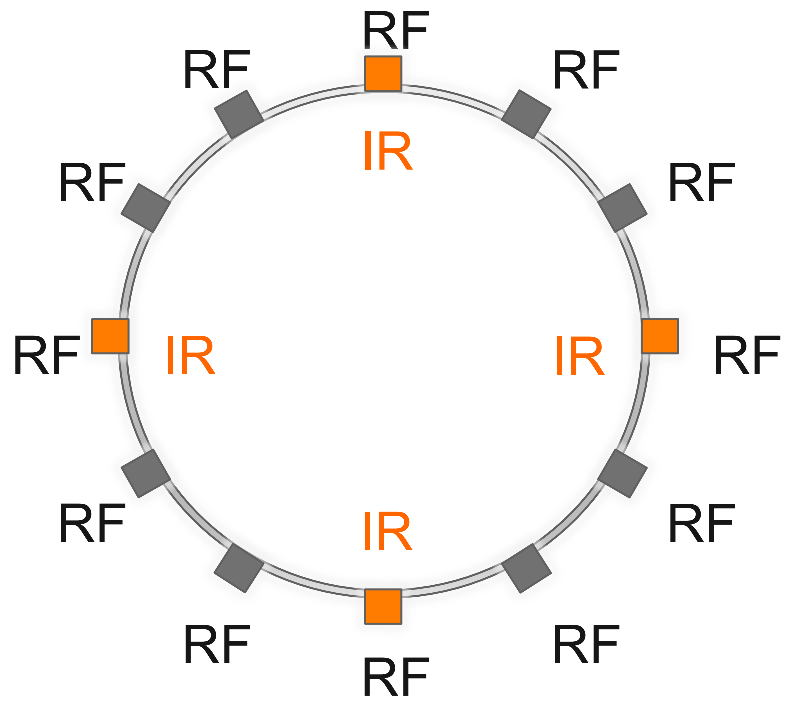
  Work in progress!

- Fine tuning wigglers required:

  → Damping, excitation, Robinson?

Chromaticity correction in the arcs – first approach

Idealized Lattice

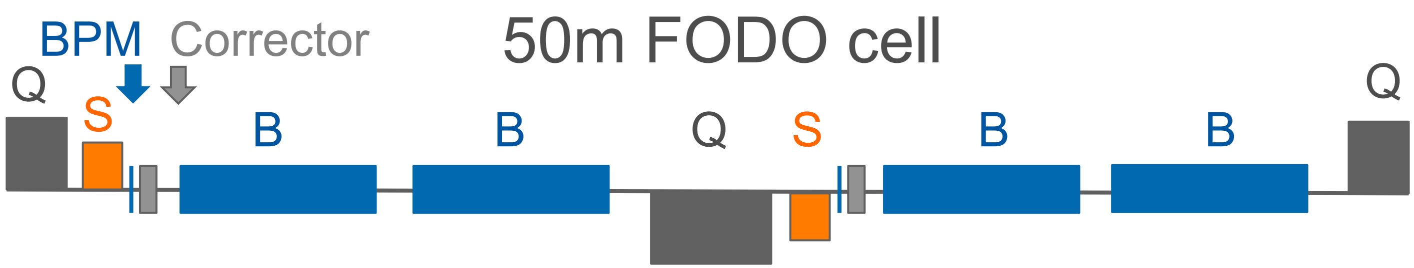


Circumference: 100 km

Arc length: 2 x 3.4 km

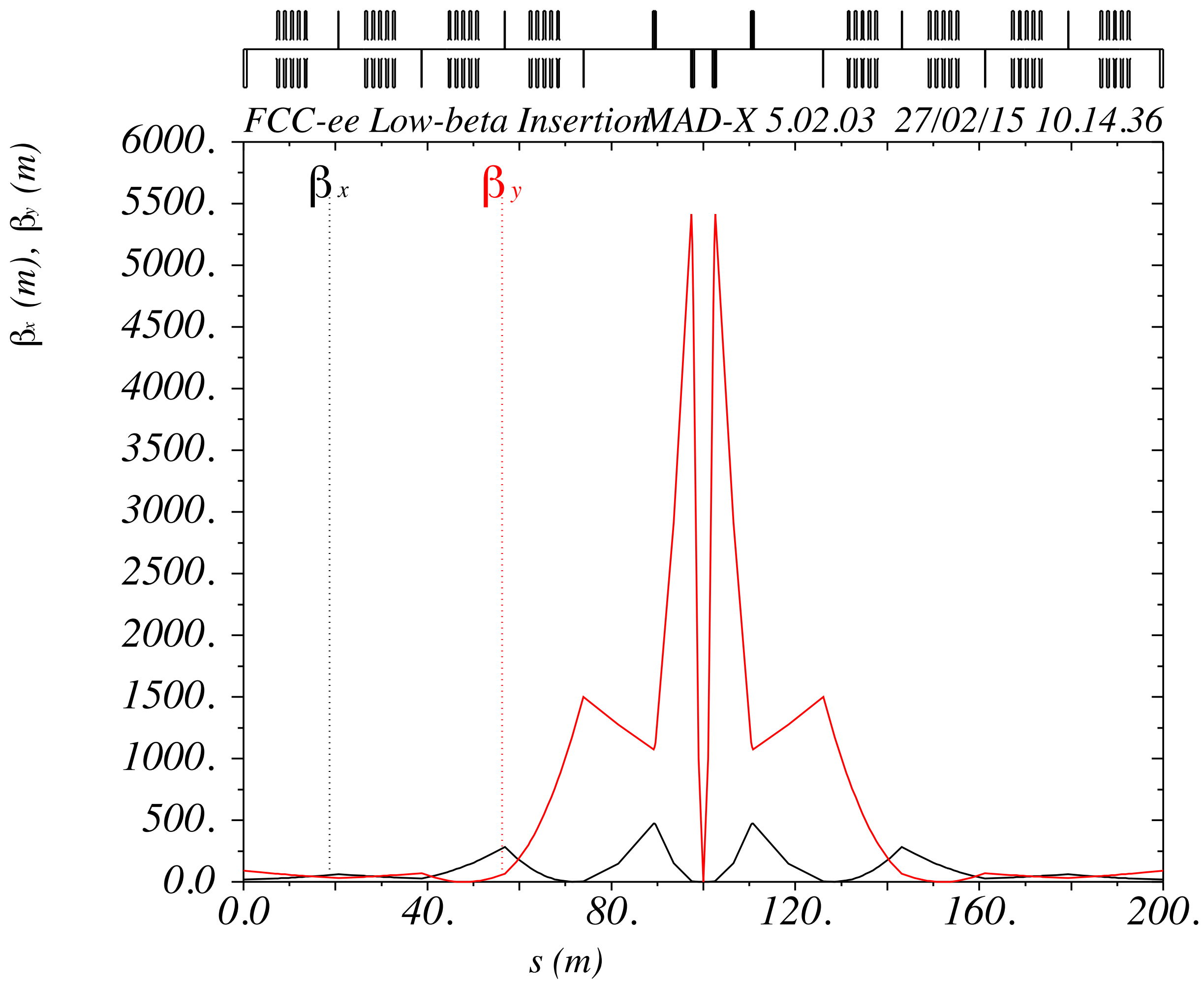
Straight section length: 1.5 km

4 mini-beta insertions (IR)!



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

Mini-beta insertions



$L^* = 2$ m
$\beta^*_x = 1$ m
$\beta^*_y = 0.001$ m

Chromaticity

- Change of the tune with energy deviation
- Textbook: $\Delta Q = \xi \cdot \Delta p / p$
- In our case not precise enough: $\left(\delta = \Delta p / p\right)$

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

FCC-ee: Natural Chromaticity

	no IRs	4 IRs	ΔQ (δ=1.5 %)
Q_x	498.85	502.16	
Q_x'	-554.93	-603.80	-9.06
Q_x''	1587.57	-8258.29	-0.93
Q_x'''	-8071.77	-1.4e+08	-79.31
Q_x''''	-3.27e+09	-2.1e+12	-4.43e+03
Q_y	331.24	334.28	
Q_y'	-458.98	-2044.43	-30.67
Q_y''	1086.30	-8.4e+06	-944.12
Q_y'''	-4547.47	-2.0e+11	-1.10e+05
Q_y''''	-3.62e+09	-6.5e+15	-1.37e+07

$Q(\delta) = Q_0 + Q' \delta + Q'' \delta^2/2 + \ldots$

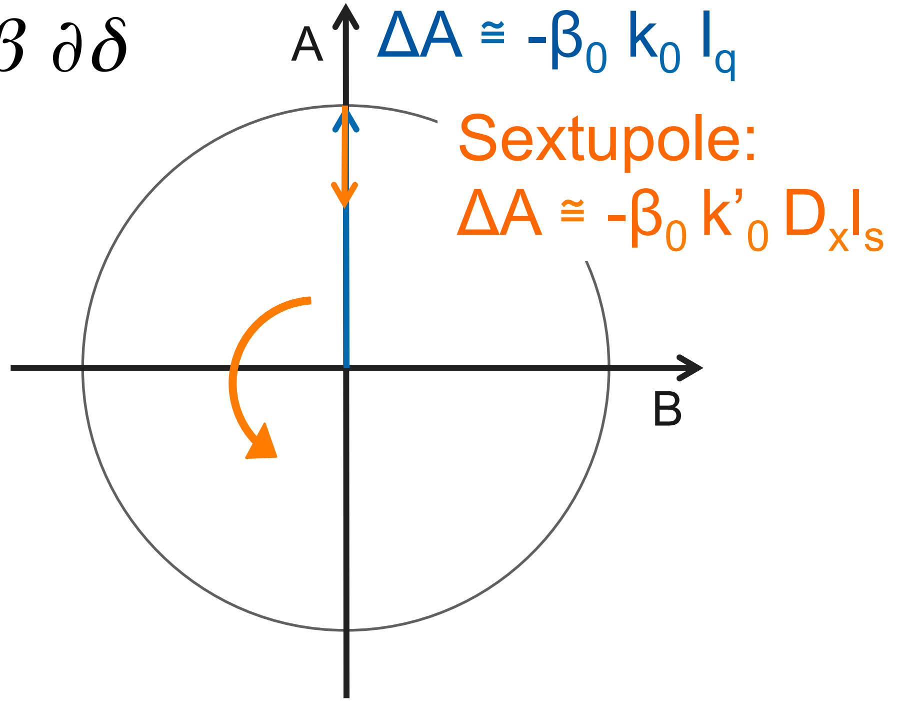
Montague functions

- Chromatic variables

$$B = \frac{1}{\beta}\frac{\partial \beta}{\partial \delta} \qquad A = \frac{\partial \alpha}{\partial \delta} - \frac{\alpha}{\beta}\frac{\partial \beta}{\partial \delta}$$

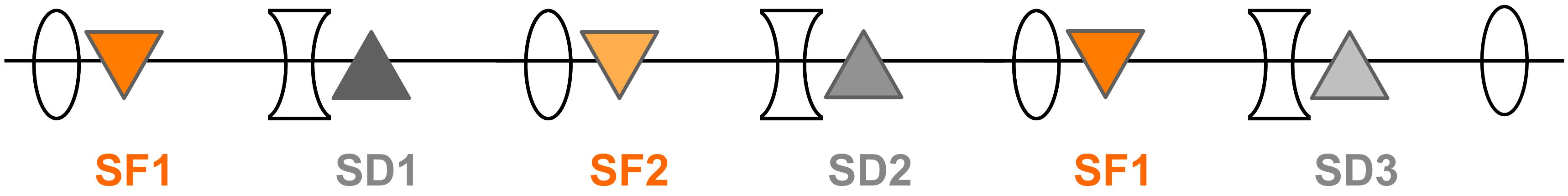
- W-vector

$$\vec{W} = \frac{1}{2}(B + iA)$$
$$= \frac{1}{2}\sqrt{A^2 + B^2}\, e^{i2\psi}$$



Rotates with twice the phase advance!

FCC-ee sextupole scheme



$\mu_x = 90° = \pi/2$ $\mu_y = 60° = \pi/3$

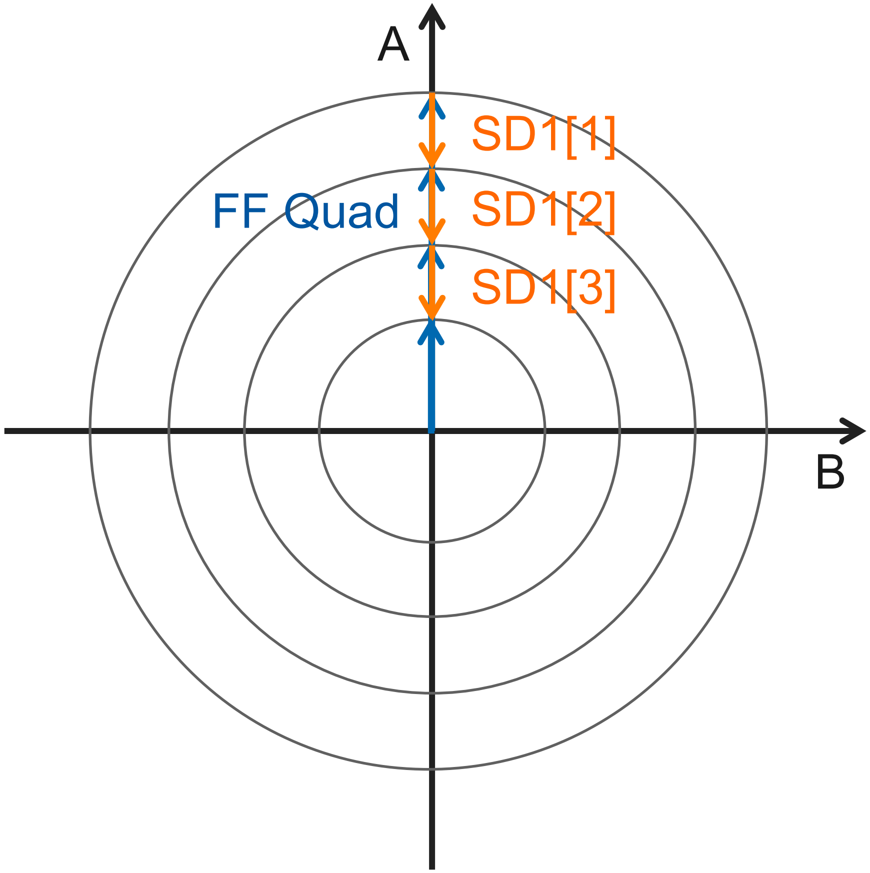
$\mu_x = 180° = \pi$ (→ -I transformation)

Even number of sextupoles per family!

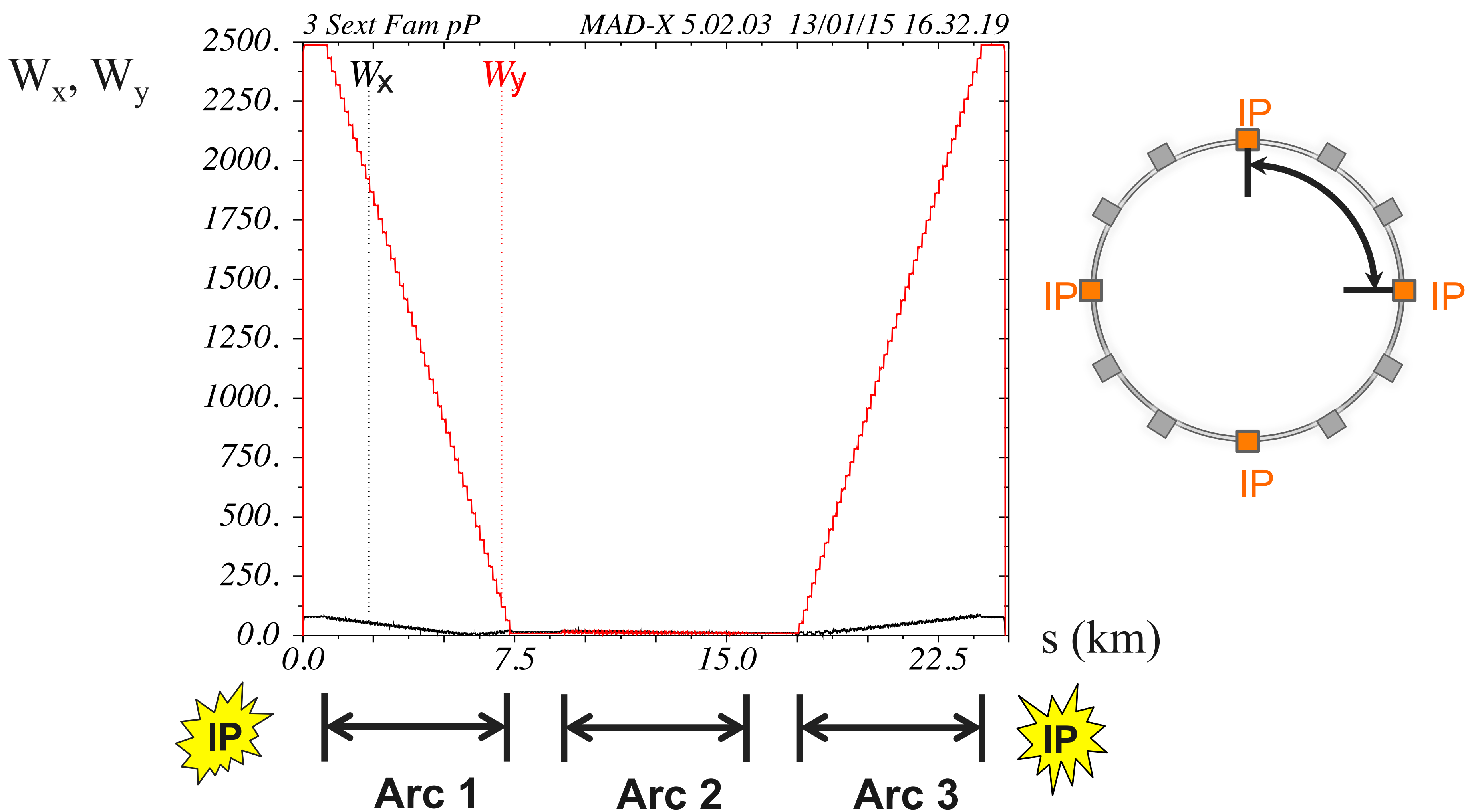
-I transformation

- Sextupoles of each family are in phase

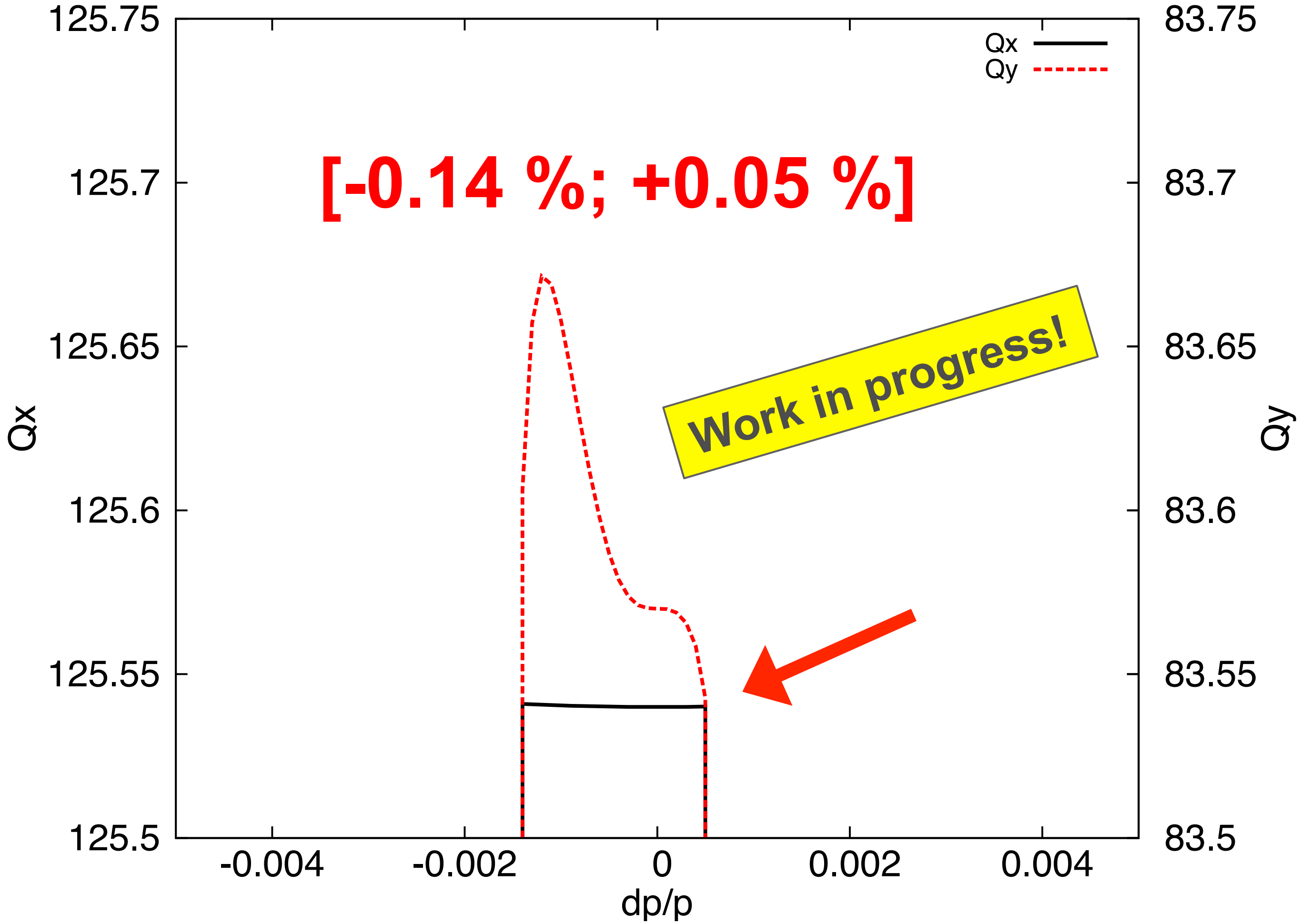
→ W-vector rotates by 2π



W functions for 1 quarter



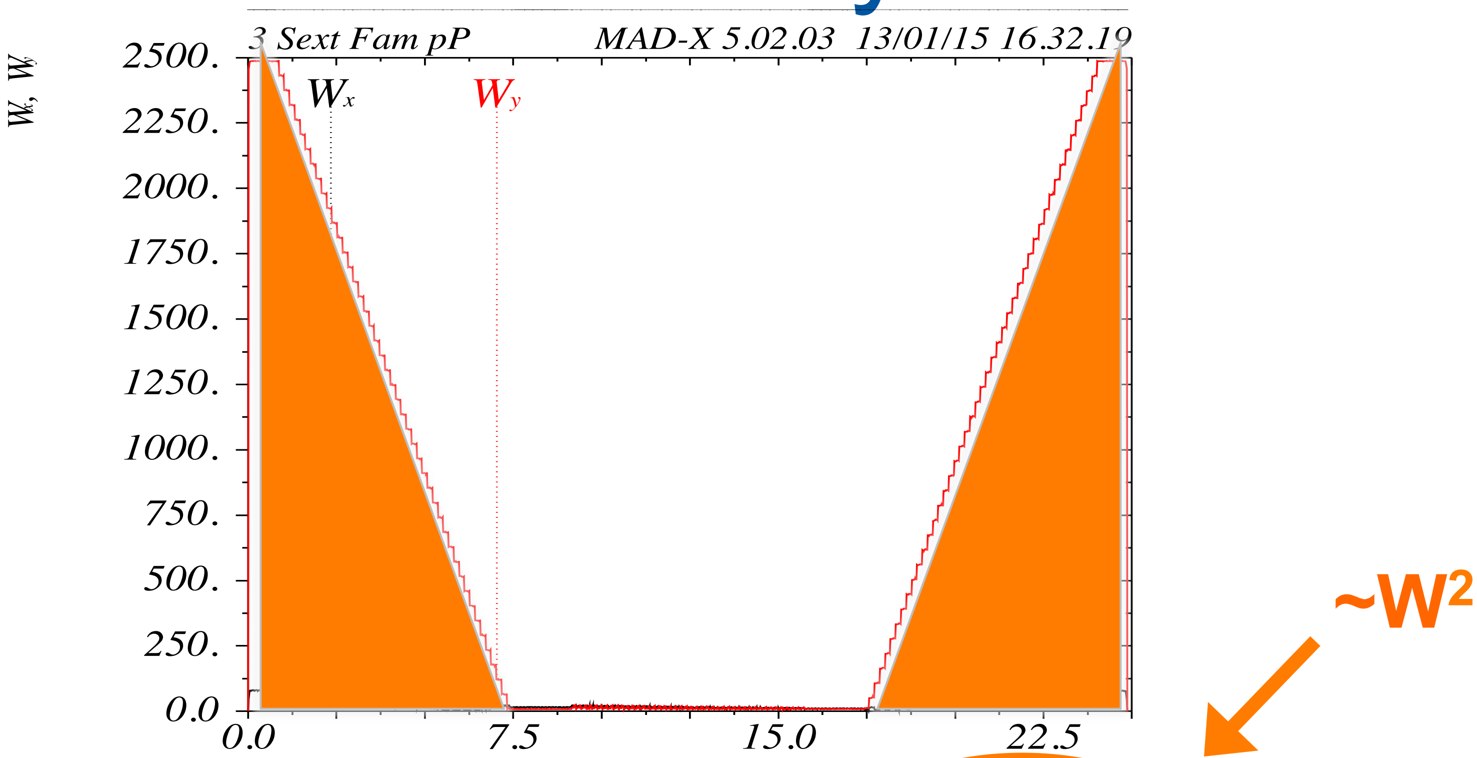
Momentum acceptance



“Corrected” Chromaticity

	Nat. Chrom.	Corr. Chrom.	ΔQ (δ=0.05 %)
Q_x	502.16	502.16	
Q_x'	-603.80	5.7e-05	2.83e-08
Q_x''	-8.3e+03	3.5e+03	4.41e-04
Q_x'''	-1.4e+08	-5.5e+05	-1.14e-05
Q_x''''	-2.1e+12	-8.5e+09	-2.20e-05
Q_y	334.28	334.28	
Q_y'	-2044.43	2.8e-01	1.39e-04
Q_y''	-8.4e+06	-1.2e+04	-1.53e-03
Q_y'''	-2.0e+11	-3.4e+09	-7.00e-02
Q_y''''	-6.5e+15	3.6e+10	9.25e-05

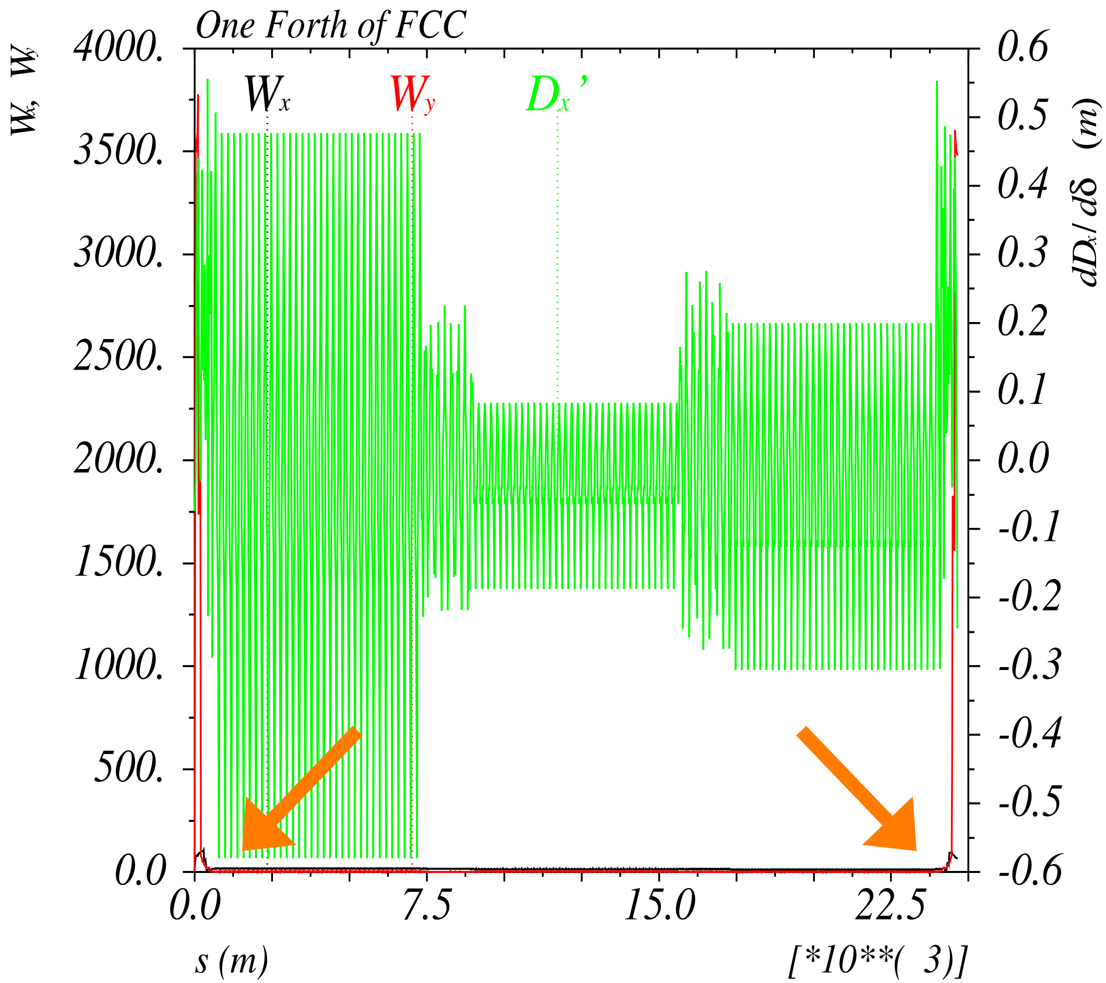
3rd order chromaticity



$$\frac{\partial^3 \varphi_y}{\partial \delta^3} = 6\frac{\partial \varphi_y}{\partial \delta} - \int_0^{\Pi} \beta_y (K_1 - K_2\eta_0)(a_{y,1}^2 + b_{y,1}^2) ds + + 3\int_0^{\Pi} \beta_y (K_2\eta_1 - K_2\eta_2) ds + \frac{3}{2}\int_0^{\Pi} \beta_y b_{y,2}(K_1 - K_2\eta_0) ds$$

Anton Bogomyagkov

Advantage of local CCS



	Value*	$\Delta Q(2\%)$
Q_x	124.54	
Q'_x	0	0
Q''_x	170	0.034
Q'''_x	$-4.5 \cdot 10^4$	-0.059
Q''''_x	$-5.3 \cdot 10^6$	-0.035
Q_y	84.57	
Q'_y	0	0
Q''_y	387	0.077
Q'''_y	$-5.3 \cdot 10^5$	-0.7
Q''''_y	$-4.3 \cdot 10^6$	-0.029

3 orders of magn. smaller!!!

Anton Bogomyagkov

* Using one quarter of the ring

Next steps

Optimization of the Chromaticity Correction Scheme

- Improve 3rd order chromaticity correction
- Find best combination of local chromaticity correction and arc sextupoles
- Optimization of the tune, phase advance

Chromaticity Correction Scheme for Low Energy Lattices

- Same chromaticity, less sextupoles in the arc available

Other ongoing studies

- Interaction Region Design
  → Anton Bogomyagkov (BINP),
  Roman Martin, Rogelio Tomas (CERN)

- Alignment tolerances, coupling, vertical emittance calculations
  → Sandra Aumon, Andreas Doblhammer (CERN)

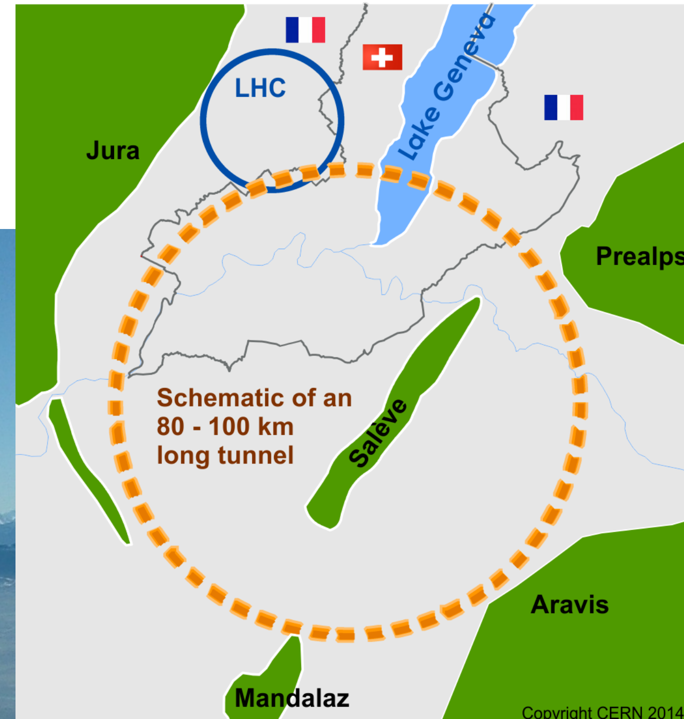
- Dynamic aperture studies
  → Pavel Piminov (BINP), Luis Medina, Rogelio Tomas (CERN)

- Solenoid compensation scheme
  → Sergey Sinyatkin (BINP)

Very much progress in the first year!

Thank you for your attention!

Courtesy to Jörg Wenninger



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Lattice modules

… used for FCC-ee:

Abbreviation	Generic name	Number	Length (km)
LSS	Long straight section	6	1.4
ESS	Extended straight section	2	4.2
TSS	Technical straight section	4	?
SARC	Short arc (incl. DS)	4	4.0
LARC	Long arc (incl. DS)	8	*depends on circumference* (Version 16: 7.7)

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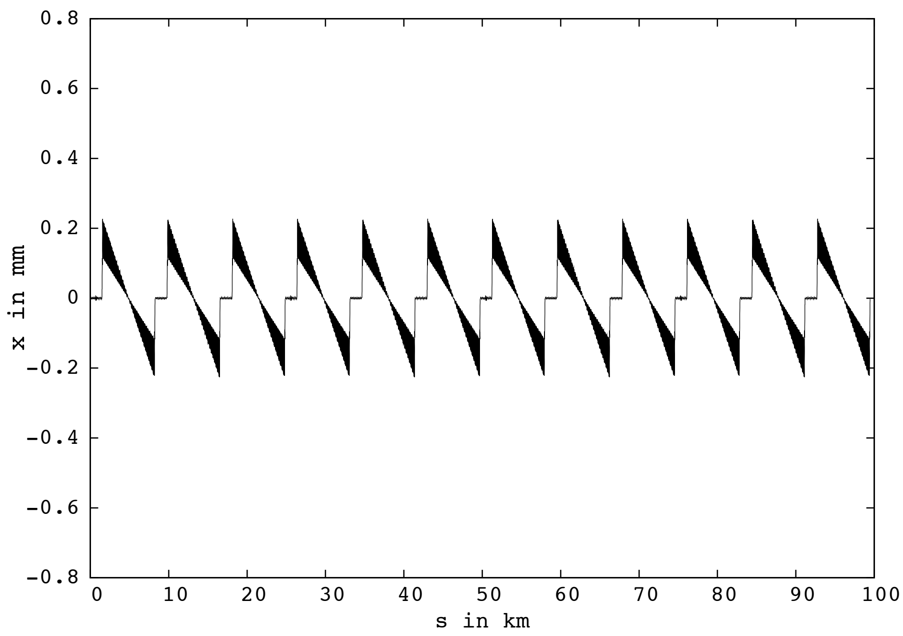
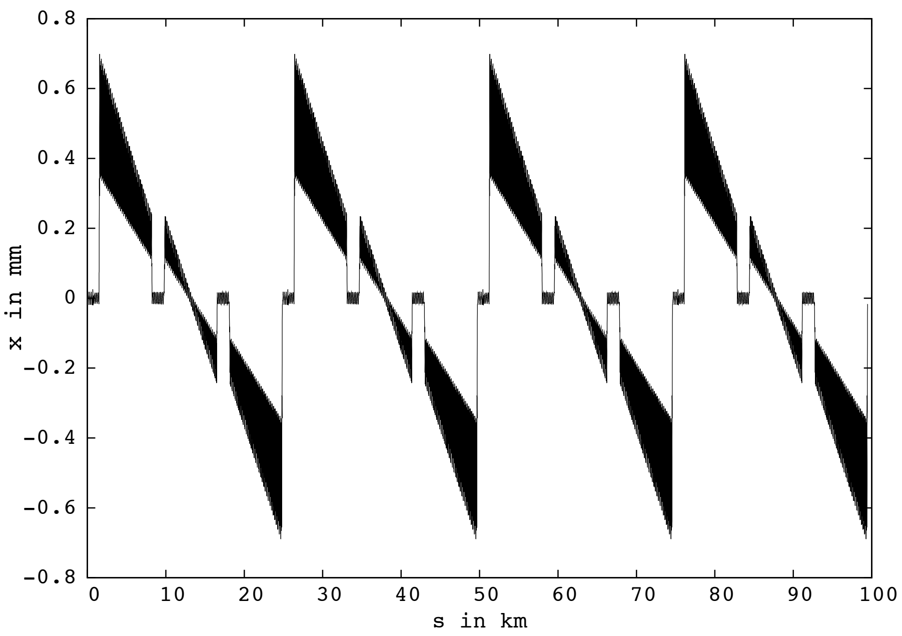
Energy sawtooth (Ideal lattice)



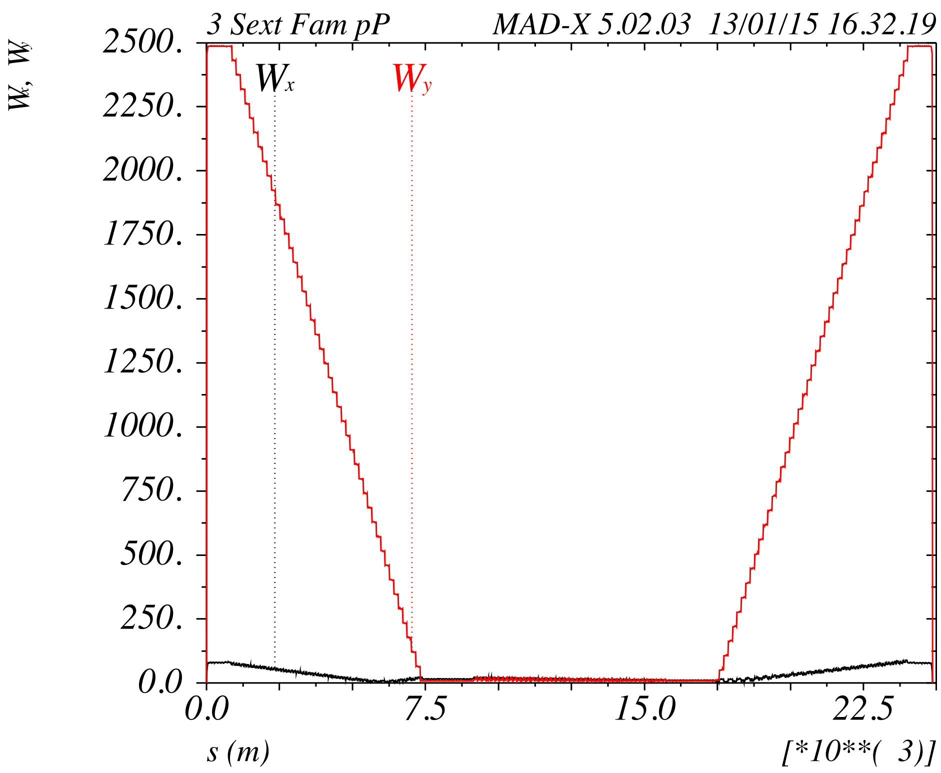
12 RF sections



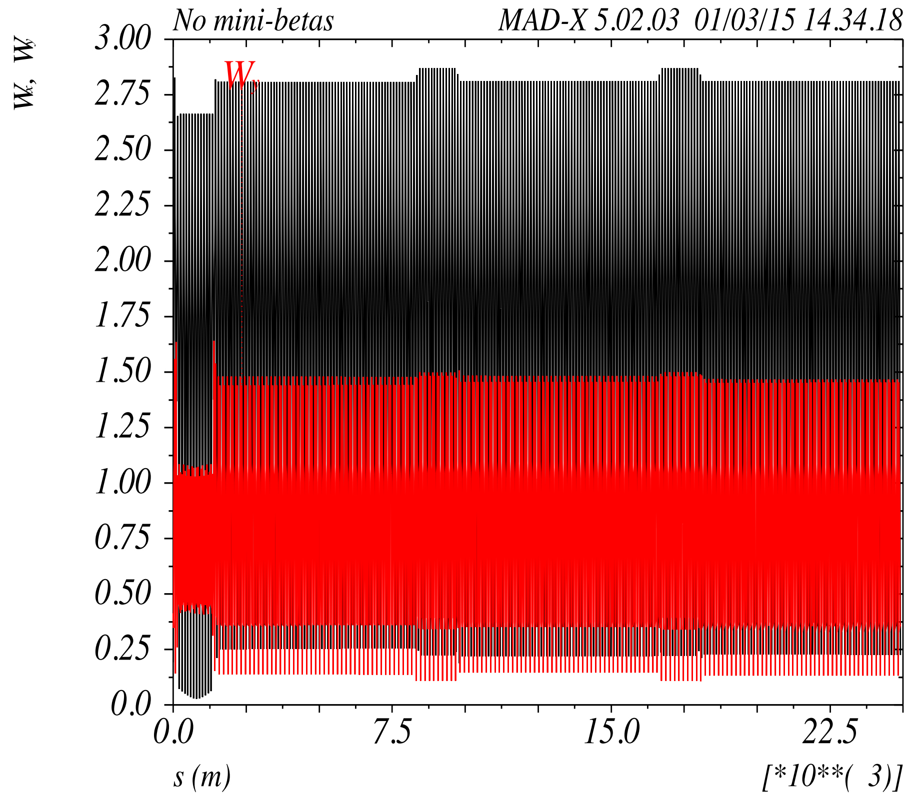
4 RF sections

Energy loss per turn: U_0 = 7.72 GeV

W functions comparison

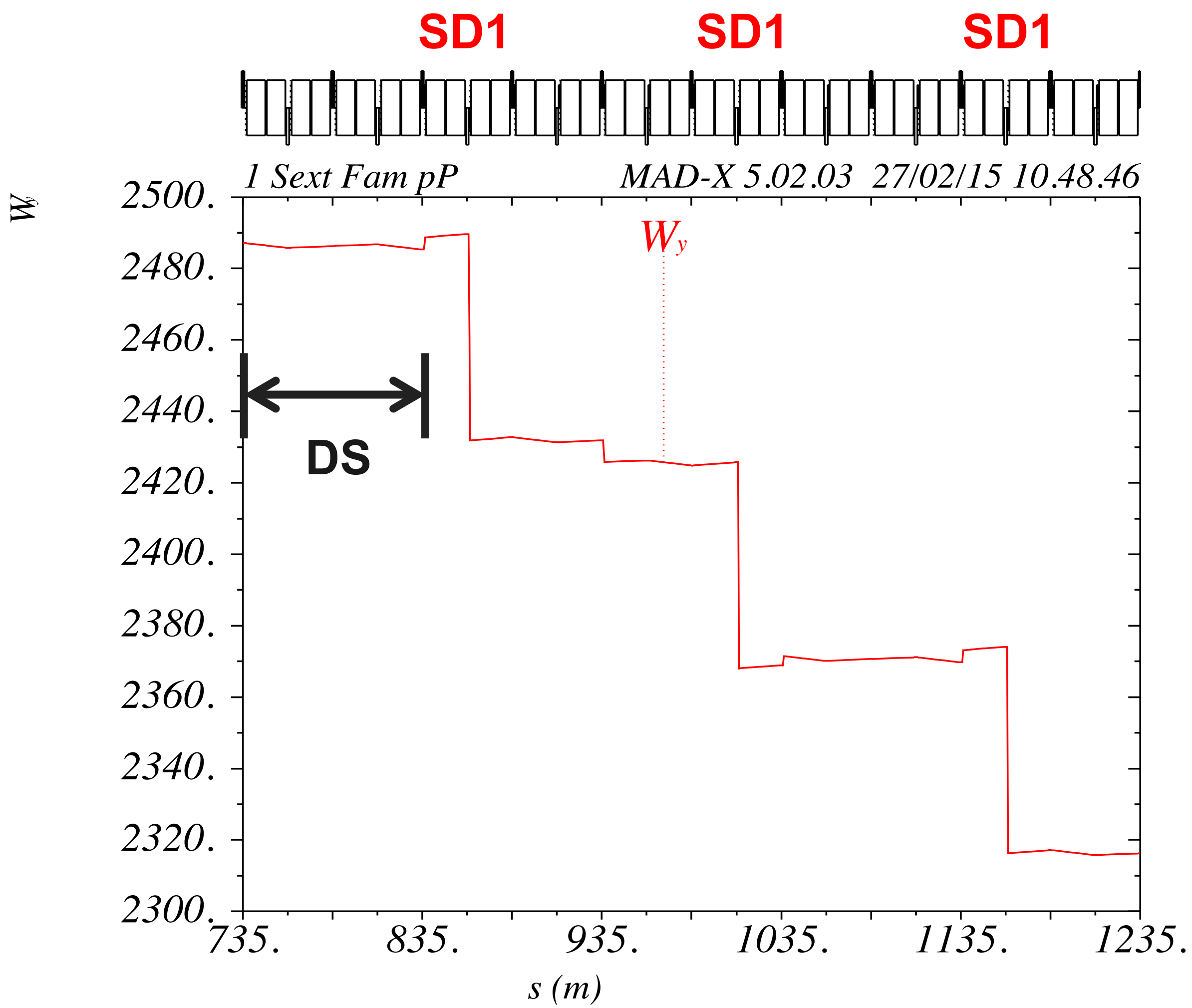


With IRs



Without IRs

Vertical W-function in Arc 1



W-functions in Arc 2