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 status and plans

B. Dalena, A. Chance , H. de Grandsaignes (CEA)

B. Haerer (KIT)

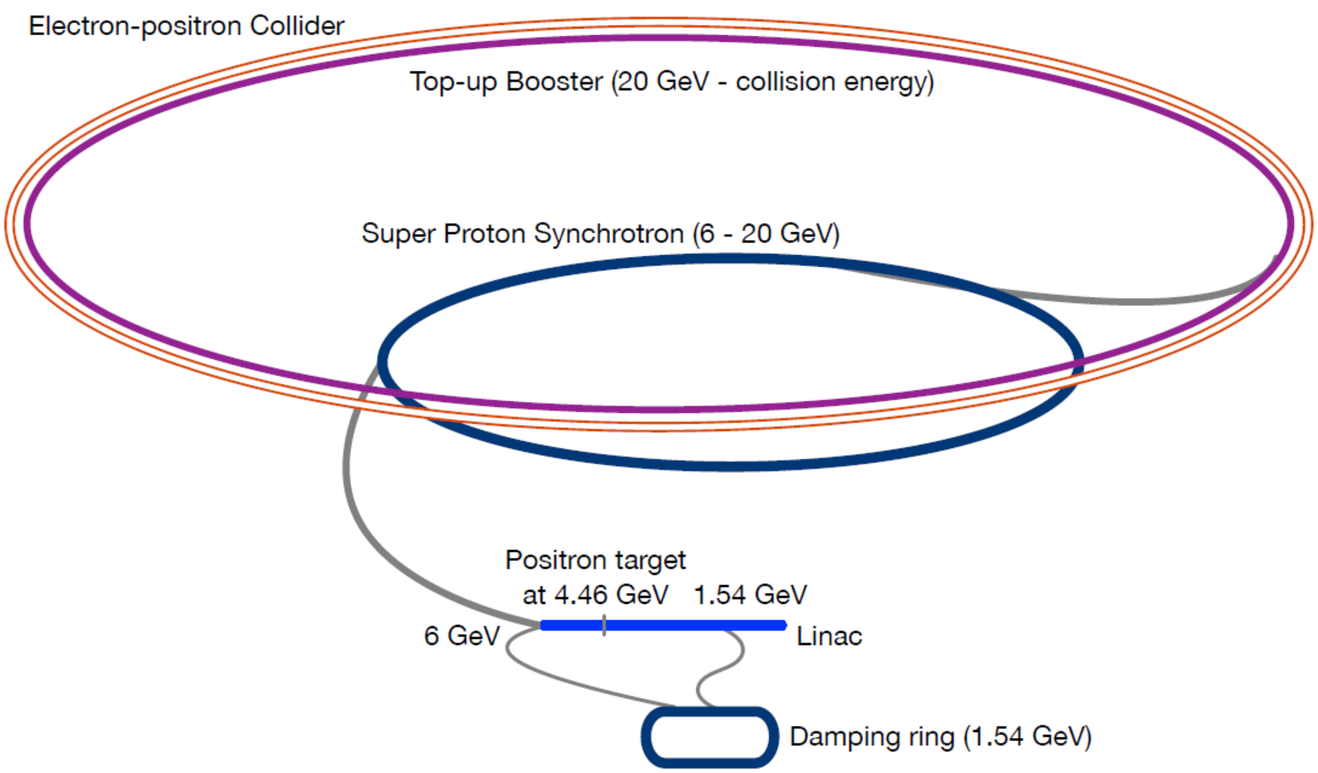
Thanks to:

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

Injection energy into the booster **20 GeV** (or 16, 14 GeV)

Ramping similar to SPS: **80 GeV / s**

Alternative: replace Linac + Pre Booster Ring with a **Linac**



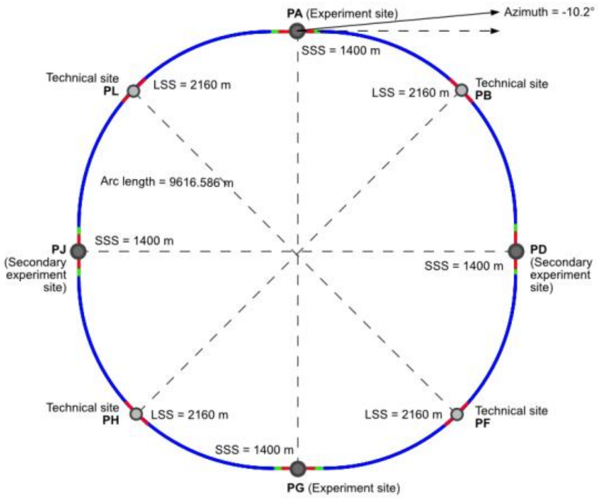
Injection Parameters (as in CDR)

Total filling time of collider < 20 min
Continuous top-up injection into the collider (Beamstrahlung and radiative Bhabha losses)
Charge variation bunch to bunch < few %

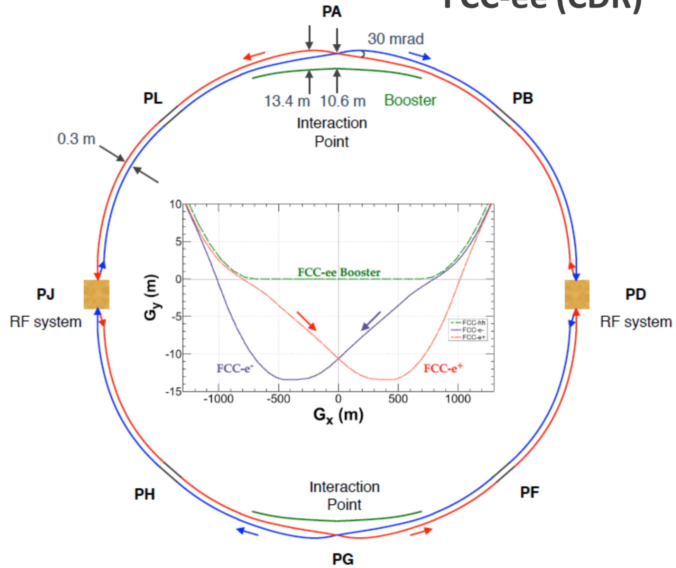
	FCC-ee Z		FCC-ee W		FCC-ee H		FCC-ee tt	
Energy (GeV)	45.6		80		120		182.5	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches, 2.8 GHz RF	2		2		1		1	
LINAC repetition rate (Hz)	200		100		100		100	
LINAC/PBR bunch popul. $\left(10^{10}\right)$	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
# of LINAC injections	1040		1000		393		50	
PBR bunch spacing (ns)	2.5		22.5		57.5		450	
# PBR cycles	8		1		1		1	
PBR # of bunches	2080		2000		393		50	
PBR cycle time (s)	6.3		11.1		4.33		0.9	
PBR duty factor	0.84		0.56		0.35		0.08	
BR # of bunches	16640		2000		393		50	
BR cycle time (s)	51.74		13.3		7.53		5.6	
# BR cycles	10	1	10	1	10	1	20	1
# injections/collider bucket	10	1	10	1	10	1	20	1
Total number of bunches	16640		2000		393		50	
Filling time (both species) (s)	1034.8	103.5	288	28.8	150.6	15.6	224	11.2
Injected bunch population $\left(10^{10}\right)$	2.13	1.06	1.44	1.44	1.13	1.13	2.00	2.00

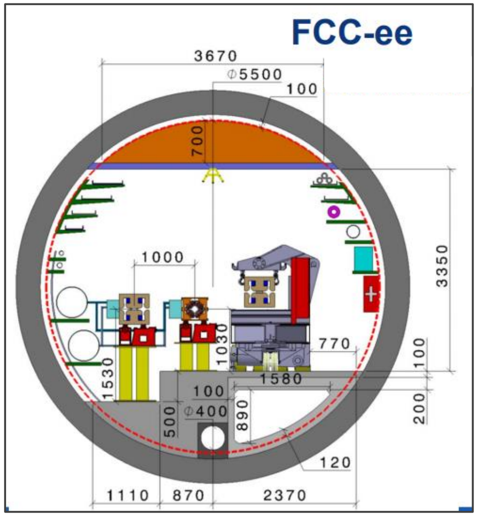
Several parameters have changed ($\Rightarrow$ **to be updated…**)

Layout constraints



FCC-ee (CDR)





CDR layout

High Energy Booster followed the FCC-hh footprint in CDR

Main Collider had a transverse offset of 1 m

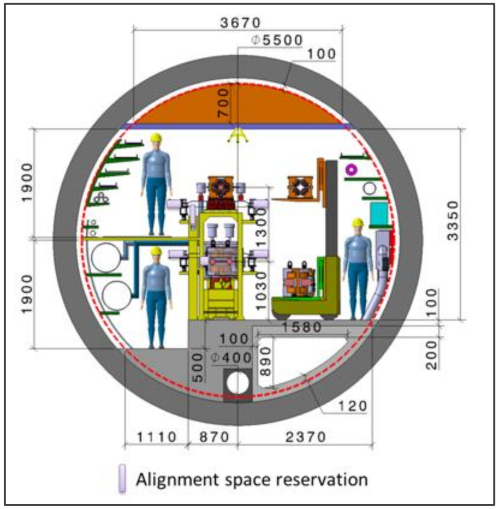
4IPs layout

Presently studying the possibility to have collider following FCC-hh footprint and booster on top of it

In current optics straight insertions are considered:

total length 91172.691 m

⇒ need to define how to by pass experiments (see A. Chance talk at ABP meeting)



Booster arc cell update

- FODO cells of 52 m
- Made of 4 dipole, 2 quadrupoles and 2 sextupoles
- Including space for correctors, flanges and interconnections

Magnet	Parameter	Unit	Value
Dipole	Field at injection (20 GeV)	G	64
	Field at ttbar energy (182.5 GeV)	G	584
	Length	m	11.1
Quadrupole	Gradient at injection (20 GeV)	T/m	2.6(60°)/3.7(90°)
	Gradient at ttbar energy (182.5 GeV)	T/m	33.7
	Length	m	1.5
Sextupole	Gradient at injection (20 GeV)	T/m^2	148.6(60°)/172.5(90°)
	Gradient at ttbar energy (182.5 GeV)	T/m^2	1575
	Length	m	0.5

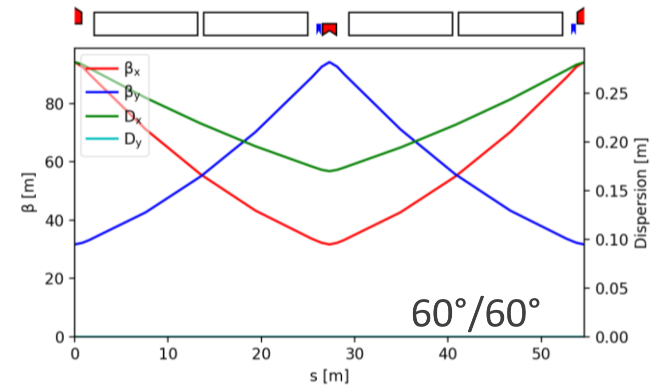
\# dipoles = 2×2944 # quadrupoles/sextpoles = 2944

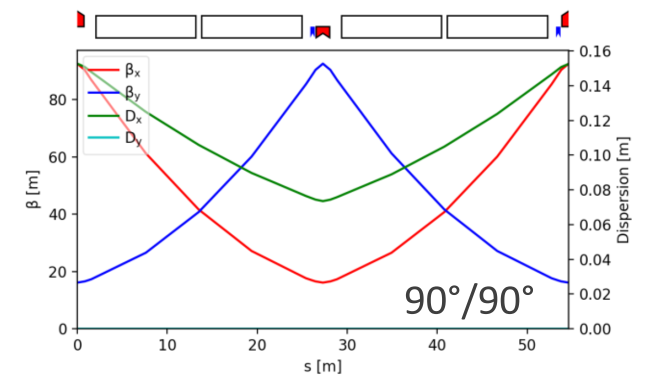
Distance between dipoles: 0.65 m
Distance between quadrupole and sextupole: 0.15 m
Distance between dipole and quadrupoles: 0.356/0.674 m
SSS length: 2.5 m to include also BPM and dipole correctors
(…but we do not have an estimates for their length yet…)

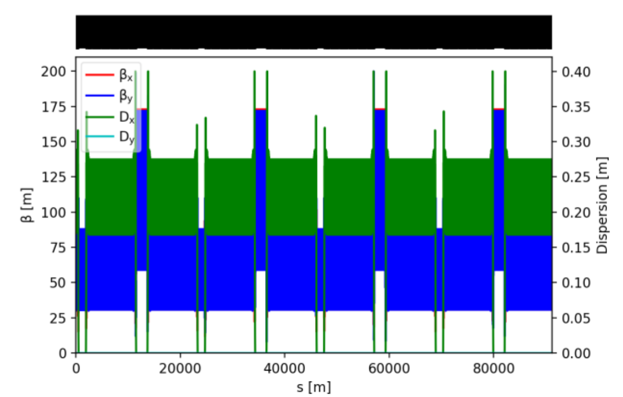
Trims quads and skew quads still to be included

⇒ Very low field dipoles (reproducibility of main field and multipoles)

Under discussion with J. Bauche







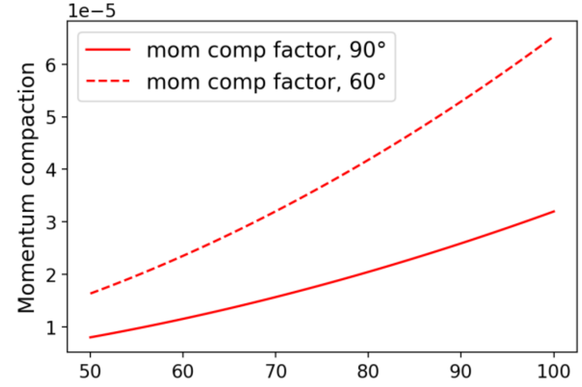
Equilibrium emittances

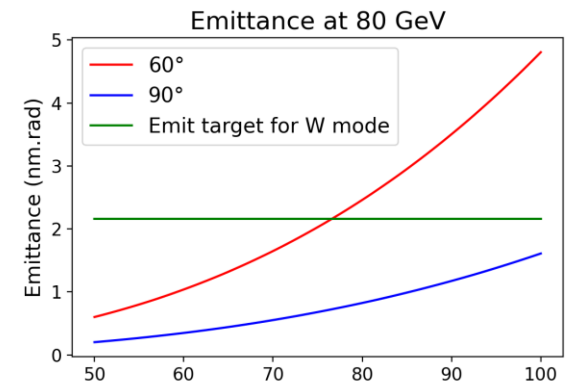
- Booster Equilibrium rms emittance ≤ collider

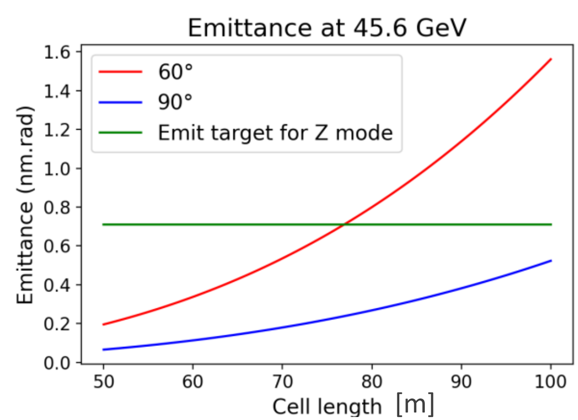
new

Beam Energy [GeV]	Eq. Emittance [nm rad] 60°/60°	Eq. Emittance [nm rad] 90°/90°	Eq. Emittance Collider [nm rad]	Eq. emittance Collider new [nm rad]
45.6 (Z)	0.235	0078	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

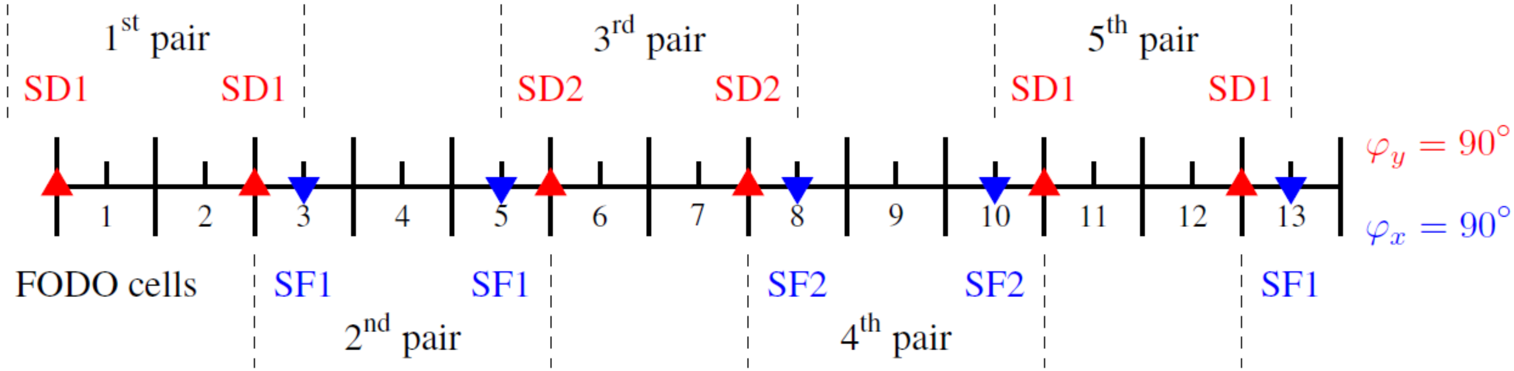






Sextupole schemes, working point and DA

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



Different schemes have been studied (***by B. Haerer***)

⇒ best cancellation of geometric aberrations given by **non-interleaved sextupoles scheme**

⇒ need for less sextupoles

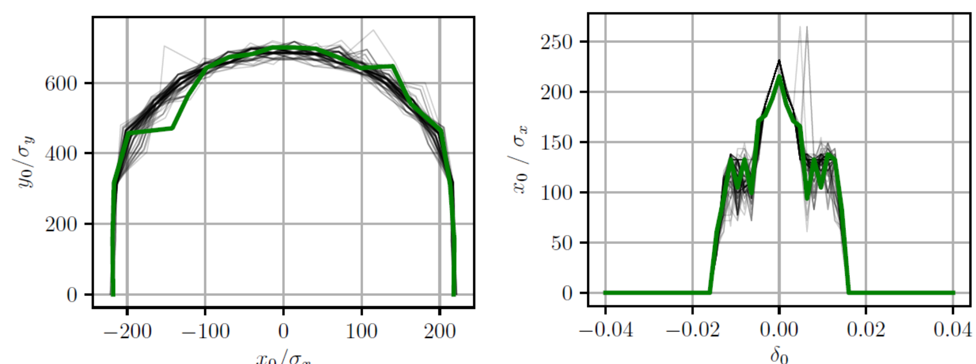
Fractional working point chosen **.225/.29**, based on Diffusion Rate given by frequency map analysis (**by *T. Tydecks***)

⇒ If needed, it can be **further optimized** (for collective effects ?)

Dynamic and **momentum aperture**, with quadrupole displacements, look OK

⇒ **impact of wigglers not included**

Linear Chromaticity corrected to **0**, do we need different value for collective effects?



Courtesy of T. Tydecks

First preliminary 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}**

⇒ Linear errors and statistics on multipole errors to be added

Courtesy of F. Zimmermann and Jie

	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

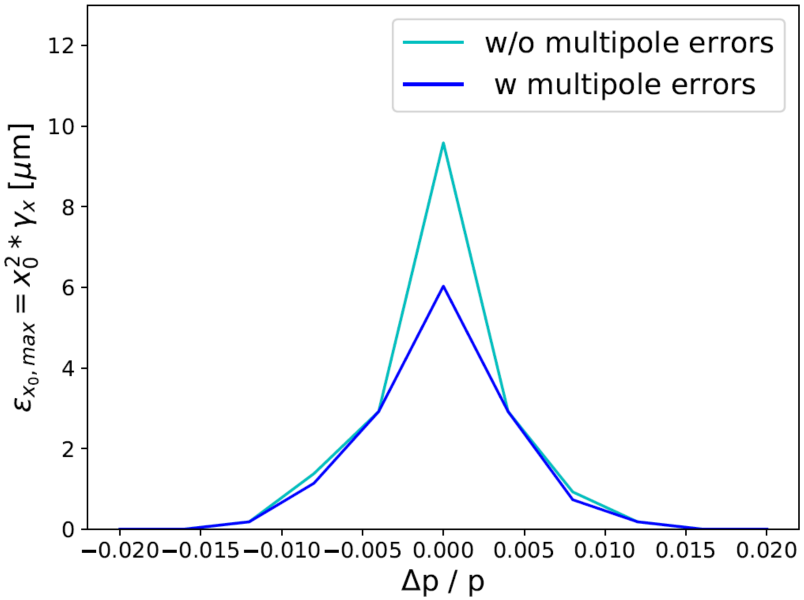
relative values @ R = 26 mm

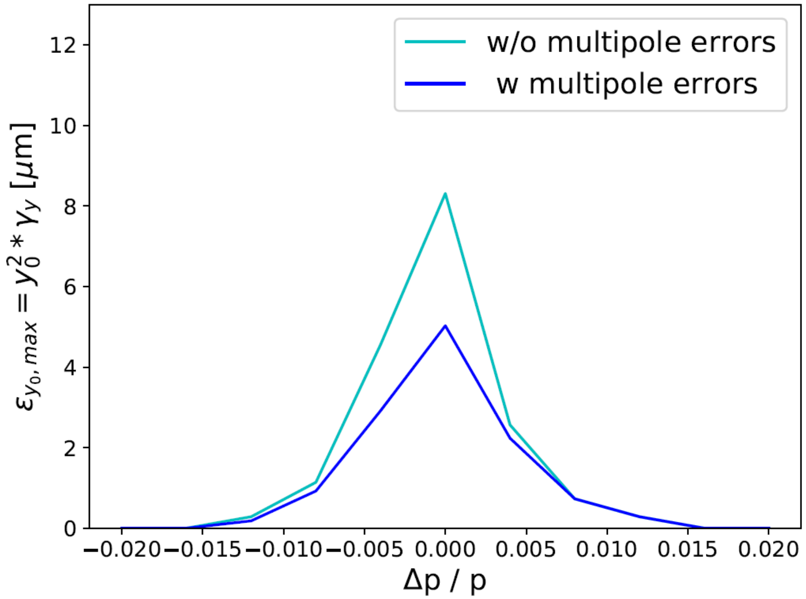
97km 60°/60° optics

Hor [mm]	15/12	12*
Ver [mm]	13/10	9*

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

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



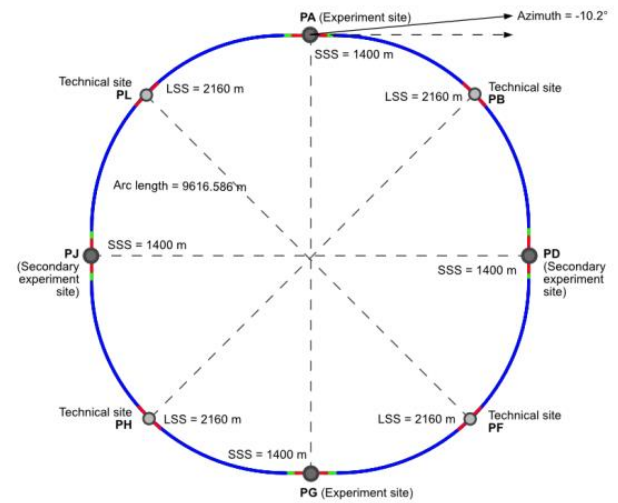


Insertions regions (as in CDR)
B. Haerer, T. Tydecks https://arxiv.org/abs/2111.14462

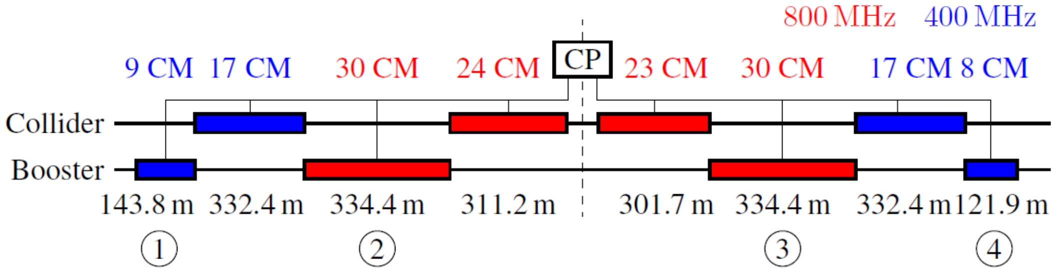
- Short straight sections of 1.4 km are made of **FODO cells** of 50 m. Long straight section have 100 m cells.

  Injection to and **extraction** from the Booster probably located in sections **PL** and **PB** ?

⇒ **to be designed** (discussion with M. Hofer, R. Ramjiawan and Y. Dutheil)



- **RF cavities** are located in same sections of the collider, but they are staggered because of CM size



	Z	W	H	ttbar$_1$	ttbar$_2$
Total RF voltage (MV)	140	750	2000	9500	10930
frequency (MHz)			**400**		
RF voltage (MV)	140	750	2000	2000	2000
E_{acc} (MV/m)	8.0	9.6	9.8	10.0	10.0
# CM	3	13	34	34	34
# cavities	12	52	136	136	136
# cells/cav.	4	4	4	4	4
frequency (MHz)			**800**		
RF voltage (MV)				7500	8930
E_{acc} (MV/m)				20	19.8
# CM				100	120
# cavities				400	480
# cells/cav.				5	5

- **Wigglers** are located in sections with RF cavities:

⇒ **good** for fast beam energy recovery

⇒ **protection** of the **cavities** from the wigglers' **radiation to be investigated**

New placement of RF in L and H still to be integrated,
RF frequency choice (F. Kuncheva Valchkova)

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 :

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

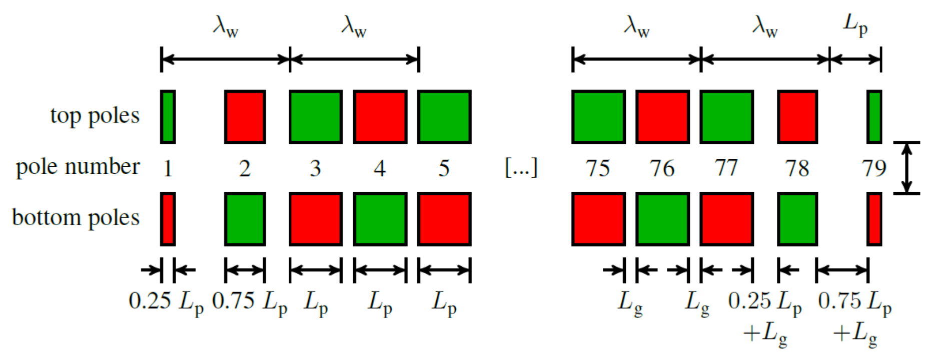
$$I_2 = \oint \frac{ds}{\rho^2} \qquad I_5 = \oint \frac{H_x}{|\rho^3|} ds$$

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

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
- $k = 2\times10^{-3}$

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

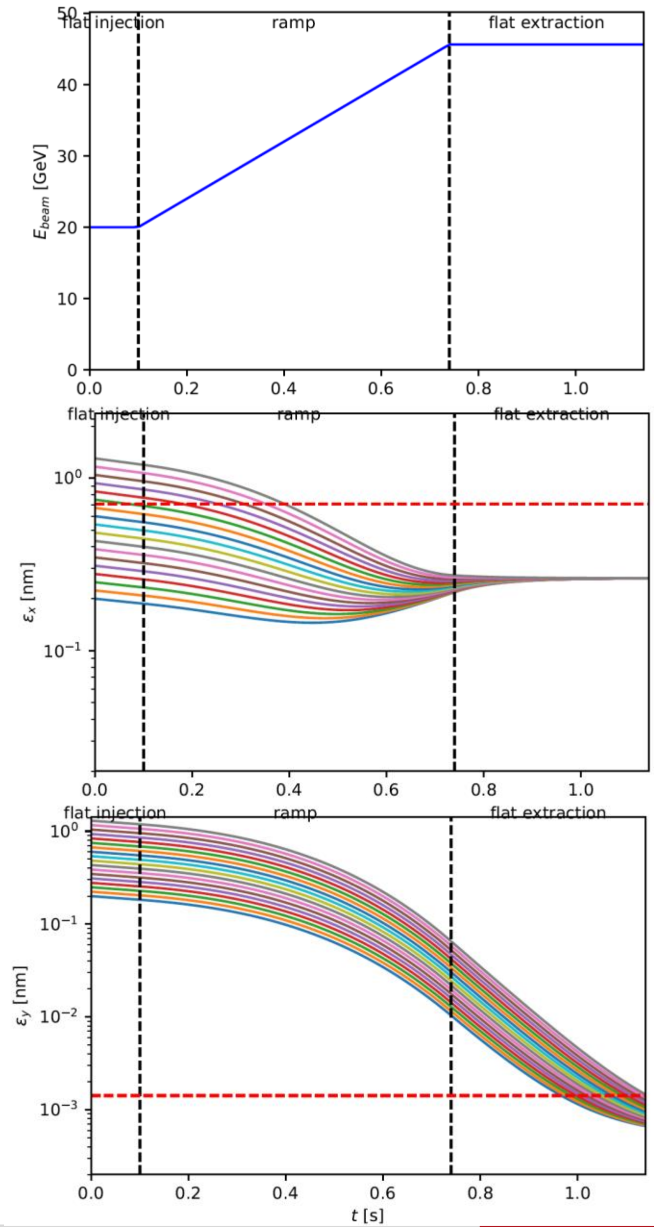
$$\frac{d\varepsilon_y}{dt} = -2\,\frac{\varepsilon_y - k\,\varepsilon_{eq}(E(t), I2, I5)}{\tau_x(E(t), I2)}$$

➢ 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**)

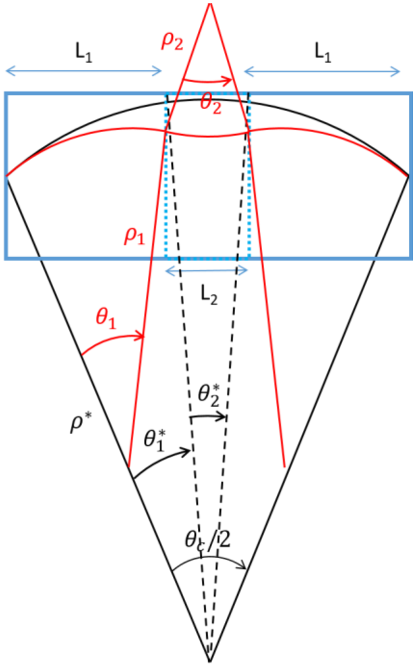
Damping time can be reduced by playing on the ratio between the two different fields.

Advantages:

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

Drawbacks:

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



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

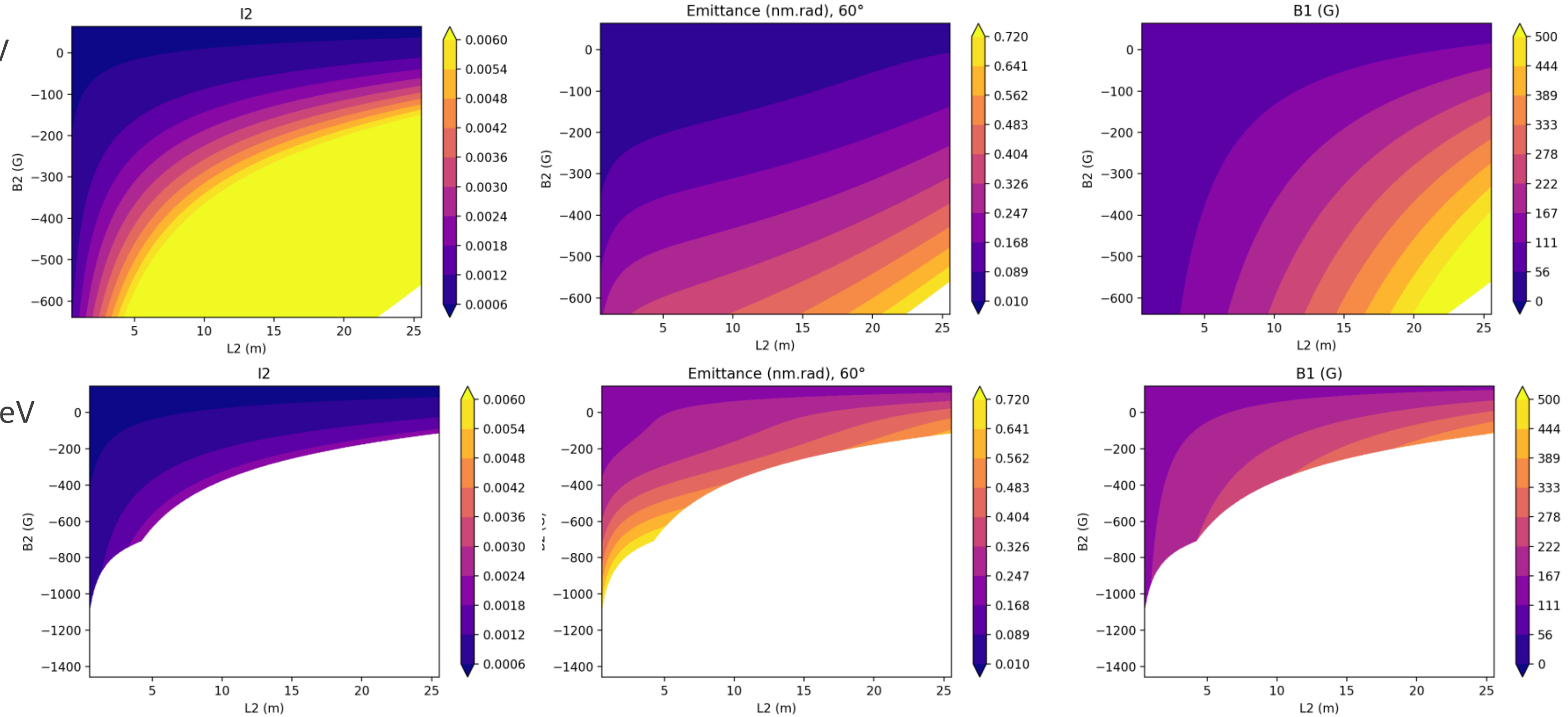
$$I_i = I_i(\mu_x, L_{cell}, \theta_c/2, a, b)$$

A. Chancé

Preliminary results of two dipoles families optics

20 GeV

45.6 GeV

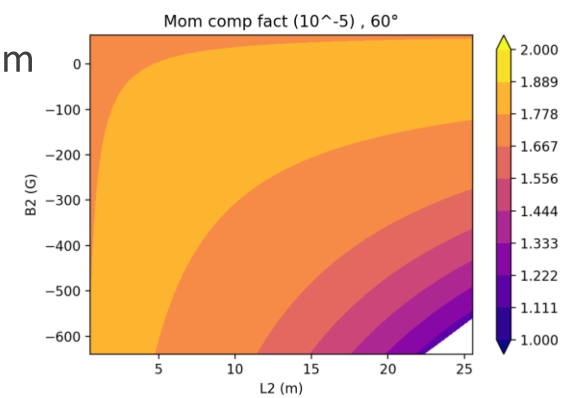


Constraints: **Energy loss** per turn ≤ 126 MeV (~wiggler), **eq. emit** < 0.72 nm

- 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

Summary HEB status

- **Two optics** for the 4 operational scenarios**:**
  - **60°/60°** for the Z and W ⇒ allows for emittance margin with new collider parameters
  - **90°/90°** for the H and ttbar

- **Non interleaved sextupole** scheme retained as baseline
  - Best cancellation of geometric aberrations
  - Less sextupoles required
- **Working point** chosen **.225/.29**
  - Allows for large DA and momentum aperture
- **First design of Wigglers** to reduce damping time **at injection** and **mitigate IBS** and **MI**

- **Possibility to lower damping** to reach collider emittances
  - First analytical study of the 2 dipole family possible alternative arc cell

- **First DA with multipoles field errors at injection**
  - Static field effect only, without linear imperfections
- A **first optics for the symmetric 4IPs** layout
  - gives not so different magnets specifications

Next steps

- **Consolidate booster layout**
- **Update booster operation strategy (injection energy, cycling time, radiative power, …)**
  - Integration of IBS in the emittance evolution model (M. Zampetakis, F. Antoniou, O. Etisken)
- **Add linear errors and correction schemes, continue on DA evaluation, emittance tuning…**
  - Use and Participate in the common framework (kick-off meeting 17/11/2021 R. Tomas)
- **Re-optimisation** of **working point and linear chromaticity**
  - taking into account collective effects ?
- **Re-optimisation** of the **wigglers or alternatives optics ?**
  - Shorter wigglers
  - Protection of RF cavities from wigglers radiation
  - Compare with alternative optics
- **Integration of Injection/extraction**
  - M. Hofer, R. Ramjiawan, Y. Dutheil
- **Tracking simulations**
  - Evaluation of beam losses (collimation? R. Bruce, M. Hofer)
  - Start to end simulations (which physics effects ? Using Xsuite, Elegant, Bmad?)

Back-up slides

Equilibrium Emittance FODO cells

[m]