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Optics studies for the FCC-ee Booster ring: status and plan

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Injection Parameters (as in CDR)

	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

Total filling time of collider < 20 min

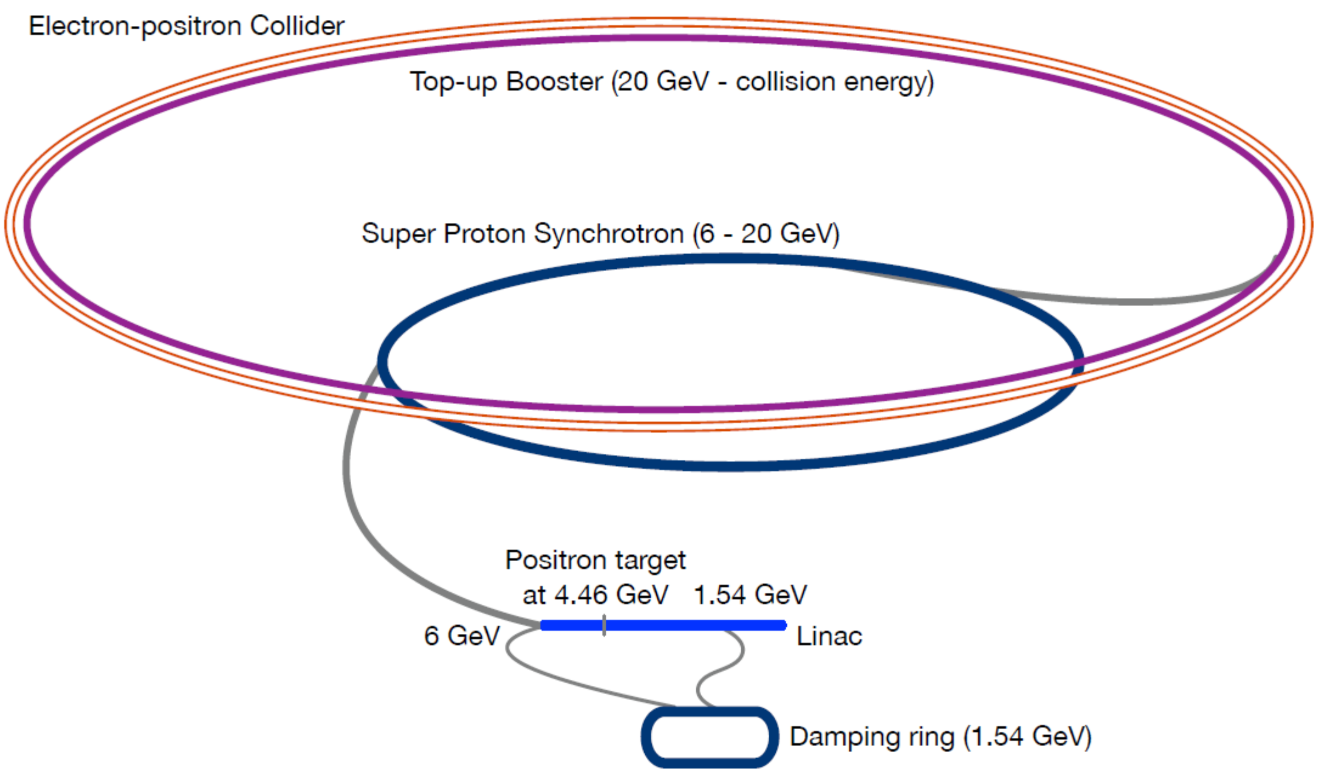
Continuous top-up injection into the collider (Beamstrahlung and radiative Bhabha losses)

Charge variation bunch to bunch < few %

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

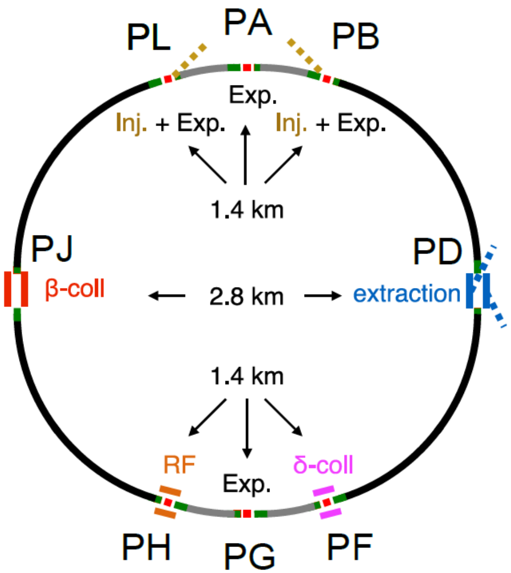
Ramping similar to SPS: **80 GeV / s**

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

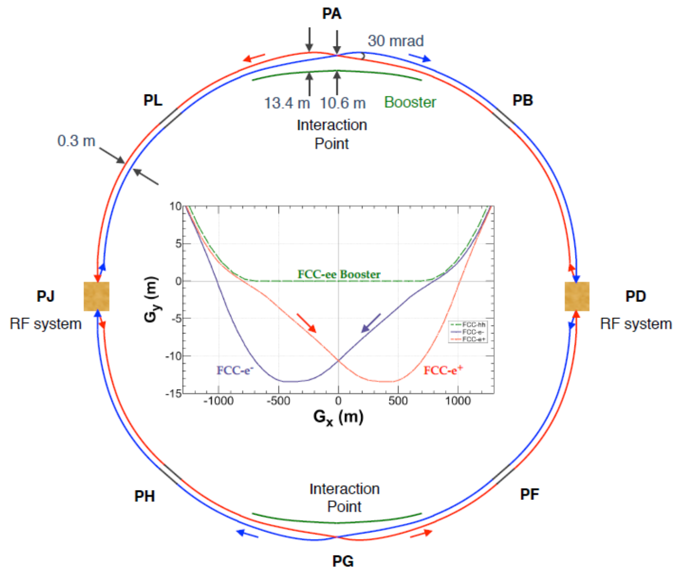


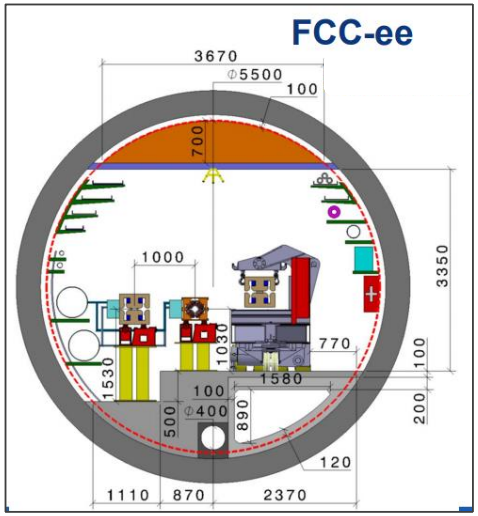
Layout constraints

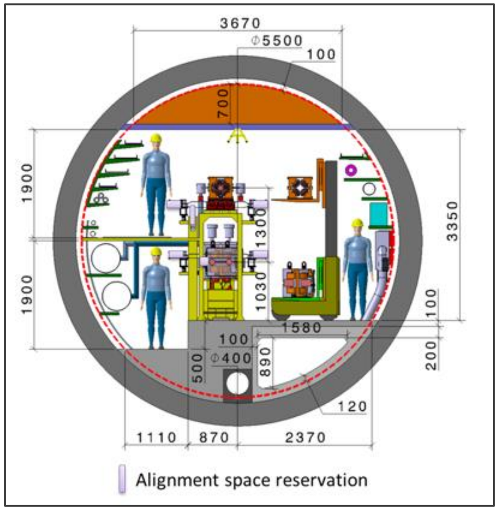
FCC-hh



FCC-ee







High Energy Booster follows the FCC-hh footprint

Main Collider has a transverse offset of 1 m (alternative with collider that follows FCC-hh footprint and booster on top of it)

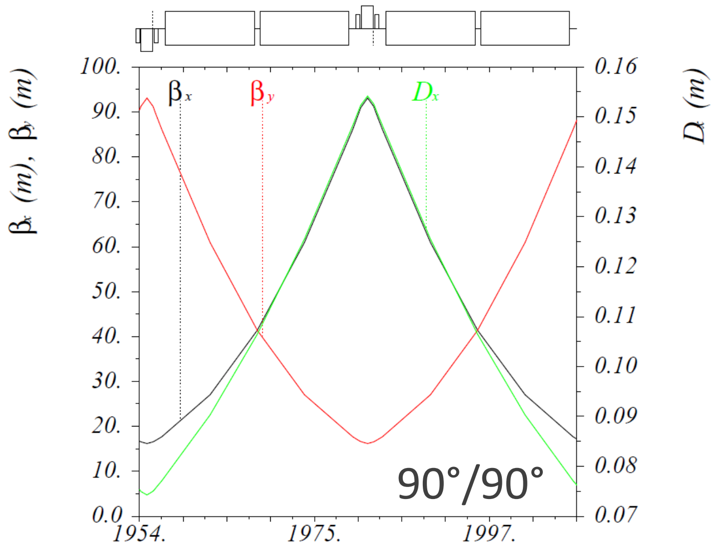
Booster bypass the FCC-ee detectors on the internal side of the cavern (following FCC-hh layout)

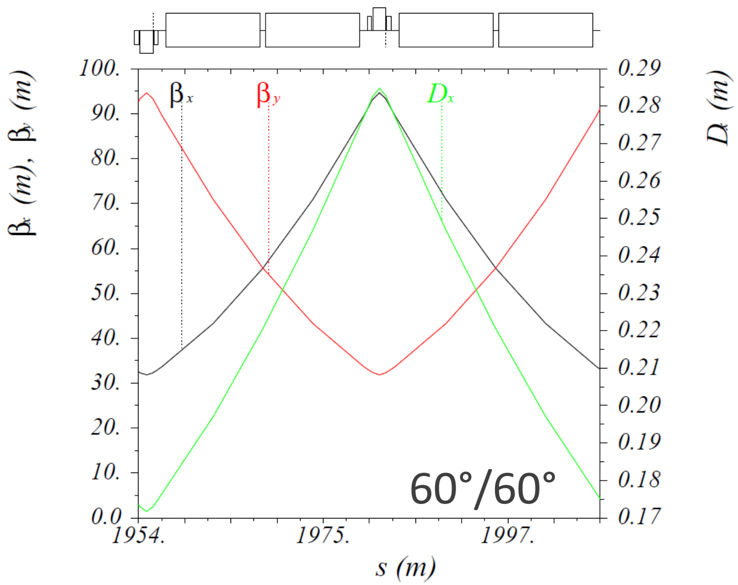
Booster arc cells

- FODO cells of 54 m
- Made of 4 dipole, 2 quadrupoles and 4 sextupoles
- Including space for correctors, flanges and interconnections

Magnet type	Parameter	Unit	Value
Dipole	Field at injection (20 GeV)	T	0.006
	Field at peak energy (182.5 GeV)	T	0.058
	Magnet length	m	11.1
Quadrupole	Max gradient at injection (20 GeV)	T/m	2.6
	Max gradient at peak energy (182.5 GeV)	T/m	23.7
	Magnet length	m	1.5
Sextupole	Max strength at injection (20 GeV)	$T m^{-2}$	161
	Max strength at peak energy (182.5 GeV)	$T m^{-2}$	1467
	Magnet length	m	0.5

$\Rightarrow$ Very challenging **low** dipole field



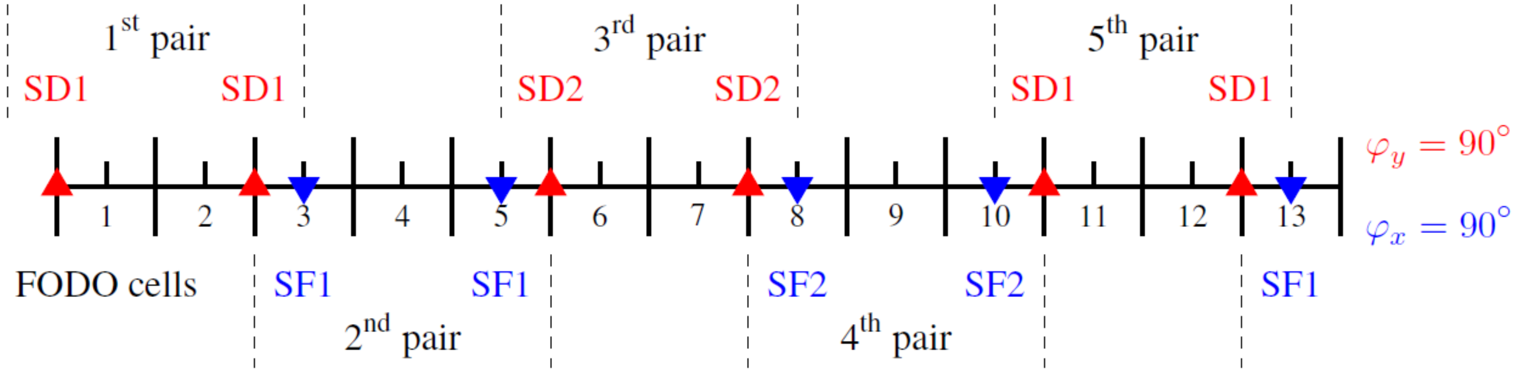


- Booster Equilibrium rms emittance ≤ collider

Beam Energy [GeV]	Eq. Emittance [nm rad] 60°/60°	Eq. Emittance [nm rad] 90°/90°	Eq. Emittance Collider [nm rad]
45.6 (Z)	0.235	0078	0.24
80 (W)	0.729	0.242	0.84
120 (H)	4.229	0.545	0.63
175 (tt)	3.540	1.172	1.48

$\Rightarrow$ 60°/60° retained for Z and W operation (mitigation of MI and IBS)
$\Rightarrow$ 90°/90° required for H and ttbar operation

Sextupole schemes, working point and DA



Different schemes have been studied

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

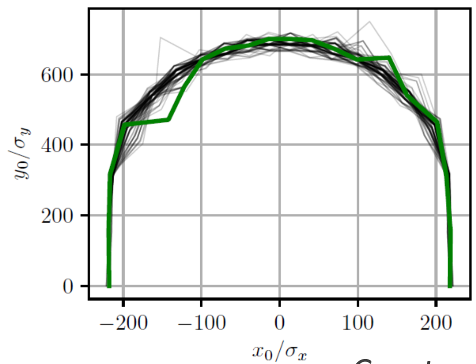
⇒ need for less sextupoles

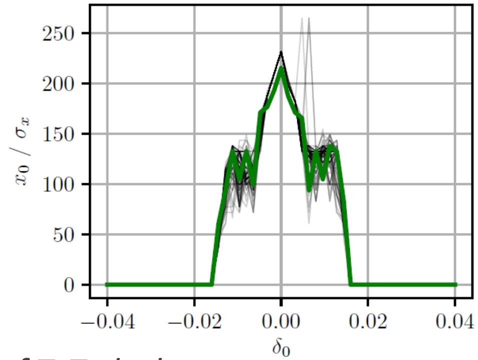
Fractional working point chosen **.225/.29**, based on Diffusion Rate given by frequency map analysis

⇒ It can be **further optimized**, also accounting for collective effects

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

⇒ **impact of wigglers to be studied**



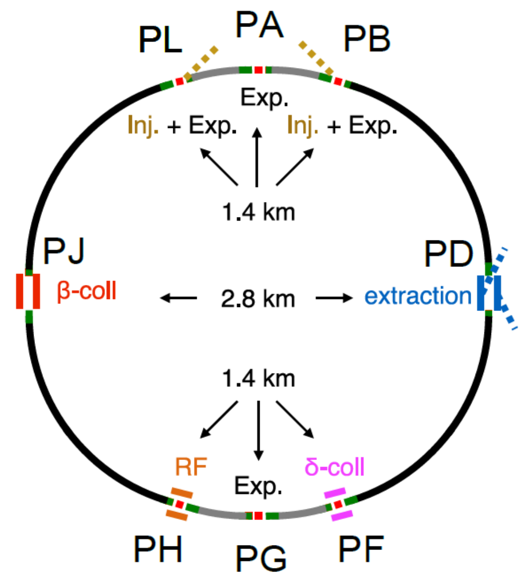


Courtesy of T. Tydecks

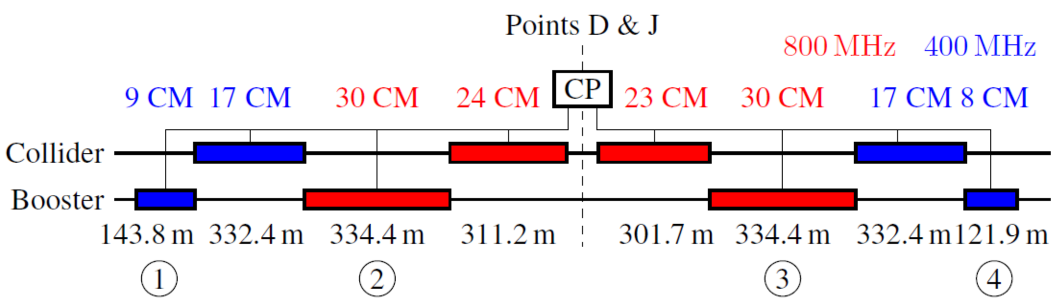
Insertions regions

- Short straight sections of 1.4 km (**PL**,**PA**,**PB**,**PH**,**PG**,**PF**) are made of **FODO cells** of 56 m.
  Injection to and **extraction** from the Booster probably located in sections **PL** and **PB**

⇒ **to be designed**



- **RF cavities** are located in sections **PJ** and **PD**, as in 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 **PJ** and **PD** with RF cavities:

⇒ **good** for fast beam energy recovery

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

Damping Wigglers

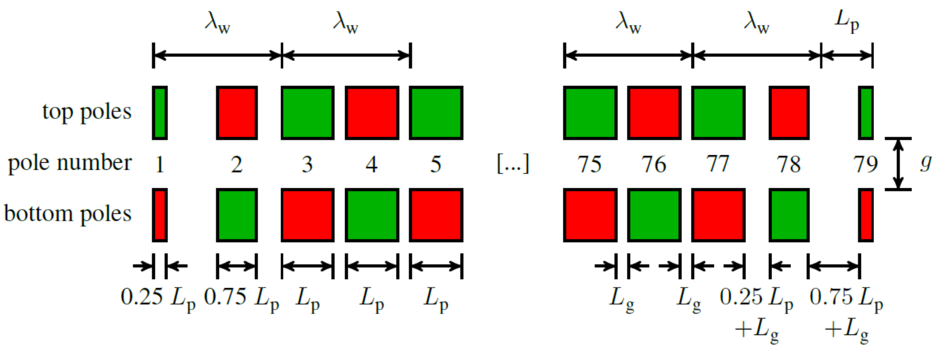
Target damping time 0.1 s (to fulfill cycle time)
Wigglers reduce damping time and increase eq. emittance :

$$\tau_x \propto \frac{1}{E^4 I_2} \qquad \varepsilon_{eq} = \frac{C_q \gamma^2 I_5}{\left(I_2\left(1-\frac{I_4}{I_2}\right)\right)}$$

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

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

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



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

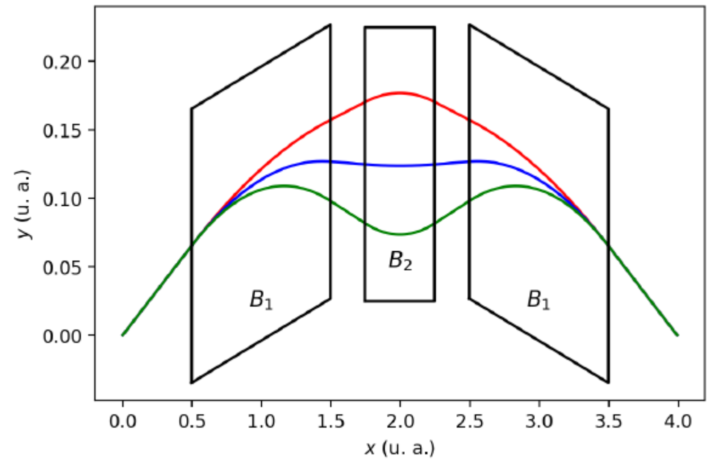
Pole length	0.095 m
Pole separation	0.020 m
Gap	0.050 m
Number of poles	79
Wiggler length	9.065 m
Magnetic field	1.45 T
Energy loss per turn	126 MeV
Hor. damping time	104 ms
Hor. emittance (60°optics)	300 pm rad

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

Alternative optics
(proposed by Antoine Chance)

2 dipole families 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.

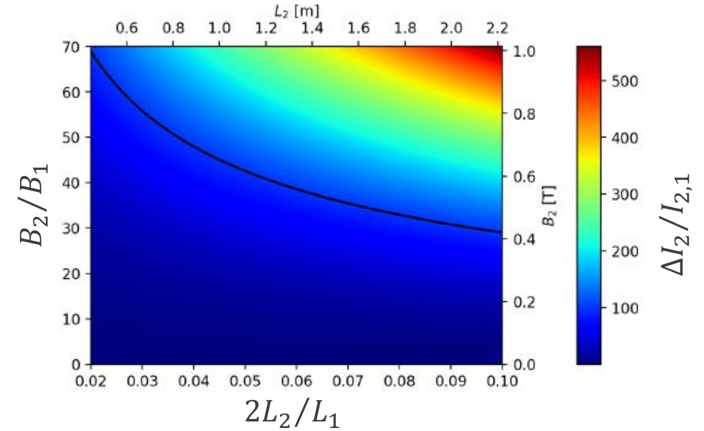


Advantages:

- No impact on the layout
- No need of damping wigglers
- Higher dipole field at injection energy

Drawbacks:

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



Summary HEB status
(thanks to Bastian Haerer)

- **Two optics** for the 4 operational scenarios:
  - **60°/60°** for the Z and W
  - **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

- **Wigglers** are **needed** to reduce damping time **at injection** and **mitigate IBS** and **MI**
  - First design exists

- A **staging RF scenario** with **staggered cryomodules,** with respect to collider, has been worked out

Next steps

- **Consolidate booster layout** and **correction schemes** accordingly to the changes on FCC-hh and FCC-ee collider
- **Re-optimisation** of **working point**
    - taking into account also collective effects
- **Re-optimisation** of the **wigglers**
    - Reduce equilibrium emittance at Z
    - Fast ramping down (Eddy current) at higher energies
    - Check possible excitation of stimulated synchrotron radiation and beam instability (due to installation on straight line)
- **Protection of RF cavities from wigglers radiation**
    - Placed in the same insertions
- **Injection extraction lines to be done**
- **Design and study an alternative optics**, based on the EIC 2 dipoles family scheme
    - Compare it with the solution with wigglers

Merci de votre attention

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