FCCIS – **The Future Circular Collider Innovation Study**. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

FCC HEB lattice options

B. Dalena, A. Chance

Thanks to:

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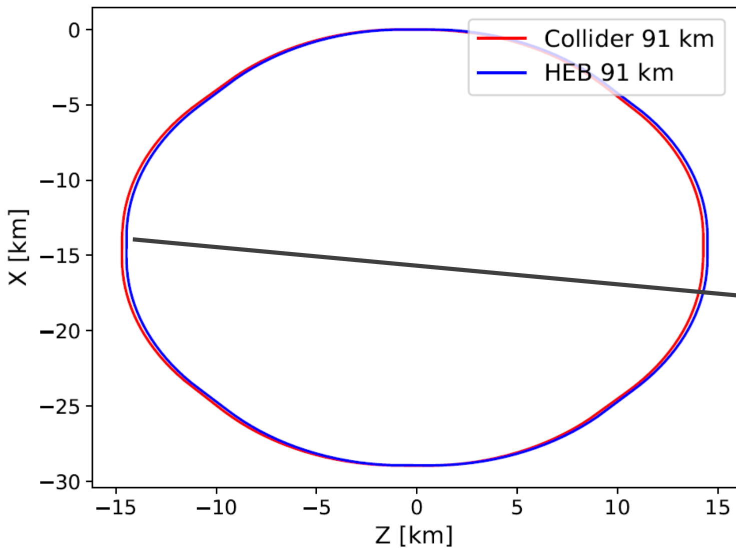
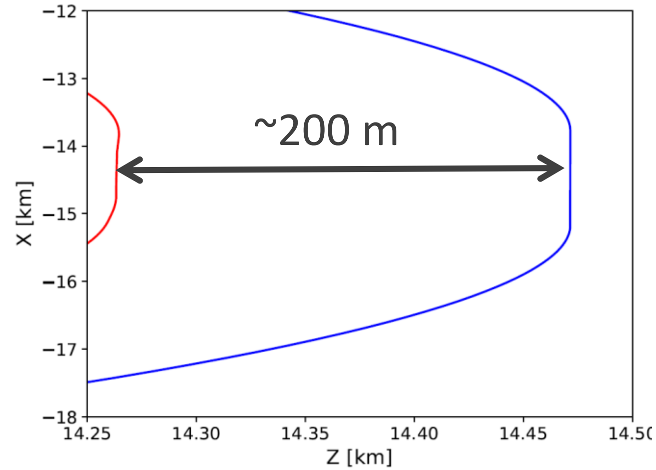
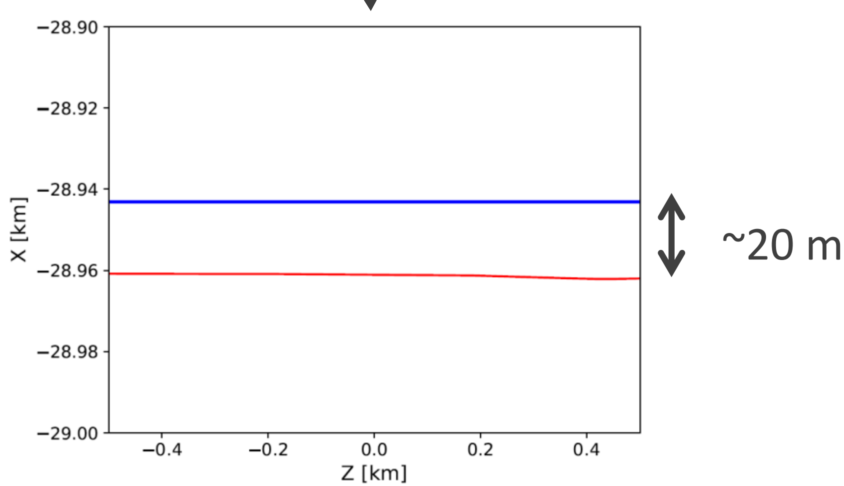
Outline

- Layout of the HEB ring
- 60°/60° and 90°/90° Optics
- DA vs momentum
- Momentum detuning

Layout







Total length	m
Collider	91174.117
HEB	91172.691

60°/60° Optics

Magnet	Parameter	Unit	Value
Dipole	Field at injection (20 GeV)	G	71
	Field at W energy (80 GeV)	G	284
	Length	m	11.1
Quadrupole	Gradient at injection (20 GeV)	T/m	1.74
	Gradient at W energy (80 GeV)	T/m	6.9
	Length	m	1.5
Sextupole	Gradient at injection (20 GeV)	T/m^2	75
	Gradient at W energy (80 GeV)	T/m^2	300
	Length	m	0.5

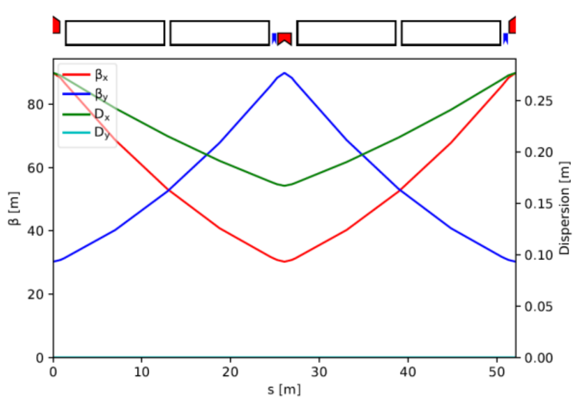
- FODO cells of ~52 m
- Made of 4 dipole, 2 quadrupoles and 2 sextupoles

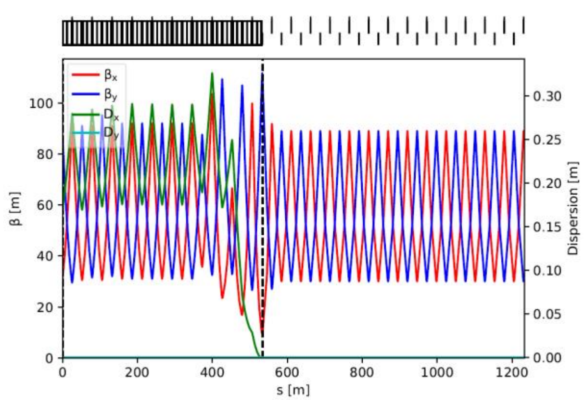
Distance between dipoles: 0.65 m
Distance between quadrupole and sextupole: 0.15 m
Distance between dipole and sextupole: 0.356
Distance between quadrupole and dipole: 0.704 m
(it includes BPM and dipole correctors)

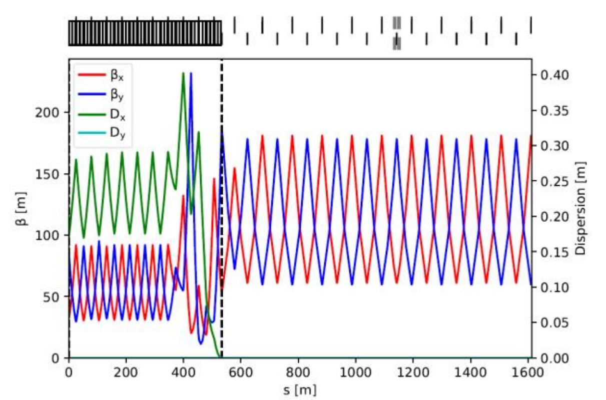
dipoles = 2×2944

quadrupoles = 2944

sextupoles = 2632/6







90°/90° Optics

Magnet	Parameter	Unit	Value
Dipole	Field at injection (20 GeV)	G	71
	Field at ttbar energy (182.5 GeV)	G	650
	Length	m	11.1
Quadrupole	Gradient at injection (20 GeV)	T/m	2.5
	Gradient at ttbar energy (182.5 GeV)	T/m	22.5
	Length	m	1.5
Sextupole	Gradient at injection (20 GeV)	T/m^2	174
	Gradient at ttbar energy (182.5 GeV)	T/m^2	1582
	Length	m	0.5

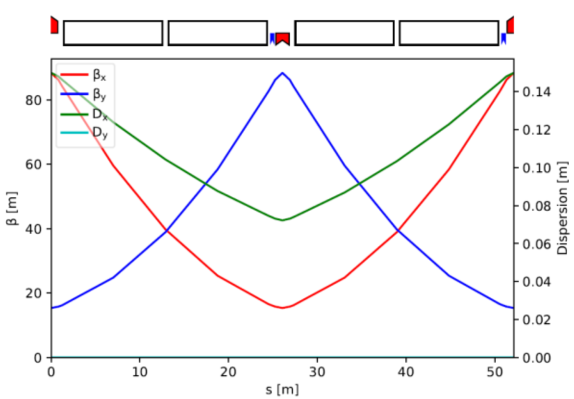
- FODO cells of ~52 m
- Made of 4 dipole, 2 quadrupoles and 2 sextupoles

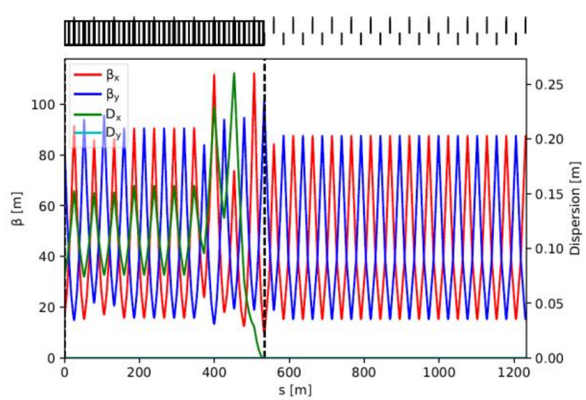
Distance between dipoles: 0.65 m
Distance between quadrupole and sextupole: 0.15 m
Distance between dipole and sextupole: 0.356
Distance between quadrupole and dipole: 0.704 m
(it includes BPM and dipole correctors)

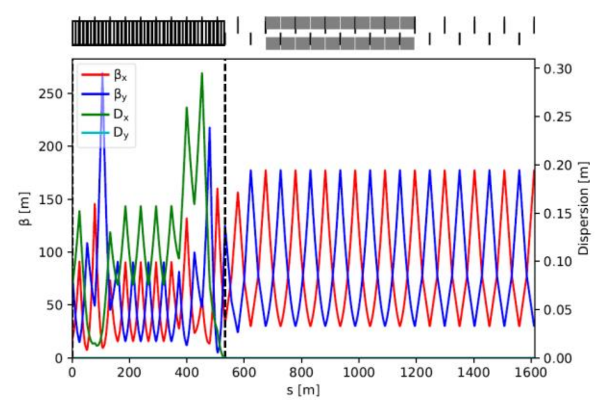
\# dipoles = 2×2944

\# quadrupoles = 2944

\# sextupoles = 2632/4







DA at injection with multipole errors

Static dipole field errors of the CT dipole design at 56Gs considered + 10% random part

Dynamic field effect not taken into account in this simulations: dipole and multipole reproducibility expected to be ≤ **5×10^{-4}**

91km 60°/60° optics

Stable initial action @ 4500 turns (~15% *tx* 20 GeV)

Geometric emittance injected 1.27e-9 nm

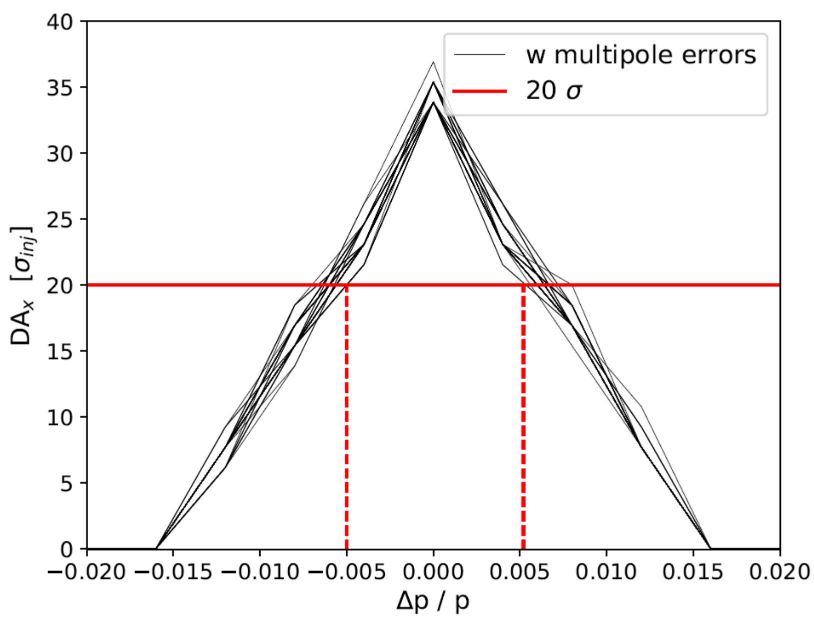
$\beta_x = 83.2 \qquad \beta_y = 32.2 \qquad D_x = 0$

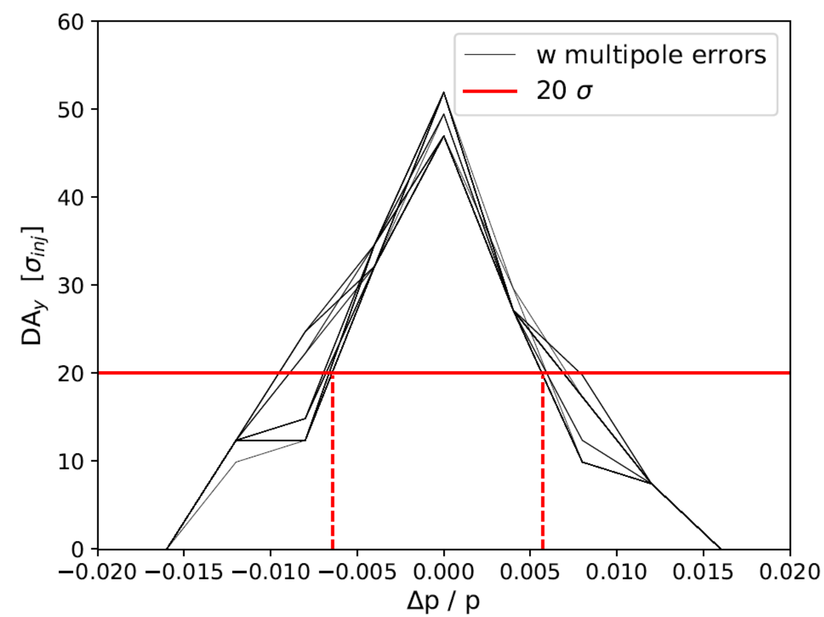
Courtesy of F. Zimmermann and Jie Gao

	CT dipole		Iron-core dipole	
GFR=R26	28Gs	56Gs	28Gs	56Gs
B1/B0	−5.20E−04	−1.04E−04	−1.56E−03	−2.60E−04
B2/B0	4.73E−04	5.41E−04	−2.03E−03	−2.03E−04
B3/B0	−7.03E−06	1.05E−04	3.52E−04	1.76E−04
B4/B0	−9.14E−04	−3.66E−04	4.57E−04	−1.83E−04
B5/B0	3.56E−05	−2.38E−05	−2.38E−05	−3.56E−05
B6/B0	6.18E−04	2.16E−04	−3.09E−04	9.27E−05

relative values @ R = 26 mm

60 seeds
MadX Thin-Lens Tracking





DA at injection with multipole errors

91km 90°/90° optics

$\beta_x = 79.5$

$\beta_y = 17.0$

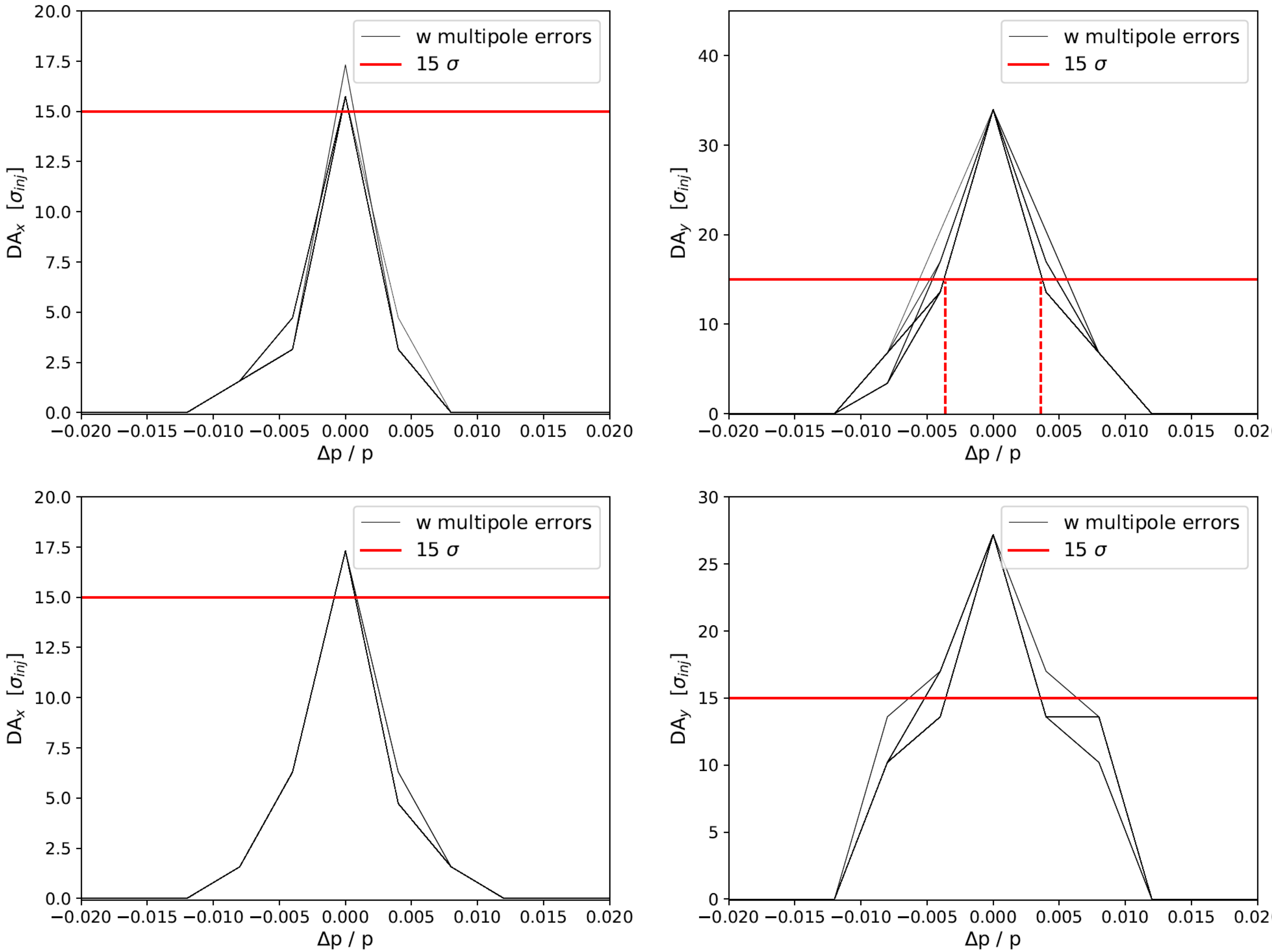
$D_x = 0$

$Q_x = 417.225$

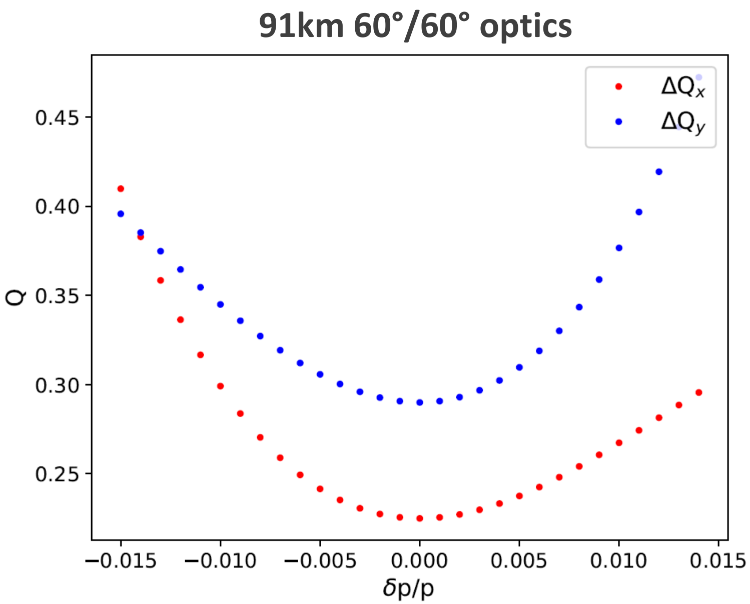
$Q_y = 413.29$

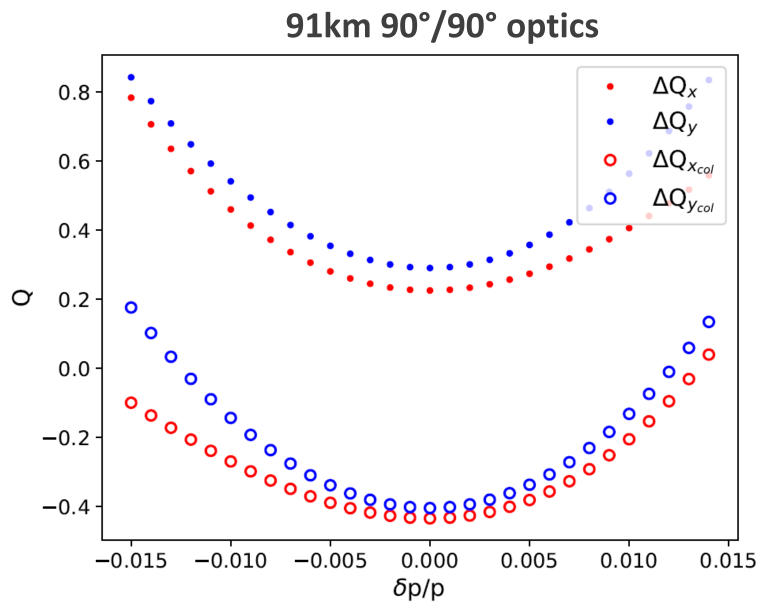
$Q_x = 416.565$

$Q_y = 413.595$



Momentum detuning





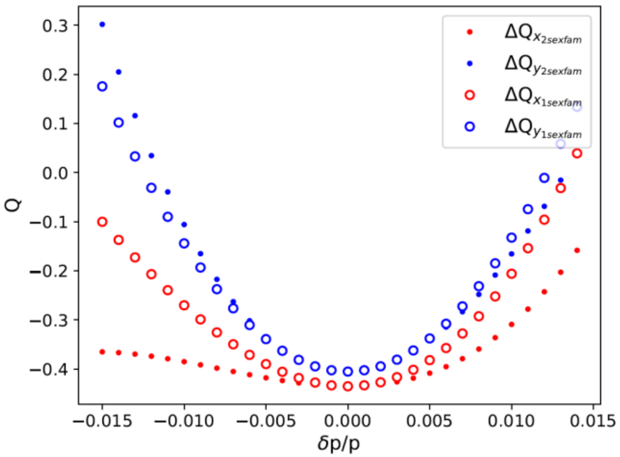
	Q	$\partial Q/\partial\delta$	$\partial^2 Q/\delta^2\delta$	$\partial^3 Q/\delta^3\delta$
x	.225	0	4155.317	-161460.363
y	.29	0	5244.035	66921.874
x	.225 (w/o sex)	-661.13	924.534	-569581.860
y	.29 (w/o sex)	125.94	1716.270	287914.529
x	.565	0	3940.796	192685.700
y	.595	0	5336.346	35042.450

Optimizing momentum detuning with two sextupole families

Strategy:

$$Q_z\left(\frac{\delta p}{p_0}\right) = Q_{z0} + Q_z'\left(\frac{\delta p}{p_0}\right) + \frac{1}{2!}Q_z''\left(\frac{\delta p}{p_0}\right)^2 + \frac{1}{3!}Q_z'''\left(\frac{\delta p}{p_0}\right)^3 + \ldots$$

$Q_z' \rightarrow 0$, $Q_z'' \rightarrow$ abs < 0.2, $Q_z''' \rightarrow$ abs < 0.05 $\left(\frac{\delta p}{p_0} = 0.01\right)$



- difficult to reduce Q'' without increasing Q'''
- Montague functions become more regular but higher
- DA doesn't improve

	Q	$\partial Q/\partial\delta$	$\partial^2 Q/\delta^2\delta$	$\partial^3 Q/\delta^3\delta$
x	.565	0	3940.796	192685.700
y	.595	0	5336.346	35042.450
x	.565 (2 sex fam)	0	1761.903	227601.518
y	.595 (2 sex fam)	0	5388.272	-178897.067

Conclusions & Perspectives

- **Iterate on HEB layout**
  - Improve superposition with collider with 10 m (< 10 m) shift at IPs
- **Improve off-momentum DA for the 90°/90° optics**
  - Octupoles ?
  - Phase advance between arcs?
  - Other strategy for sextupoles families optimizations (MOGA,…) ?

- **HEB optics repository and alternative optics**

- **Define tolerances and correctors for linear imperfections**

Back-up

Multipoles field errors at injection (> b2)

Static dipole field errors of the CT dipole design at 56Gs considered + 10% random part

Dynamic field effect not taken into account in this simulations: dipole and multipole reproducibility expected to be ≤ **5×10^{-4}**

97km 60°/60° optics

Stable initial action @ 4500 turns (~15% *tx* 20 GeV)

Geometric emittance injected 1.27e-9 nm

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B2/B0	4.73E-04	5.41E-04	-2.03E-03	-2.03E-04
B3/B0	-7.03E-06	1.05E-04	3.52E-04	1.76E-04
B4/B0	-9.14E-04	-3.66E-04	4.57E-04	-1.83E-04
B5/B0	3.56E-05	-2.38E-05	-2.38E-05	-3.56E-05
B6/B0	6.18E-04	2.16E-04	-3.09E-04	9.27E-05

relative values @ R = 26 mm

60 seeds

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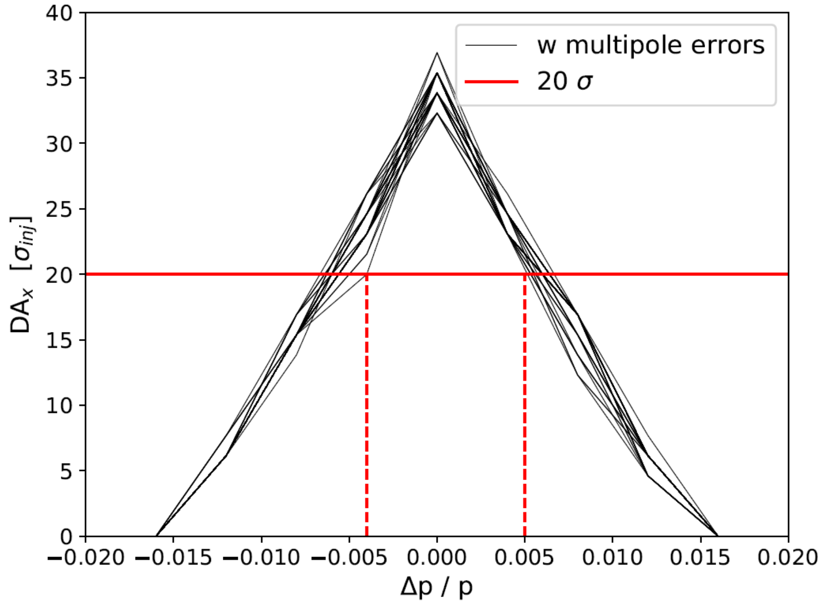
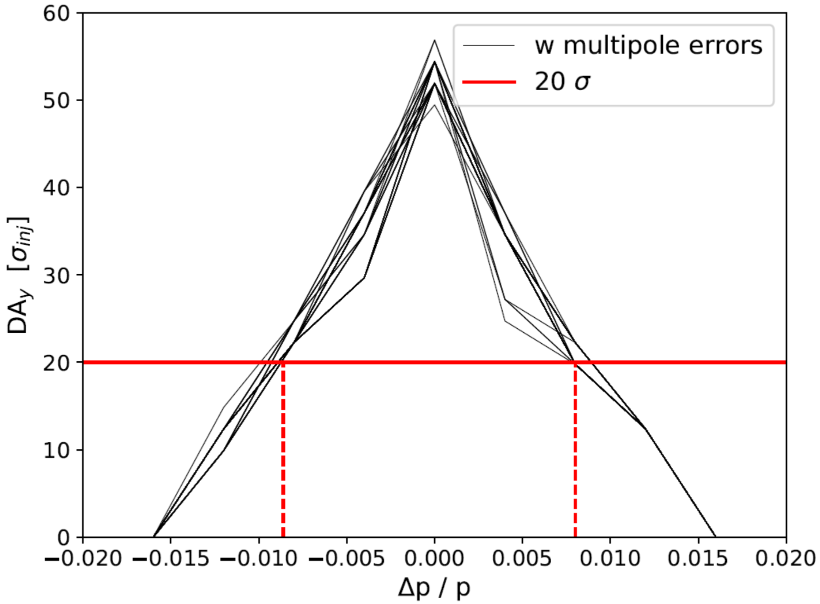
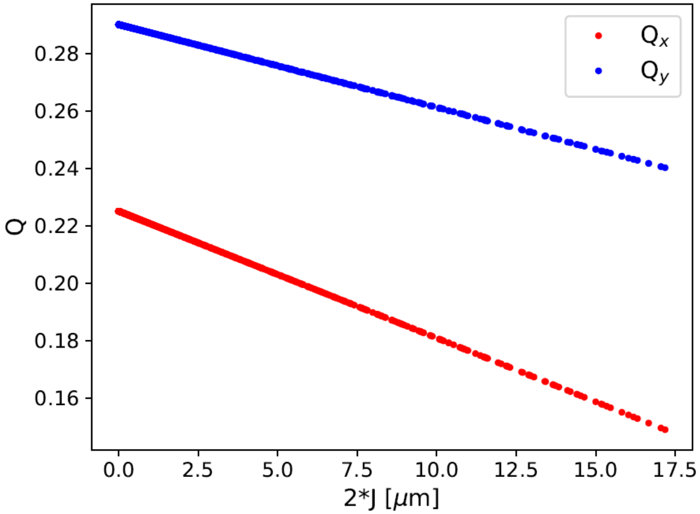
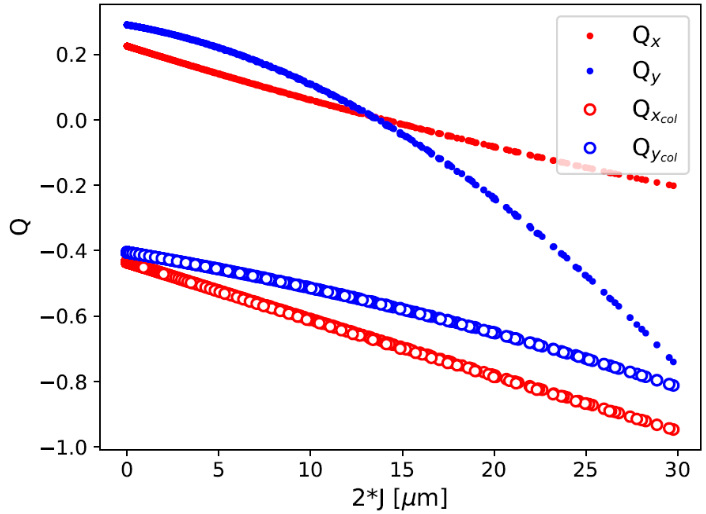




Amplitude detuning





Equilibrium emittances

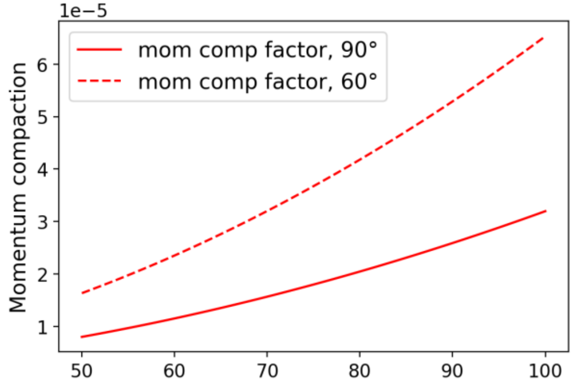
- Booster Equilibrium rms emittance ≤ collider

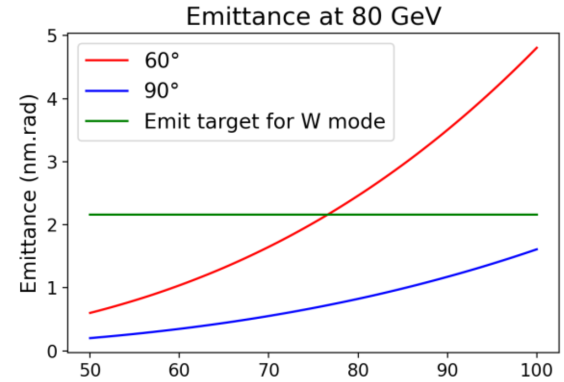
Beam Energy [GeV]	Eq. Emittance [nm rad] 60°/60°	Eq. Emittance [nm rad] 90°/90°	Eq. Emittance Collider [nm rad]	new Eq. emittance Collider new [nm rad]
45.6 (Z)	0.235	0.078	0.24	**0.71**
80 (W)	0.729	0.242	0.84	**2.16**
120 (H)	4.229	0.545	0.63	**0.64**
175 (tt)	3.540	1.172	1.48	**1.49**

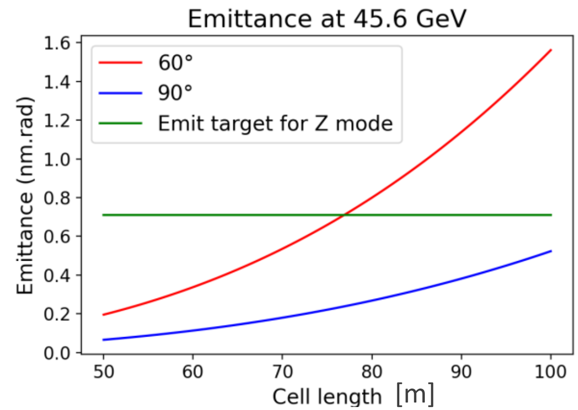
⇒ 60°/60° retained for Z and W operation (mitigation of MI and IBS)

⇒ 90°/90° 100 m cell could gain a bit in momentum compaction at Z & W

⇒ 90°/90° required for H and ttbar final emittances







2 dipoles families optics

2 dipoles with two different curvatures, proposed for the electron-ion collider (**EIC**)

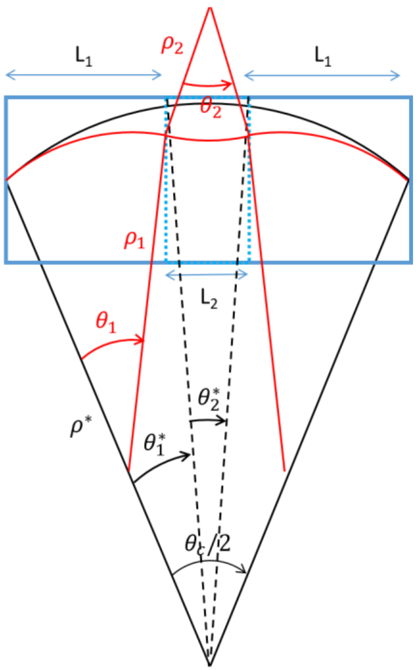
Damping time can be reduced by playing on the ratio between the two different fields.

Advantages:

- No impact on the layout
- Increase I2 without damping wigglers
- Higher dipole field at injection energy

Drawbacks:

- Different reference orbits ⇒ **reduction of beam stay clear?**
- **More synchrotron** radiation and in **opposite direction** of foreseen absorber (at injection) ⇒ **vacuum quality to be investigated**



$$a = \frac{L2}{L0} \qquad b = \frac{\rho^*}{\rho_2}$$

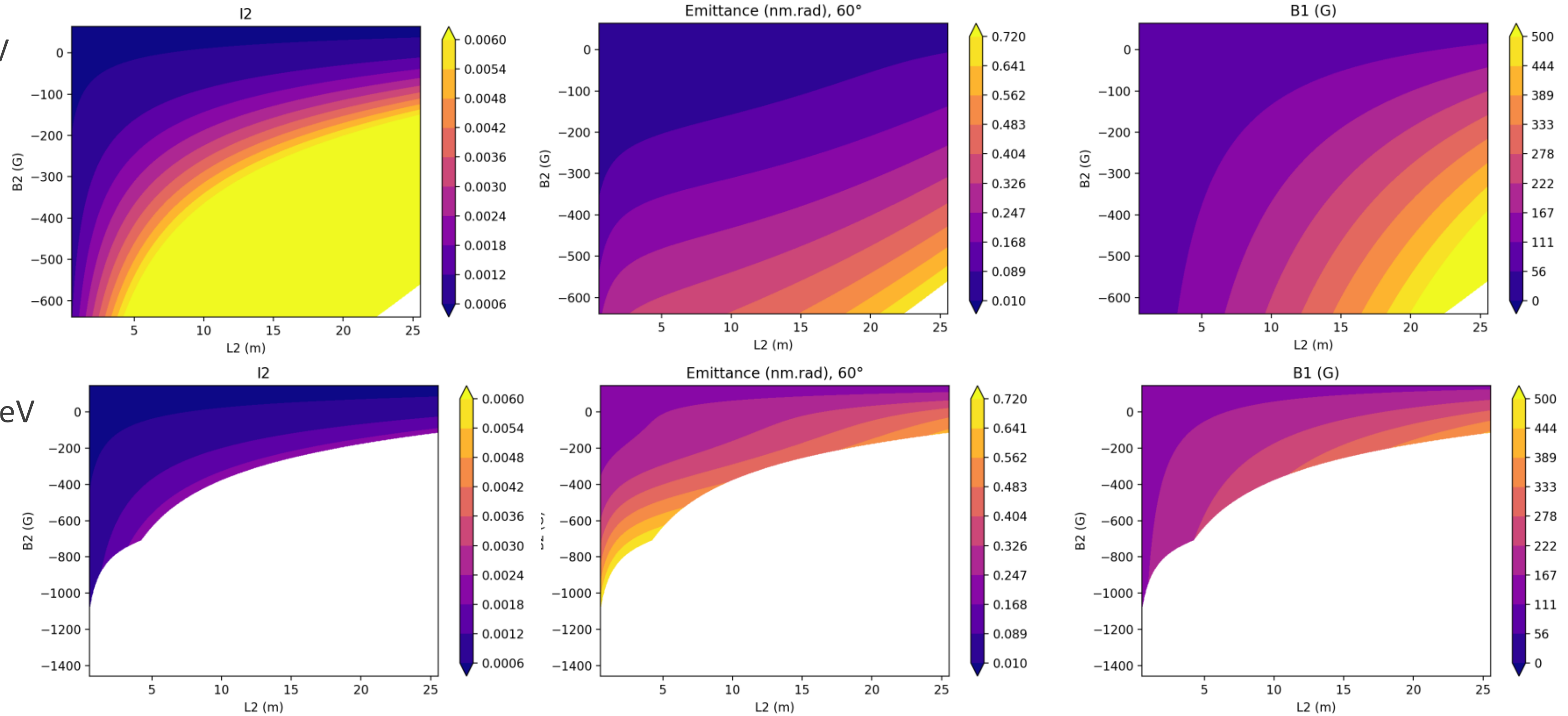
$$I_i = I_i(\mu_x, L_{cell}, \theta_c/2, a, b)$$

A. Chancé

Preliminary results of two dipoles families optics

20 GeV

45.6 GeV

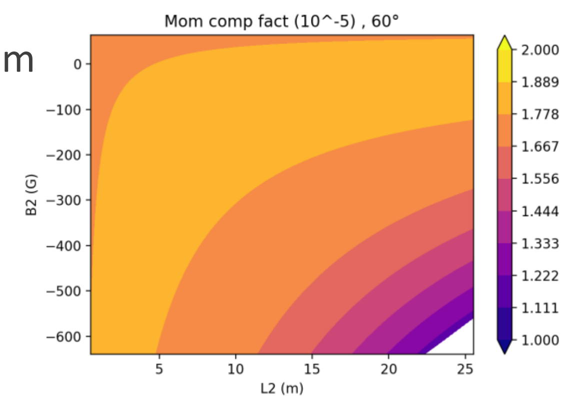


Constraints: **Energy loss** per turn ≤ 126 MeV (~wiggler), **eq. emit** < 0.72 nm

- 4 × I2 can be obtained with a L2 ~5 m, B2~-200 G, B1 ~170 G at 20 GeV and B_2 ~-400 G, B1 ~200 G at 45.6 GeV
- Minimum dipole field at injection ~ 3×present lattice
- Momentum compaction ~1.8 10^{-5} (~ 60°/60° lattice)

⇒ Which is the maximum allowed budget for radiated power ?

⇒ Which is the possible maximum field derivative for the two dipoles ?



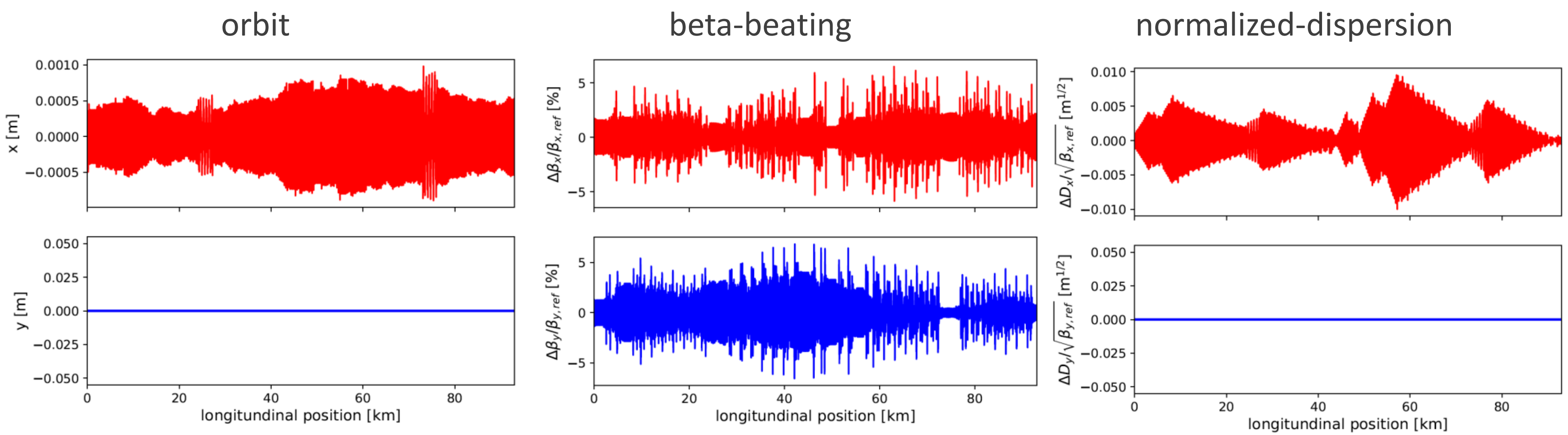
H. De Grandsaignes, A. Chance

Main Linear field errors (b1, b2) only

Main quadupoles :
b2 = 2×10^{-4} relative random error
Main Dipoles:
b1 = 1×10^{-4} relative random error
b2 = -1×10^{-4} relative systematic error + 10% random component

Courtesy of F. Zimmermann and Jie Gao

Without orbit, beta-beating and dispersion correction:



100 μm random quadrupole offset only (x,y)

Removing all other mis-alignment except for quadrupole offsets
Reducing the randomly distributed offset values to ±3 σ= 100 μm

Type	Δx (μm)	Δy (μm)	ΔS (μm)	ΔTheta (μrad)	ΔPhi (μrad)	ΔPsi (μrad)	Field Errors
Arc quad	100	100					
Arc sext							
Dip							
Girders							
BPM							

Without orbit, beta-beating and dispersion correction:

orbit | beta-beating | normalized-dispersion