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.

Status of the High Energy Booster

A. Chance, B. Dalena

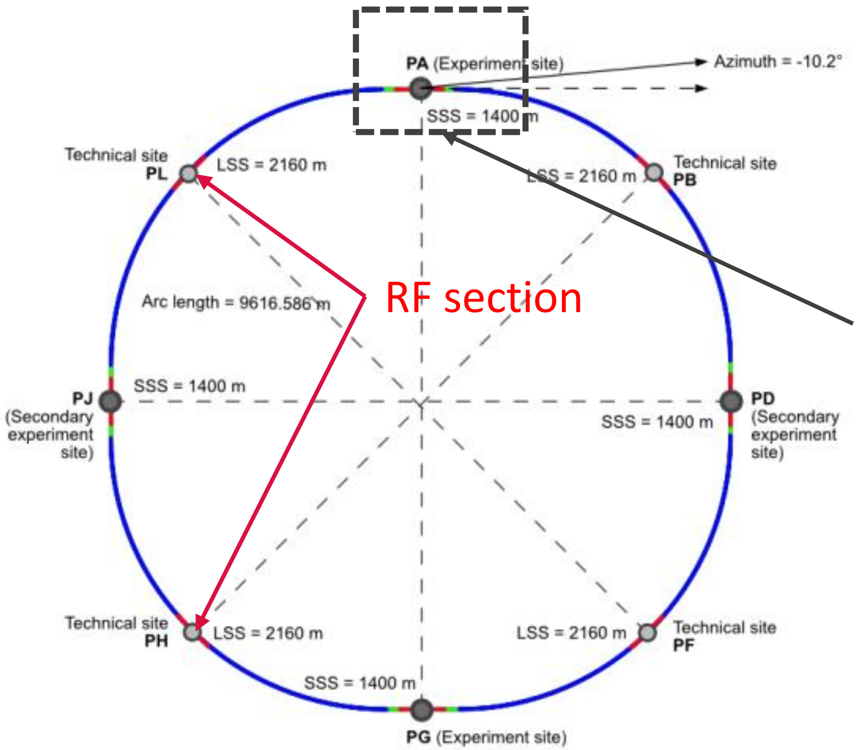
Thanks to:

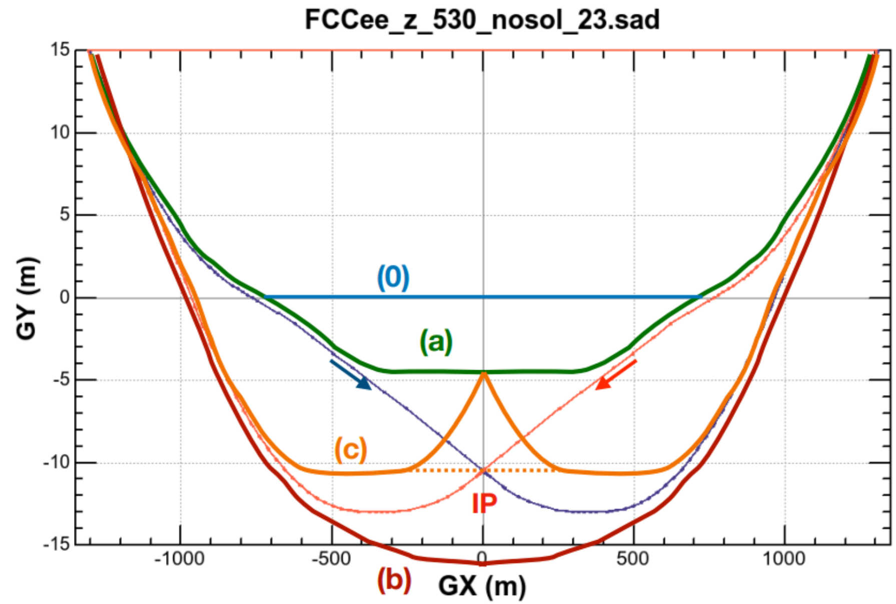
B. Haerer, L. Van Riesen-Haupt, T. Charles, R. Tomas, T. Persson, F. Antoniou, O. Etisken, M. Zampetakis, M. Hofer, F. Carlier, B. Holzer, A. Franchi, A. Latina

Outline

- Layout of the HEB ring
- 60°/60° and 90°/90° Optics
- DA vs momentum
- Momentum detuning
- Emittance evolution
    - Proposal of 2 dipole families

Booster layout





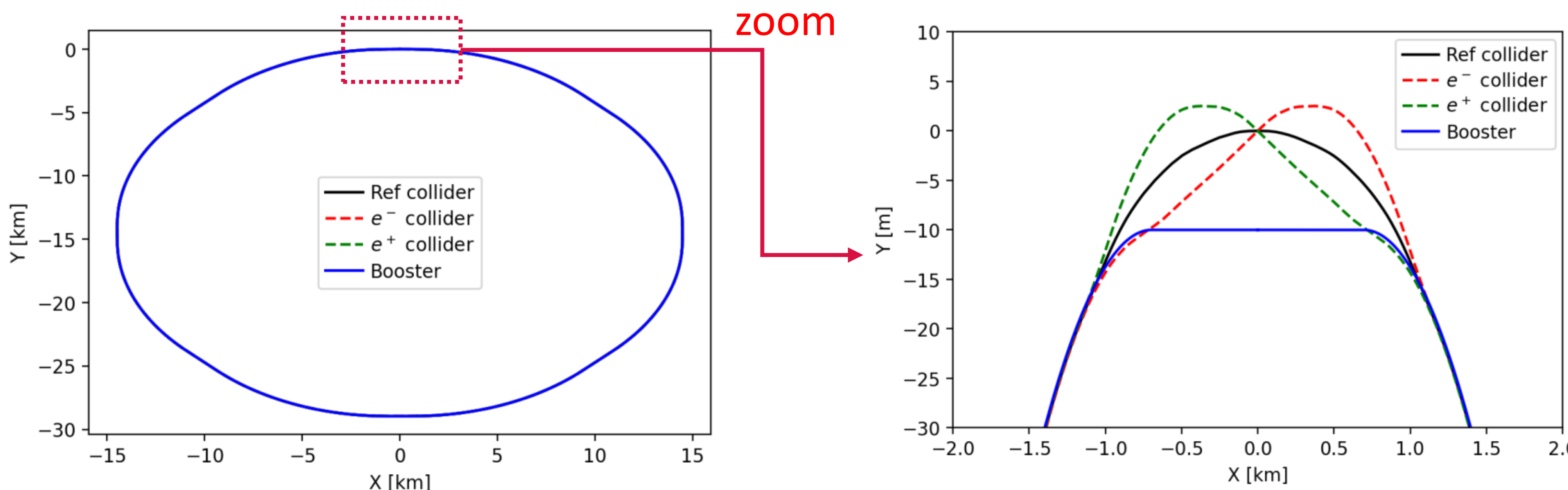
- **Bypass of the booster near the detector still an open question.**
- In the current booster version, **cavities are located in sections H and L.**
- Booster **layout updated** to follow the last collider survey version.
- **Use of a booster generator**

Updates on the booster generator

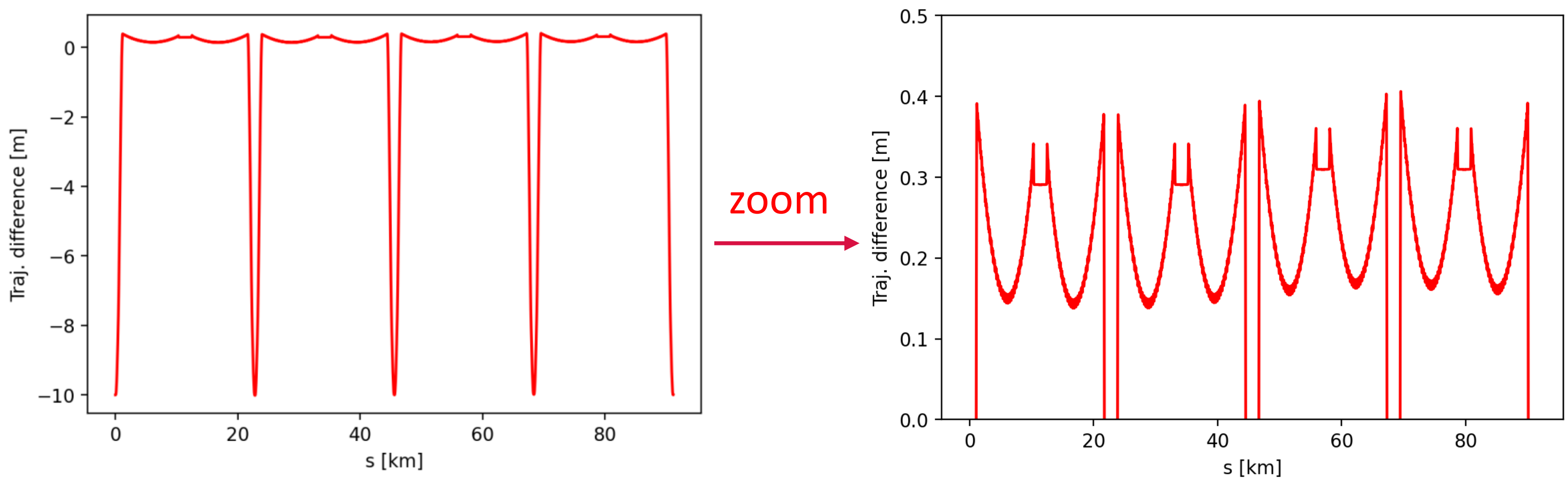
- The booster generator can now **take into account an offset at the IPs** (can be an offset in angle and position).
- Possible to have an **offset on the booster circumference** compared to the collider circumference.
- The generator calculates the **optimum angle and cell length** in the dispersion suppressors (entrance and exit of the arcs) and in the arcs to m**inimise the distance** in a Frenet frame between the booster and the collider geometry (using a survey file).
  - The arcs are not perfectly symmetric anymore because the average curvature radius in the dispersion suppressors at the entrance and exit of the arcs
- The cavities are also directly integrated in the RF sections.
- The non-interleaved sextupole scheme is implemented.

Booster layout

- The booster generator has been applied to last collider survey file.
- **Same total circumference**: 91174.117 m



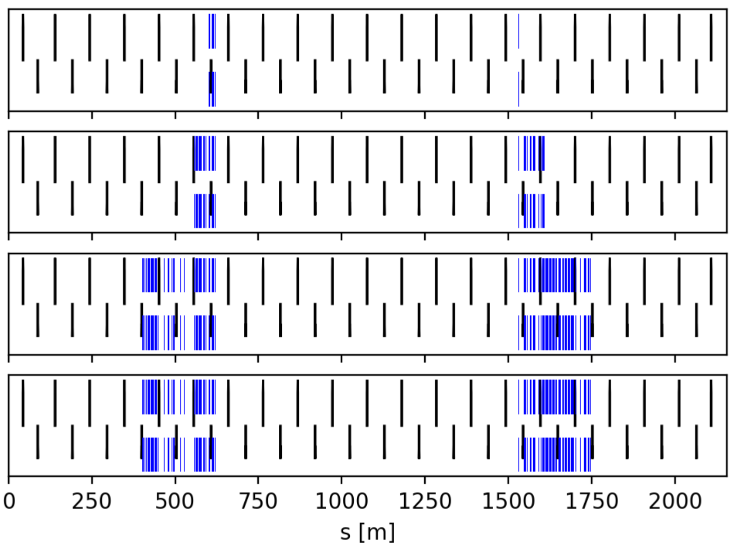
Distance between booster and collider



RF insertions

- Currently, the cavities are inserted in the insertions H and L.
- The cell FODO length in the RF insertion is 104 m.
- **400 MHz cryomodule** length: 11.4 m
- **800 MHz cryomodule** length: 7.5 m

Insertion L



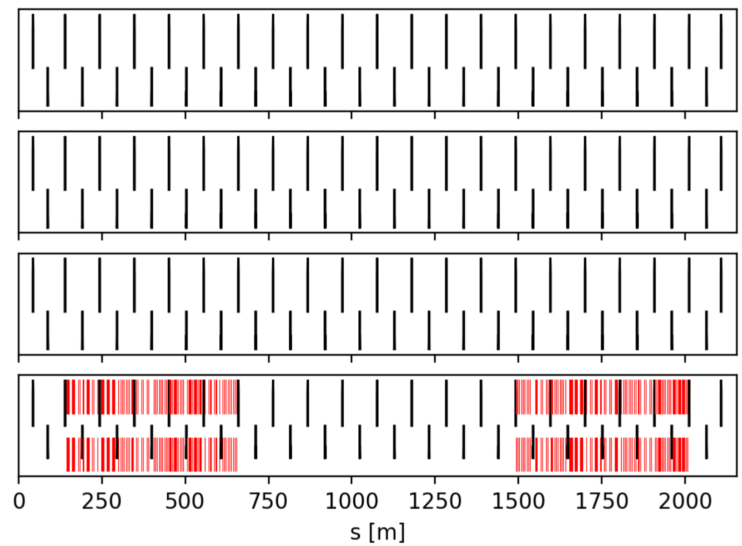
Z mode

W mode

H mode

tt mode

Insertion H



- Z mode: 2 CM left, 1 CM right
- W mode: 7 CM left, 6 CM right
- H mode: 17 CM left, 17 CM right
- tt mode: 17 CM left, 17 CM right

- Z mode: 0 CM left, 0 CM right
- W mode: 0 CM left, 0 CM right
- H mode: 0 CM left, 0 CM right
- tt mode: 60 CM left, 60 CM right

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

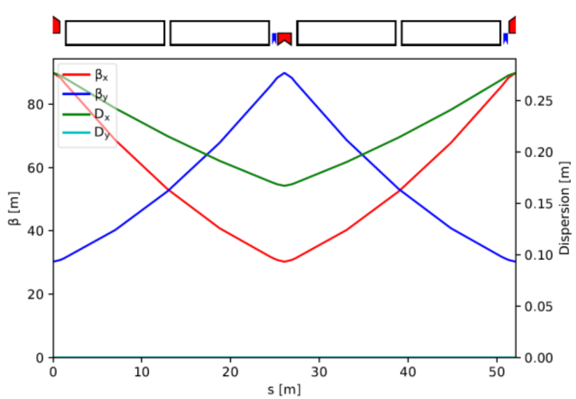
- FODO cells of ~52 m
- Made of 4 dipole, 2 quadrupoles and 2 sextupoles

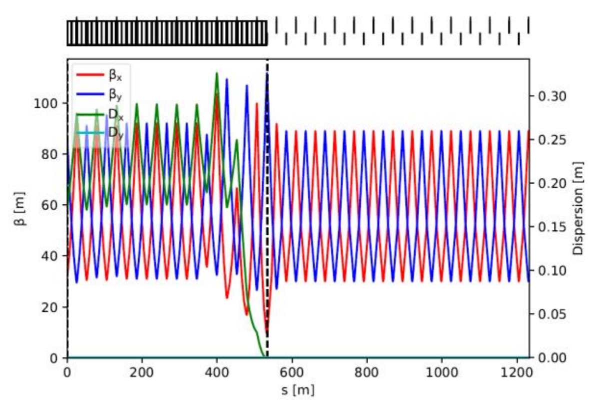
Distance between dipoles: 0.4 m
Distance between quadrupole and sextupole: 0.165 m
Distance between dipole and sextupole: 0. 504 m
Distance between quadrupole and dipole: 0.869 m
(it includes BPM and dipole correctors)

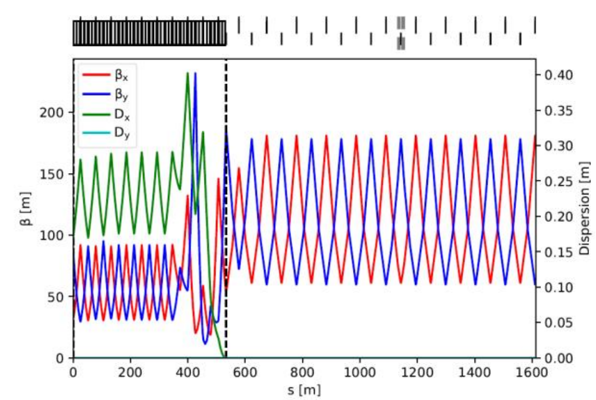
dipoles = 2×2944

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

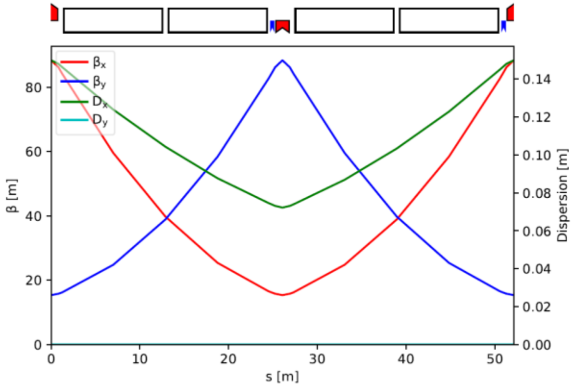
- FODO cells of ~52 m
- Made of 4 dipole, 2 quadrupoles and 2 sextupoles

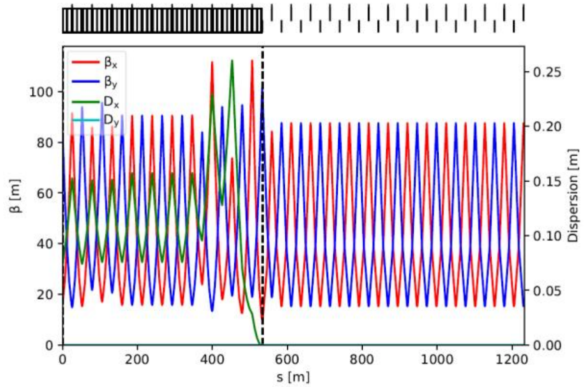
Distance between dipoles: 0.4 m
Distance between quadrupole and sextupole: 0.165 m
Distance between dipole and sextupole: 0. 504 m
Distance between quadrupole and dipole: 0.869 m
(it includes BPM and dipole correctors)

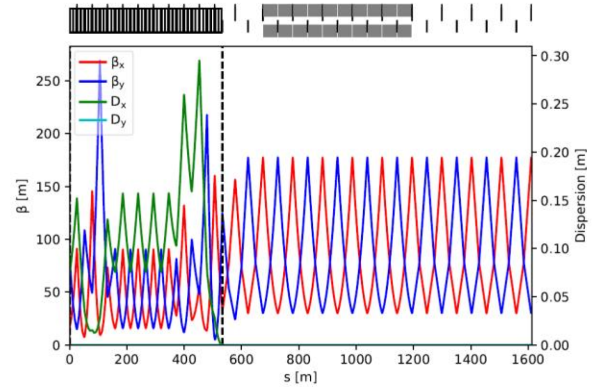
\# dipoles = 2×2944

\# quadrupoles = 2944

\# sextupoles = 2632/4





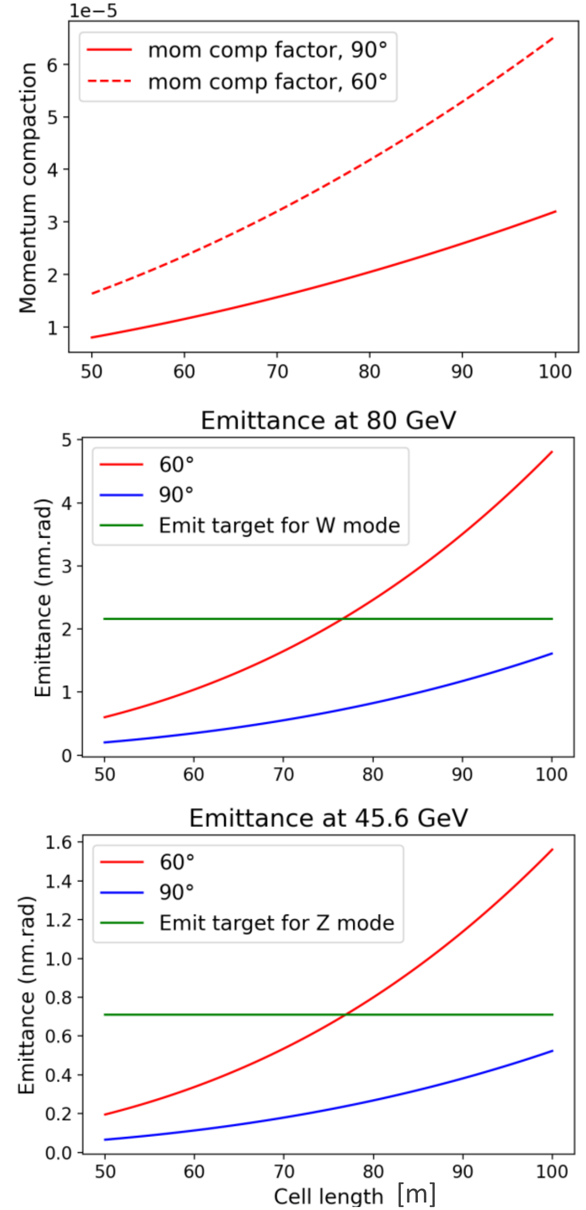


Equilibrium emittances

- 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



DA at injection with multipole errors 60°/60°

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}**

60 seeds
MadX Thin-Lens Tracking
Geometric emittance injected 1.27 nm

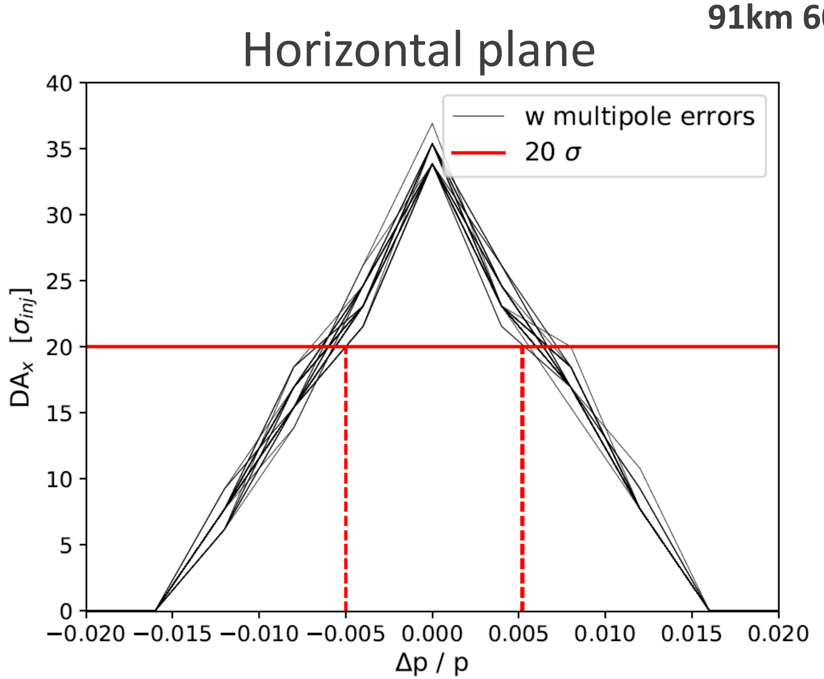
Courtesy of F. Zimmermann and Jie Gao

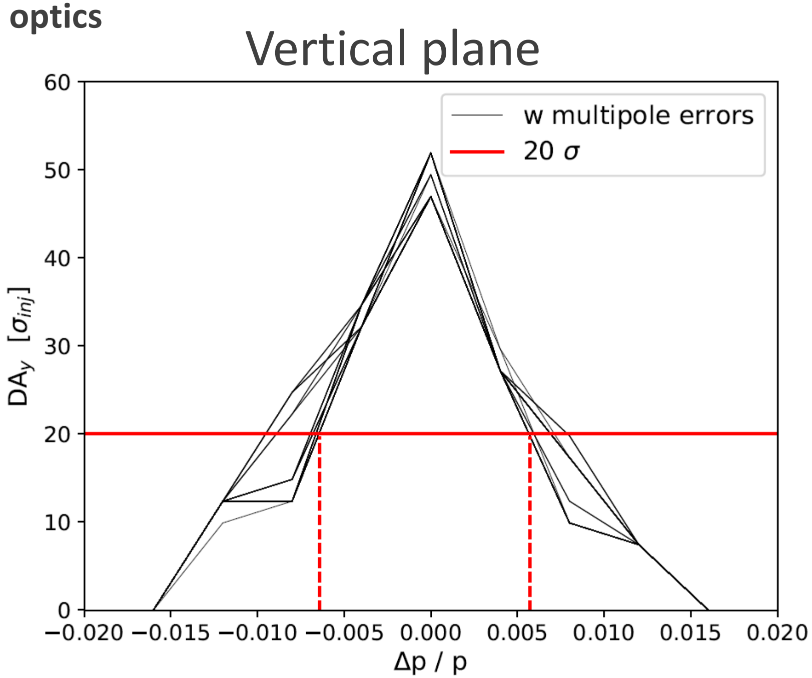
	CT dipole		Iron-core dipole	
GFR=R26	28Gs	56Gs	28Gs	56Gs
B1/B0	-5.20E-04	-1.04E-04	-1.56E-03	-2.60E-04
B2/B0	4.73E-04	5.41E-04	-2.03E-03	-2.03E-04
B3/B0	-7.03E-06	1.05E-04	3.52E-04	1.76E-04
B4/B0	-9.14E-04	-3.66E-04	4.57E-04	-1.83E-04
B5/B0	3.56E-05	-2.38E-05	-2.38E-05	-3.56E-05
B6/B0	6.18E-04	2.16E-04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

relative values @ R = 26 mm

$$\beta_x = 83.2 \text{ m} \; \beta_y = 32.2 \text{ m} \; D_x = 0 \text{ m}$$

91km 60°/60° optics





B. Dalena

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

DA at injection with multipole errors 90/90°

$\beta_x = 79.5$ m

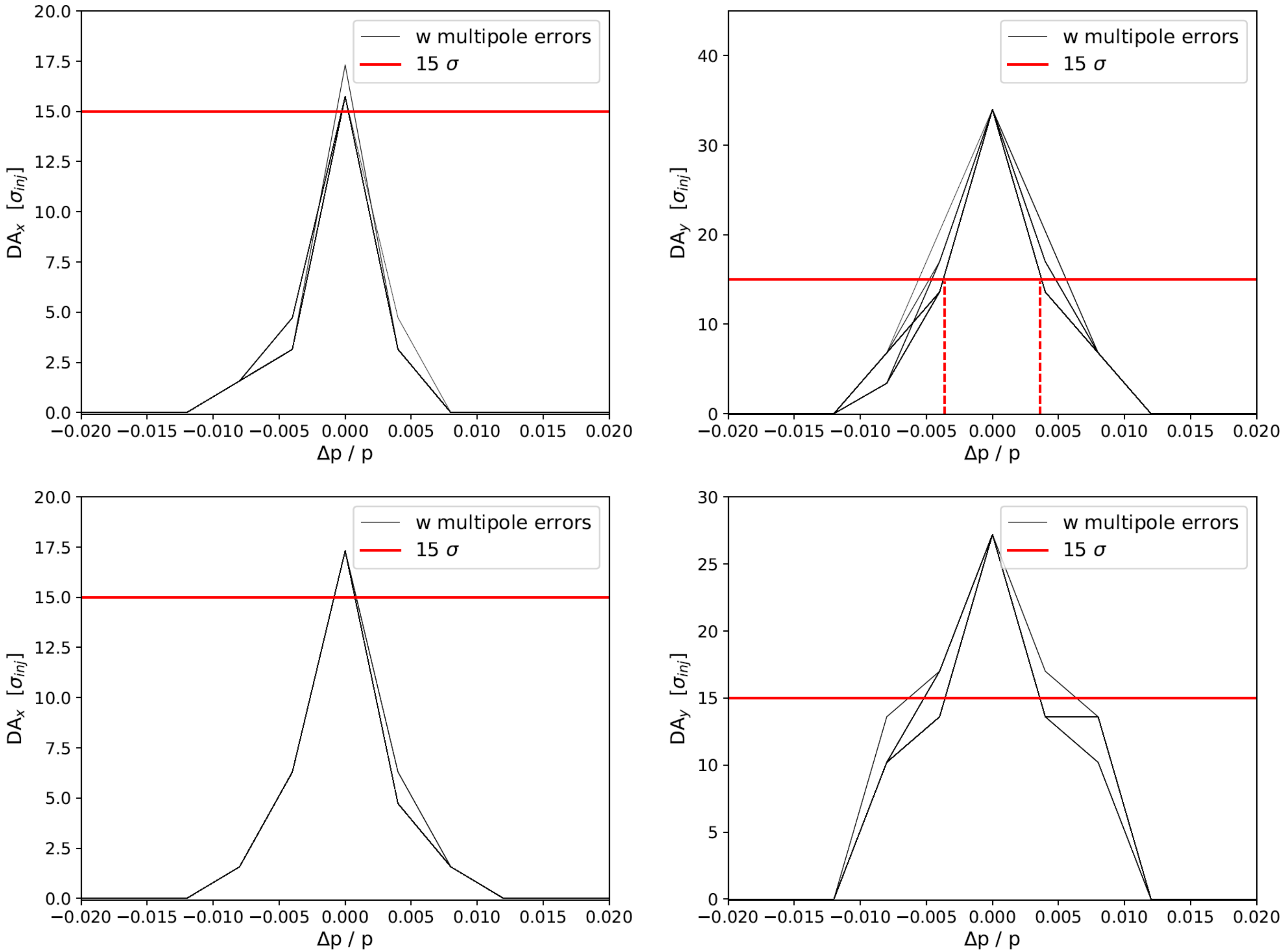
$\beta_y = 17.0$ m

$D_x = 0$ m

$Q_x = 417.225$

$Q_y = 413.29$

Horizontal plane — 91km 90°/90° optics — Vertical plane



$Q_x = 416.565$

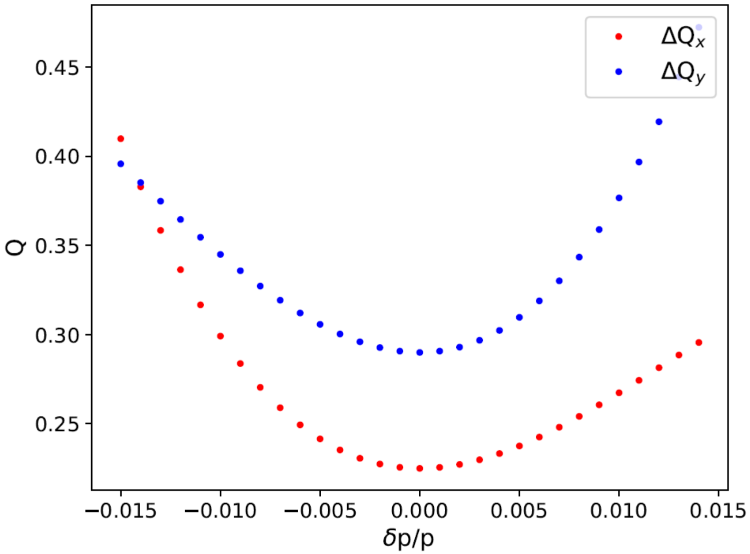
$Q_y = 413.595$

B. Dalena

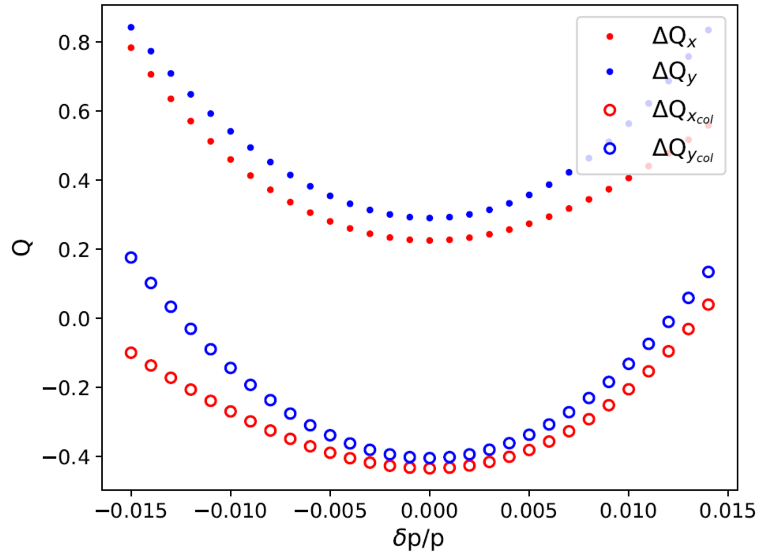
Momentum detuning

B. Dalena

91km 60°/60° optics



91km 90°/90° optics



	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

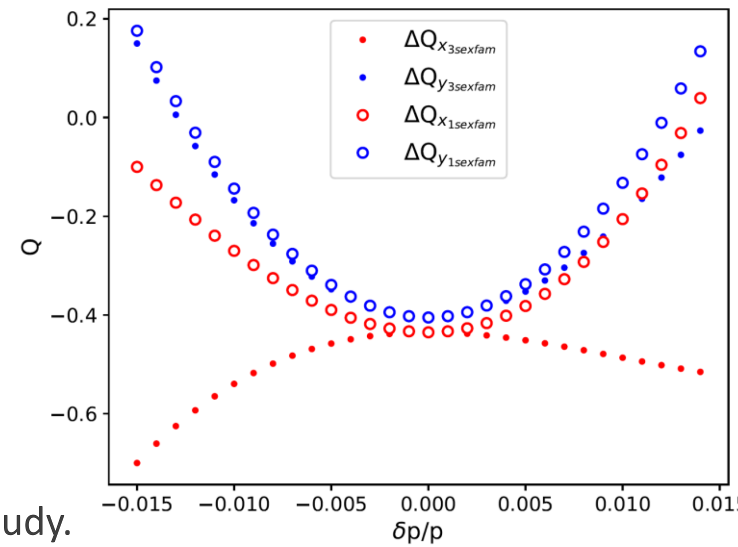
Optimizing momentum detuning with two sextupole families

Strategy:

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

$Q_z' \rightarrow 0$ $\quad Q_z'' \rightarrow$ abs < 0.2 $\quad Q_z''' \rightarrow$ 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 improvement on going
- DA better when multipole errors are off
- The differences between thin and thick lattices are under study.



	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
x	.565 (3 sex fam)	0	-1559.264	158675.883
y	.595 (3 sex fam)	0	4378.176	-110651.2

Damping Wigglers as in CDR

B. Haerer, T. Tydecks https://arxiv.org/abs/2111.14462

Target damping time 0.1 s (to fulfill cycle time)

Wigglers reduce damping time and increase eq. emittance :

$$\tau_x \propto \frac{1}{E^3 I_2} \qquad \varepsilon_{eq} = \frac{C_q \gamma^2 I_5}{\left(I_2\left(1 - \frac{I_4}{I_2}\right)\right)}$$

$$I_2 = \oint \frac{ds}{\rho^2} \qquad I_5 = \oint \frac{H_x}{|\rho^3|} ds$$

They **mitigate IBS** and **MI** too

A **normal conducting wigglers** foreseen

⇒ **can be further optimized** for poles length and for number of poles

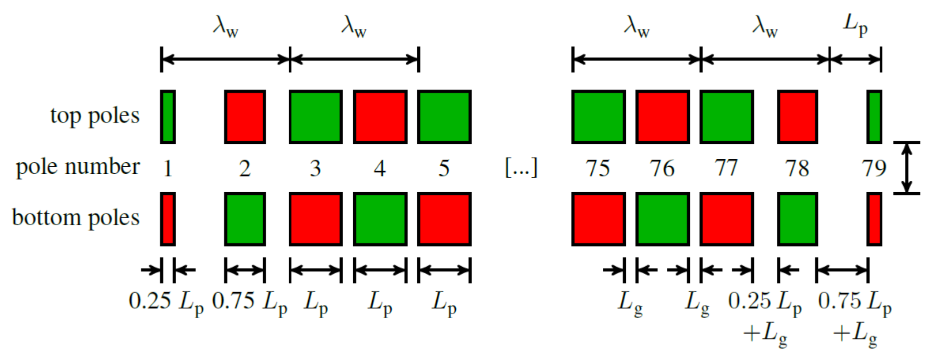
It **should be switched off** during acceleration

⇒ **Eddy current** effect to be investigated

Total length of installed wigglers is of the > **100 m** in the **same straight line**

⇒ Possible stimulated **additional radiation** and **instability** (like in FEL) to be studied

Beam energy (GeV)	Eq. emittance (nm rad) 60°/60° optics	Eq. emittance (nm rad) 90°/90° optics	Transv. damping time (s)
20.0	0.045	0.015	10.054
45.6	0.235	0.078	0.854
80.0	0.729	0.242	0.157
120.0	4.229	0.545	0.047
175.0	3.540	1.172	0.015



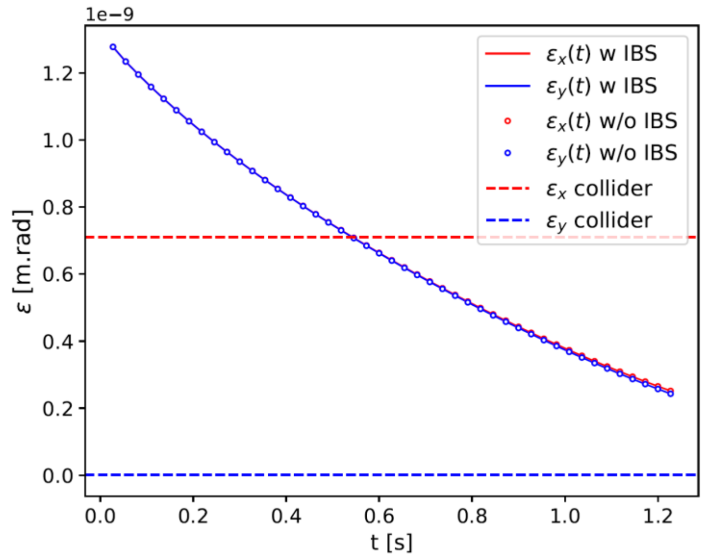
Pole length	0.095 m
Pole separation	0.020 m
Gap	0.050 m
Number of poles	79
Wiggler length	9.065 m
Magnetic field	1.45 T
Energy loss per turn	126 MeV
Hor. damping time	104 ms
Hor. emittance (60°optics)	300 pm rad

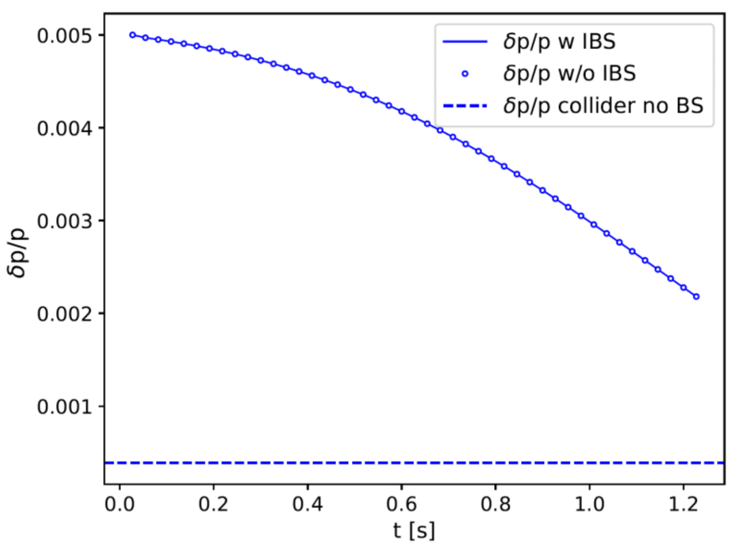
Hor. Emittance (60° optics) 1.7 nm @ 45.6 GeV

Impact of IBS (only acceleration)

- **We consider the Z mode:**
  - No accumulation
  - We ramp from 20 GeV to 45.6 GeV for 1.2 s.
- **The injection is from the linac at 20 GeV:**
  - Normalized emittance of 50 µm.
  - Energy spread of 0.5%
  - 2.53e+10 particles per bunch (4 nC)
- **Acceleration time is short enough to see no IBS effect.**
- **Synchrotron integrate I2 is too small to reach equilibrium parameters within 1.2 s.**

- Thanks to M. Zampetakis, F. Antoniou, O. Etisken to include **IBS**

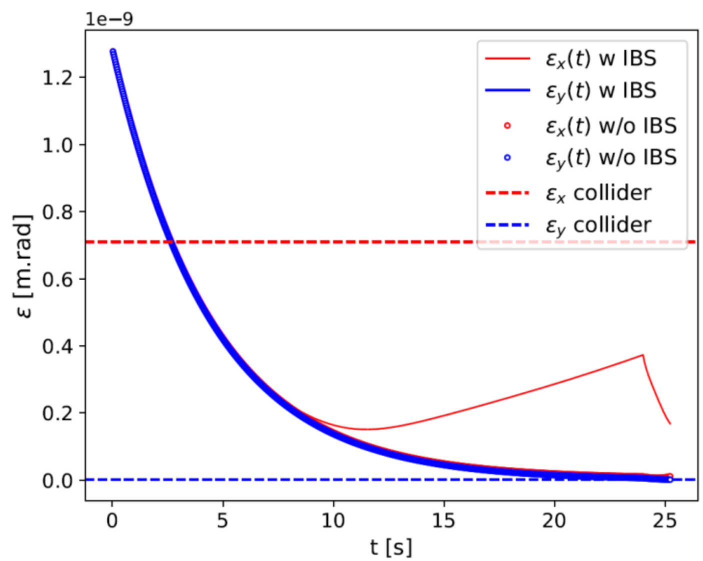


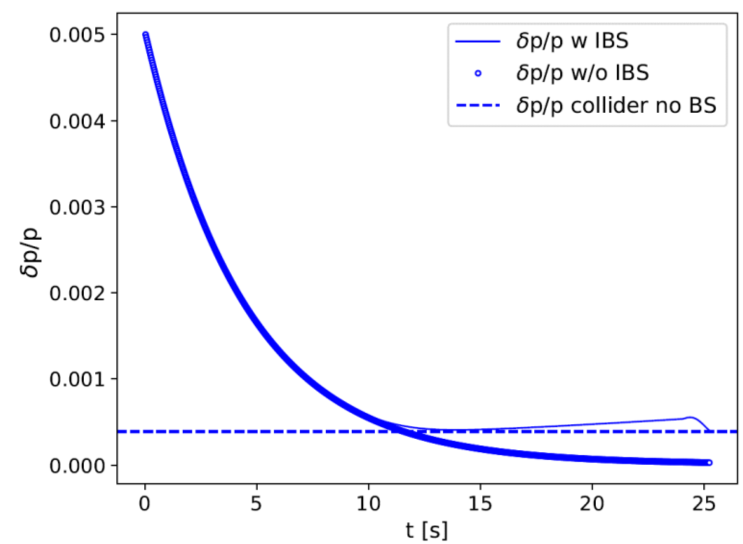


Impact of IBS (accumulation + ramp)

- **We consider the Z mode:**
  - We accumulate in the booster for 24 s
  - We ramp from 20 GeV to 45.6 GeV for 1.2 s.
- **The injection is from the linac at 20 GeV:**
  - Normalized emittance of 50 µm.
  - Energy spread of 0.5%
  - 2.53e+10 particles per bunch (4 nC)
- **The IBS is not negligible during accumulation process.**
- **The beam parameters (emittance and energy spread) will vary from a bunch to another. The problem remains if equilibrium is not reached at extraction energy.**

➢ Thanks to M. Zampetakis, F. Antoniou, O. Etisken to include **IBS**





How fast do we need to ramp to reach collider emittances ?

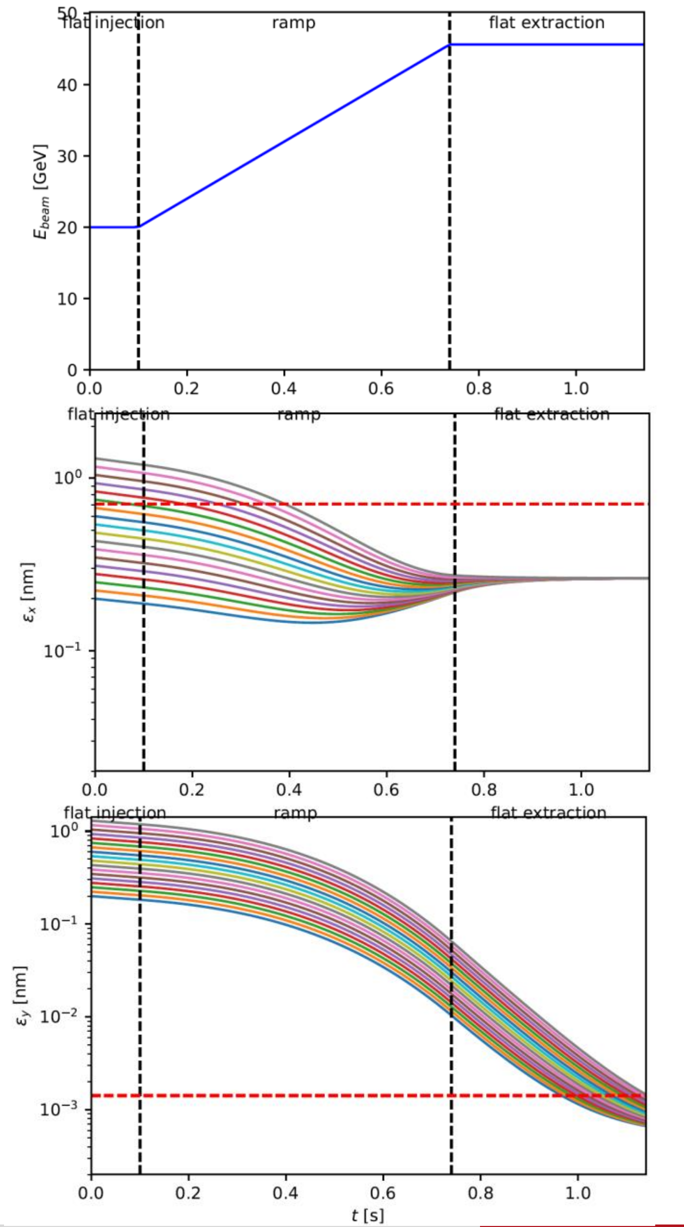
Do we need to reach ε_{eq} at 20 GeV (one order of magnitude less than collider) before to accelerate?

Simple model with synchrotron radiation only

- Injection energy 20 GeV
- Injection rms emittance **0.2-1.3 nm**
- Energy injection + ramp + extraction ~**1.2 s**
- **4**×I2 (**4**×I5) synchrotron radiation integrals
- dE/dt = 40 GeV/s
- $k = 2\times10^{-3}$

$$\frac{d\varepsilon_x}{dt} = -2\frac{\varepsilon_x - \varepsilon_{eq}(E(t), I2, I5)}{\tau_x(E(t), I2)}$$

$$\frac{d\varepsilon_y}{dt} = -2\frac{\varepsilon_y - k\,\varepsilon_{eq}(E(t), I2, I5)}{\tau_x(E(t), I2)}$$



- ➢ Contact with M. Zampetakis, F. Antoniou, O. Etisken to include **IBS**, other effects should be included ?
- ➢ **Start to end simulation** to validate **emittance reach** and **beam losses**

⇒ How much **time** can we use **for cycling at Z**?
⇒ Limit for **radiative power** ?

2 dipoles families optics

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

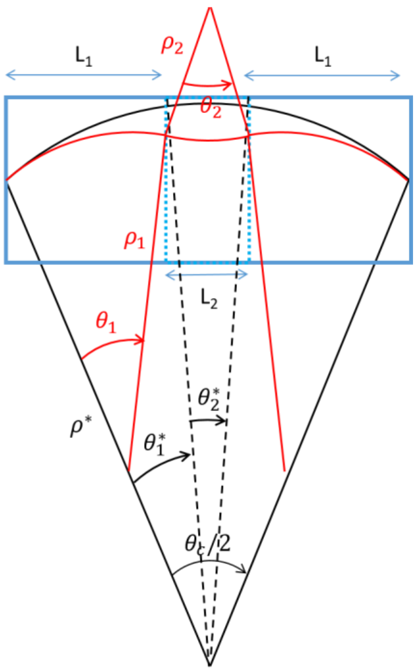
Damping time can be reduced by playing on the ratio between the two different fields.

Advantages:

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

Drawbacks:

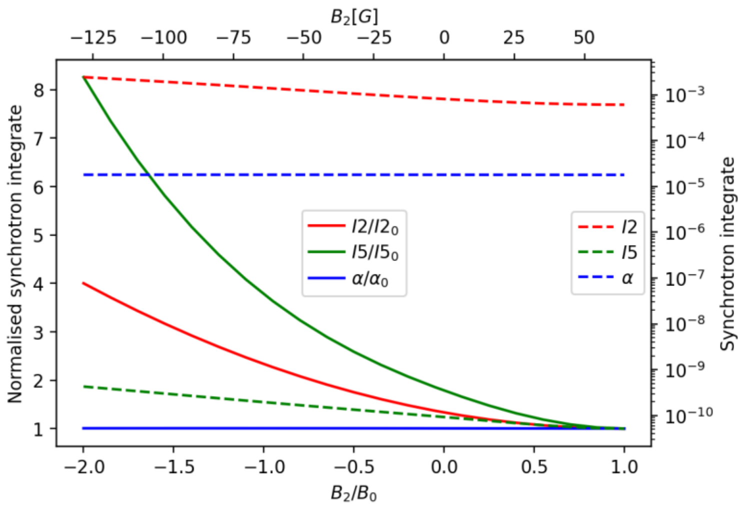
- Different reference orbits ⇒ **reduction of beam stay clear?**
- **More synchrotron** radiation and in **opposite direction** of foreseen absorber (at injection) ⇒ **vacuum quality to be investigated**

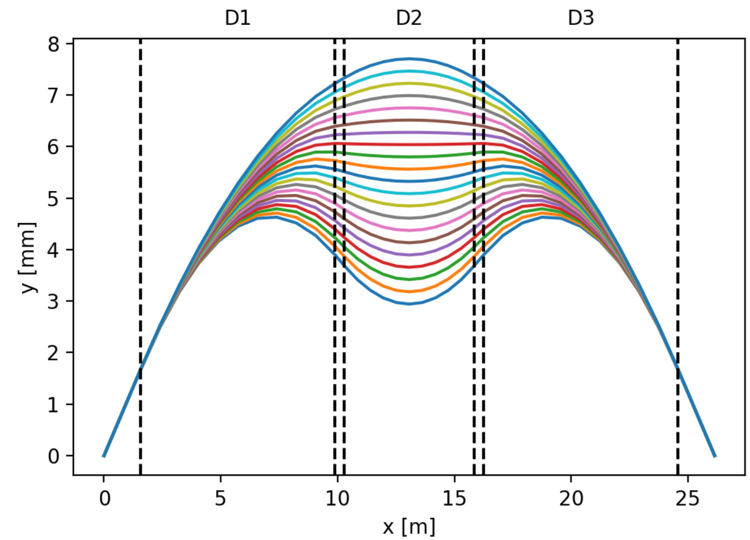


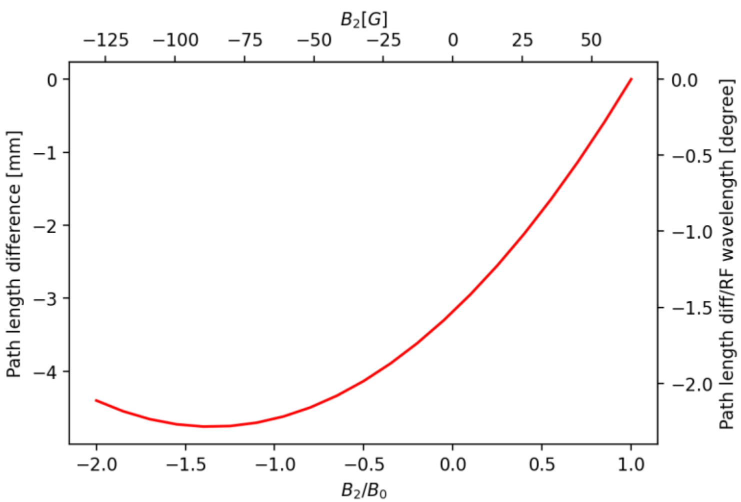
$$a = \frac{L2}{L0} \qquad b = \frac{\rho^*}{\rho_2}$$

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

Impact of different field in the magnets







- 4 × I2 can be obtained with L2 ~5,5 m, B2~-128 G, B1 ~128 G at 20 GeV (to be compared with B~64 G with one single magnet family),
- Minimum dipole field at injection ~ 2×present lattice
- Momentum compaction ~1.8 10^{-5} (~ 60°/60° lattice)
- Variation of the path length difference below 5 mm
- Difference between the different orbits in the dipoles of 5 mm
- **Still room for optimization.**

Conclusions & Perspectives

- **Booster generator updated** to follow the collider layout
  - Enables a shift at each IP
  - New booster version has exactly the same circumference
  - Orbit offset in the arcs below 400 mm.
  - To generate other layouts depending on the bypass in the experimental area.

- **Improve off-momentum DA for the 90°/90° optics**
  - A contact has been taken with Ahmad Mashal to perform an optimisation strategy for sextupoles families (MOGA,…),
  - Octupoles ?
  - Phase advance between arcs?
  - When multipole errors in the dipoles are off, the DA is better. How to mitigate the da at 90) is under investigation.

- **HEB optics repository and alternative optics**
  - Path length and orbit difference implemented in the scheme with 2 magnet families
  - In the current version, the path length difference is below 5 mm. The orbit difference may be a bit large: up to 5 mm. We may increase the number of magnets to reduce the offset.

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

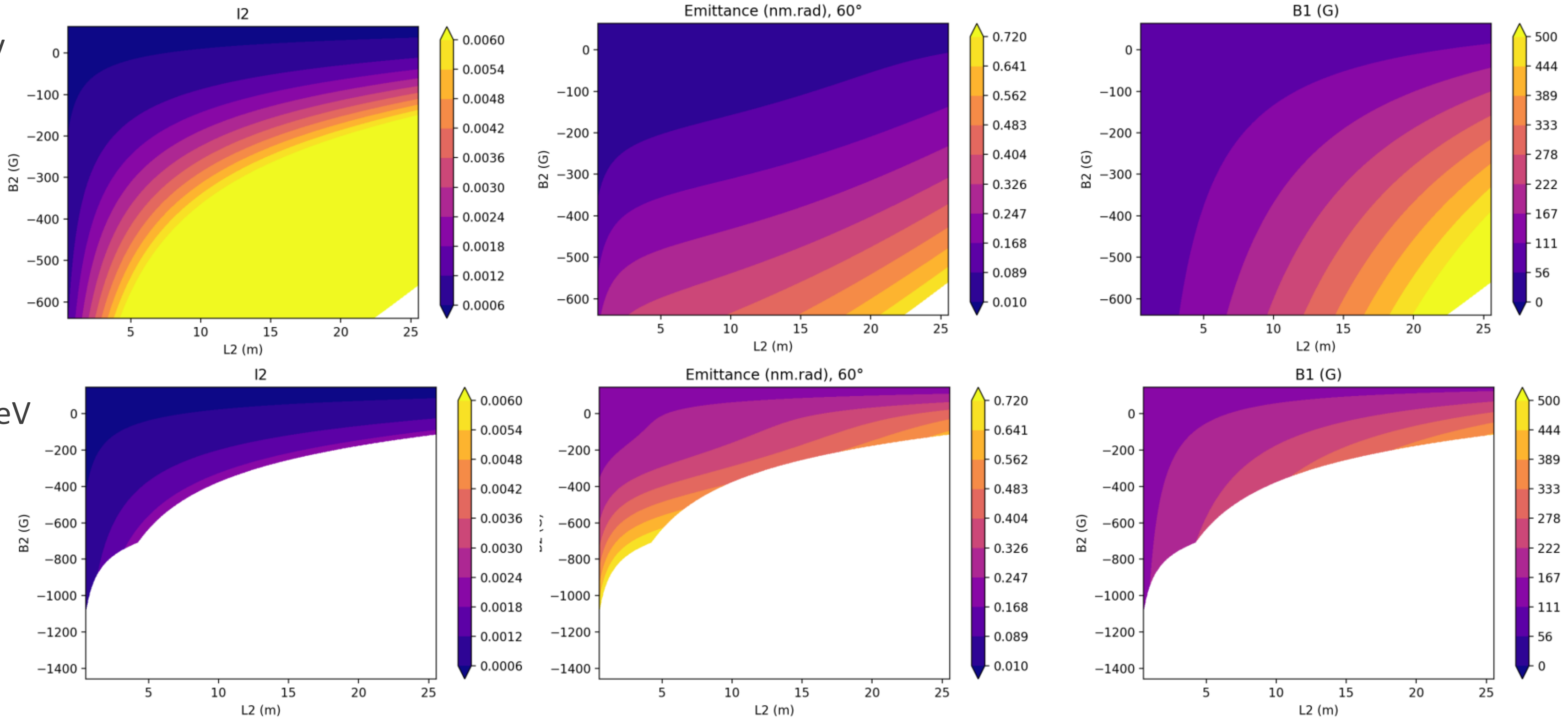
Thank you for your attention

Back-up

Preliminary results of two dipoles families optics

20 GeV

45.6 GeV

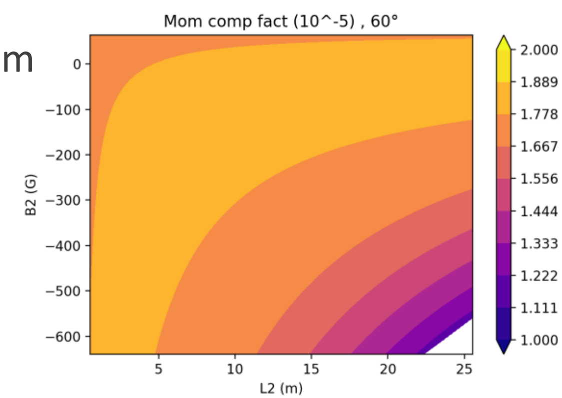


Constraints: **Energy loss** per turn ≤ 126 MeV (~wiggler), **eq. emit** < 0.72 nm

- 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

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

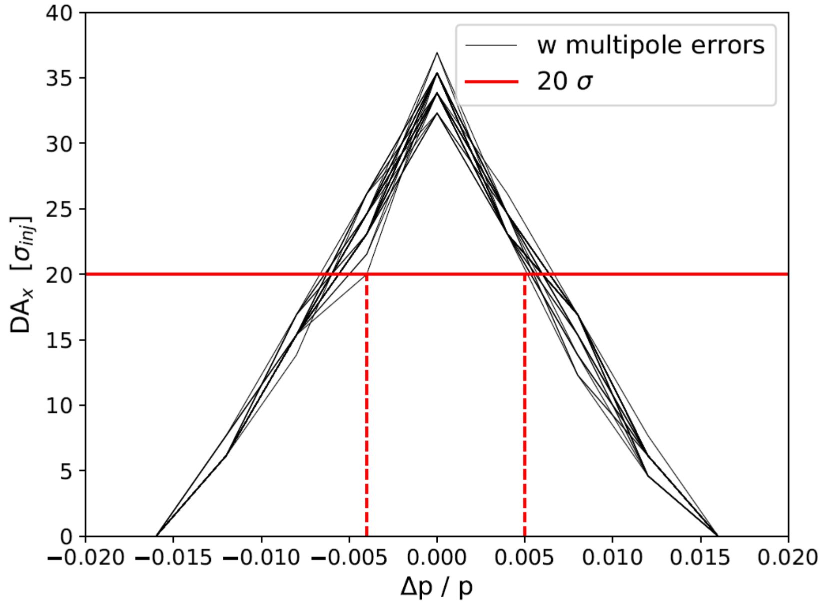
Courtesy of F. Zimmermann and Jie Gao

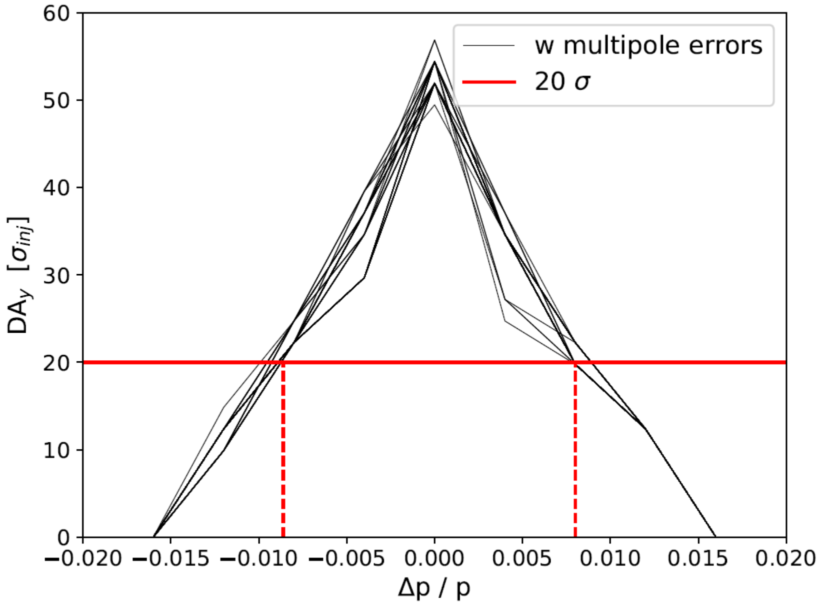
	CT dipole		Iron-core dipole	
GFR=R26	28Gs	56Gs	28Gs	56Gs
B1/B0	-5.20E-04	-1.04E-04	-1.56E-03	-2.60E-04
B2/B0	4.73E-04	5.41E-04	-2.03E-03	-2.03E-04
B3/B0	-7.03E-06	1.05E-04	3.52E-04	1.76E-04
B4/B0	-9.14E-04	-3.66E-04	4.57E-04	-1.83E-04
B5/B0	3.56E-05	-2.38E-05	-2.38E-05	-3.56E-05
B6/B0	6.18E-04	2.16E-04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

relative values @ R = 26 mm

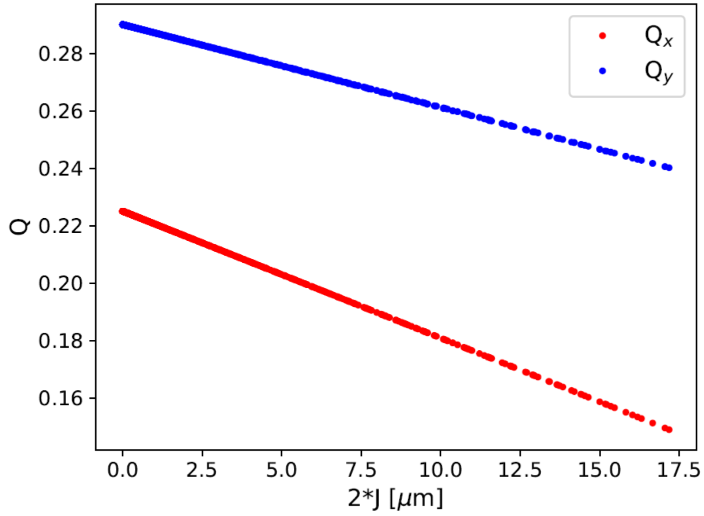
60 seeds

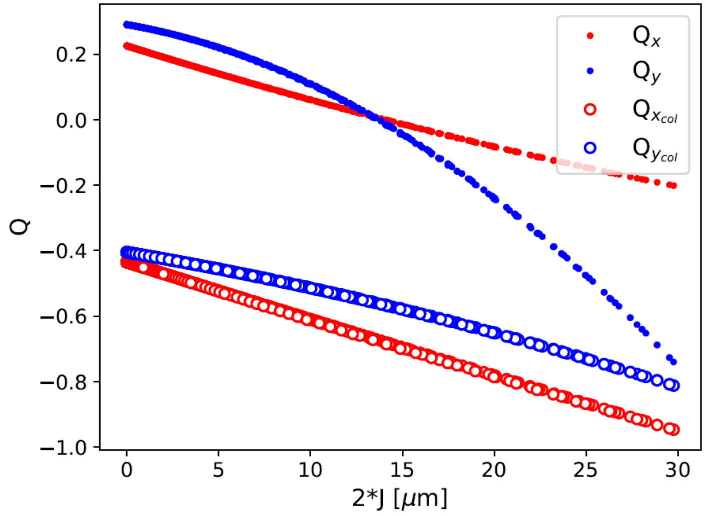
MadX Thin-Lens Tracking





Amplitude detuning





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

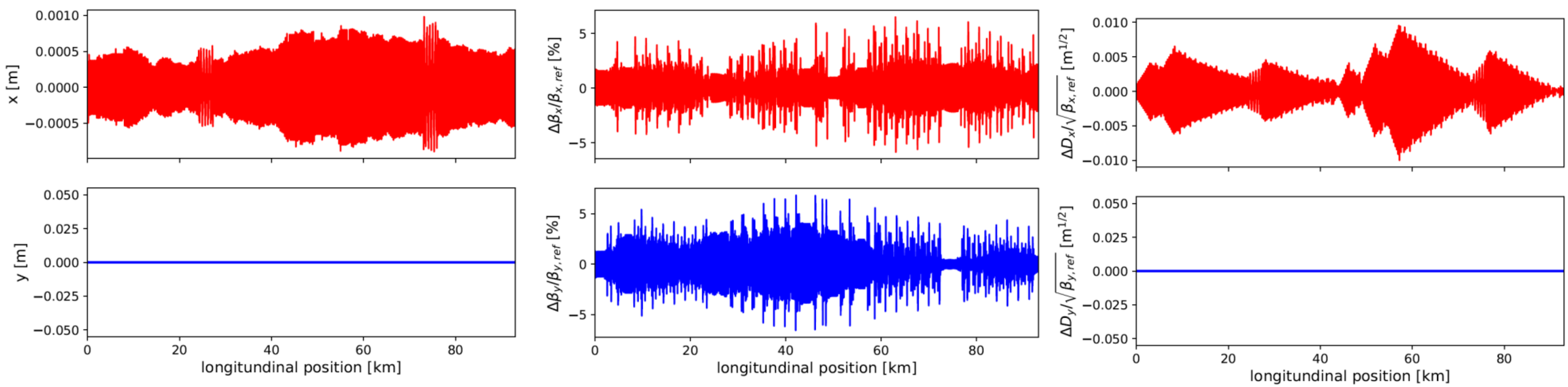
b2 = -1×10^{-4} relative systematic error + 10% random component

↓

Courtesy of F. Zimmermann and Jie Gao

Without orbit, beta-beating and dispersion correction:

orbit | beta-beating | normalized-dispersion



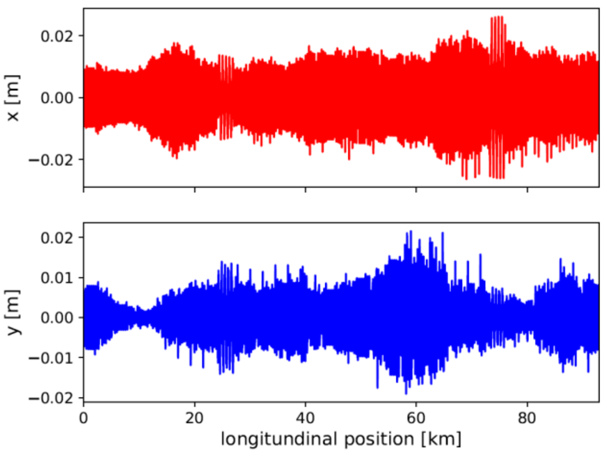
100 μm random quadrupole offset only (x,y)

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

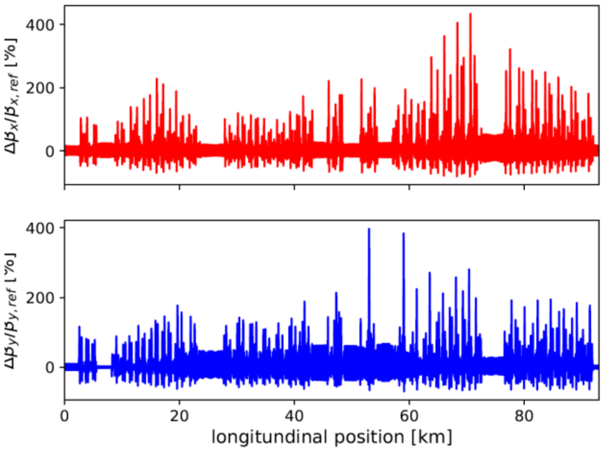
Type	Δx (μm)	Δy (μm)	ΔS (μm)	ΔTheta (μrad)	ΔPhi (μrad)	ΔPsi (μrad)	Field Errors
Arc quad	100	100					
Arc sext							
Dip							
Girders							
BPM							

Without orbit, beta-beating and dispersion correction:

orbit



beta-beating



normalized-dispersion