FUTURE CIRCULAR COLLIDER

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

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Thanks to:

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

Outline

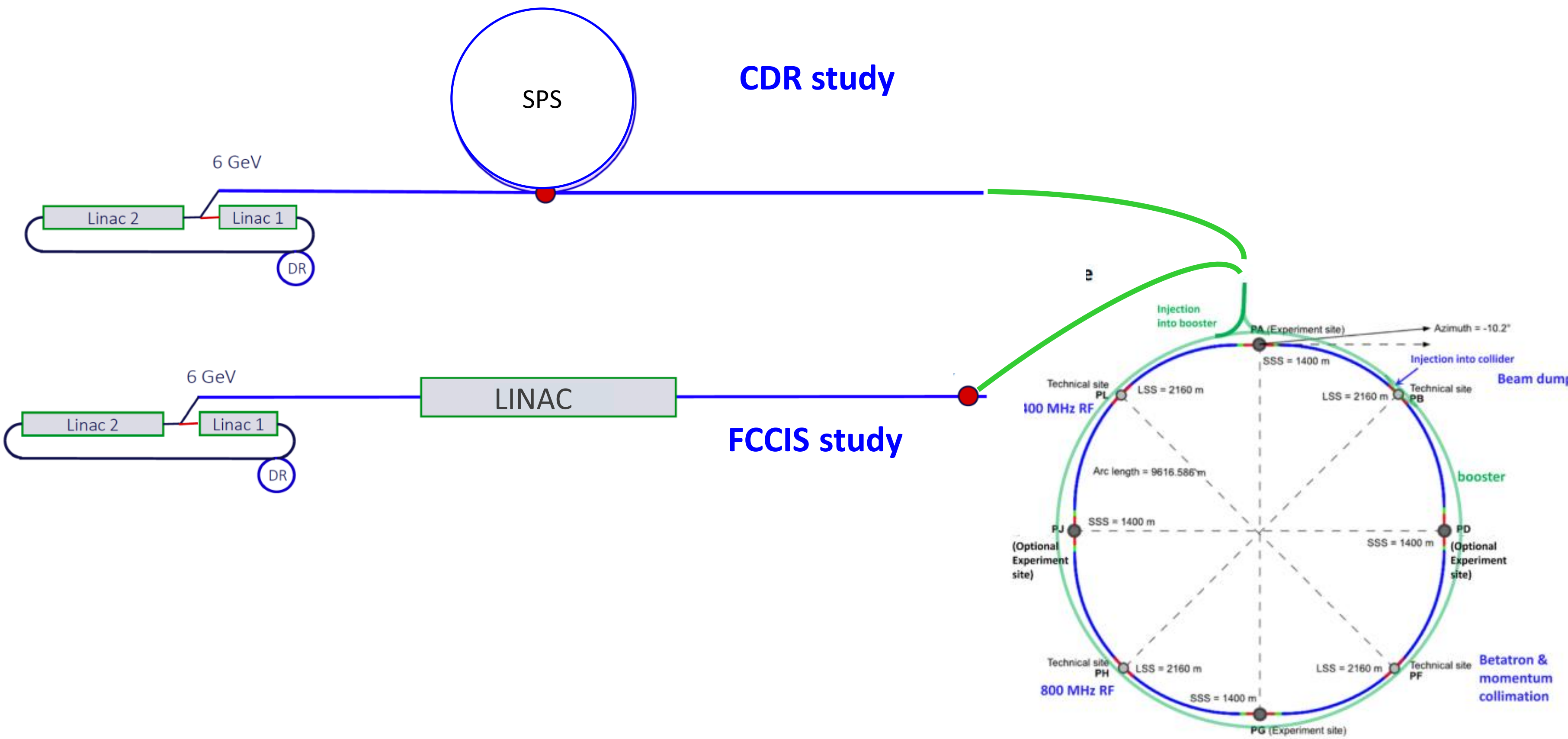
- The injector complex
  - Layout of the High Energy Booster (HEB)
- Optics design
- Injection energy and emittances
  - Dynamic Aperture and Momentum Acceptance
- Emittance Evolution and Booster Operations

Injection energy into the booster **20 GeV** (or lower ?)

Ramping: **80-100 GeV / s (< 1 s)**

Alternatives: SPS as Pre Booster Ring (**PRB**) and a **Linac**

⇒ See "The FCCee injector complex" by P. Craievich



Injectors parameters

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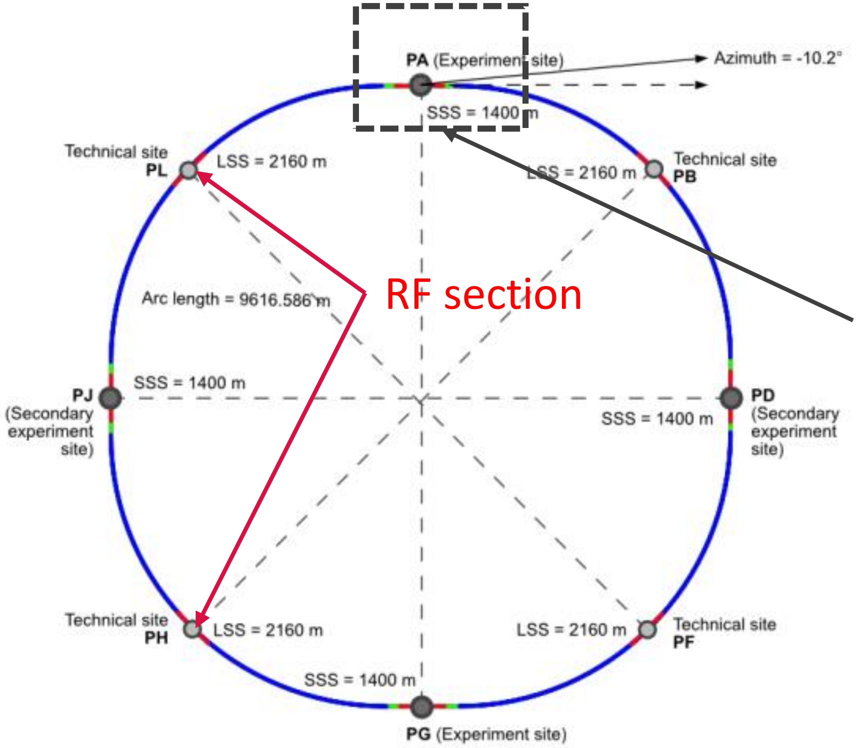
Injection time for each specie (20 GeV Linacßß, 4 IP)

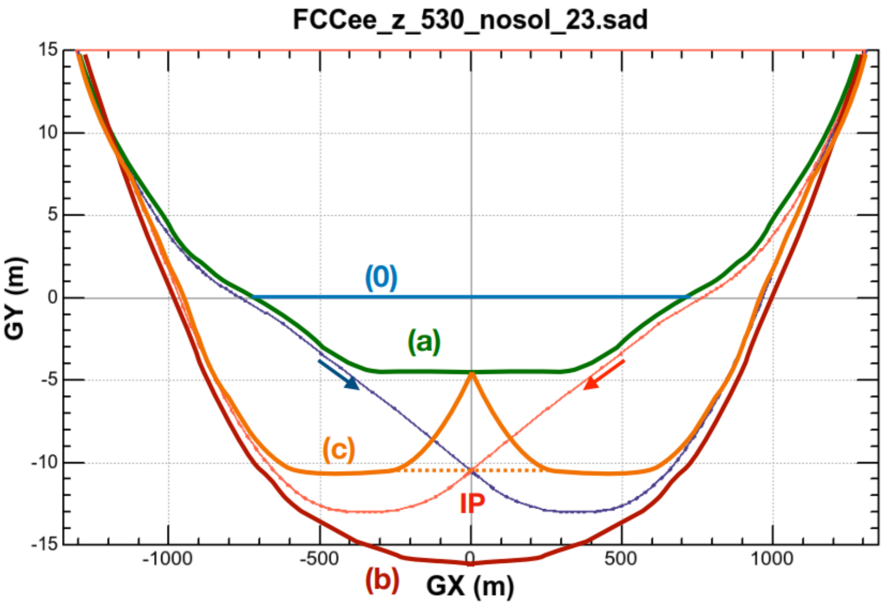
	Z	WW	ZH	tt
Collider energy [GeV]	45.6	80	120	182.5
Collider & BR bunches / ring	10000	880	248	40
Collider particles / bunch [10^{10}]	24.3	29.1	20.4	23.7
Injector particles / bunch [10^{10}]	≦ 3.0 *			
Bootstrap particles / bunch [10^{10}]	2.43	1.746	1.224	1.422
# of BR ramps (to 1/2 stored current)	3	3	3	4
# of BR ramps (bootstrap)	6	8	6	7
BR ramp time (up + down) [s]	0.6	1.5	2.5	4.1
Linac bunches / pulse	2			
Linac pulses	5000	440	124	20
Linac repetition frequency [Hz]	200	50		
Collider filling time from scratch [s]	**230.4**	**113.3**	**44.82**	**49.5**
Collider filling time for top-up [s]	**25.6**	**10.3**	**4.98**	**4.5**
Allowable charge imbalance Δ [±%]	5	3		
Lum. lifetime (2 IP) [s]	2258			
BS lifetime (2 IP) [s]	100000	100000	2130	8124
Lattice lifetime (2 IP) [s]	1260	2400	3000	3600
Collider lifetime (2 IP) [s]	802.2	2140	465.7	885.7
Collider top-up interval (between e+ and e-)(2 IP) [s]	**40.1**	**64.2**	**13.971**	**26.571**
Lum. lifetime (4 IP) [s]	1129	1070	596	744
BS lifetime (4 IP) [s]	100000	100000	1065	4062
Lattice lifetime (4 IP) [s]	840	1600	2000	2400
Collider lifetime (4 IP) [s]	479.3	1070	382.1	542.8
Collider top-up interval (between e+ and e-)(4 IP) [s]	**24.0**	**32.1**	**11.463**	**16.284**

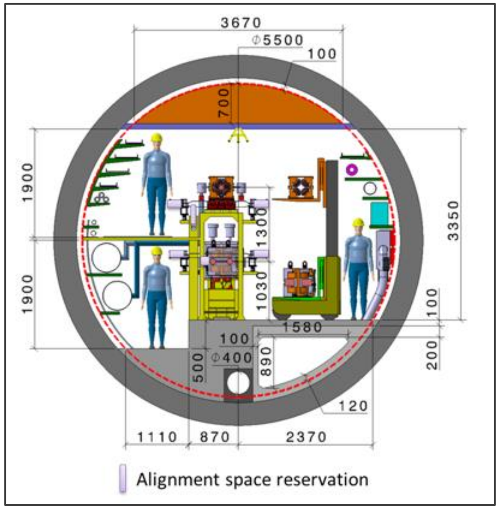
Sep 21, 2021
K. Oide

⇒ See “Main ring and MDI region” by K. Oide

Booster layout (after CDR)







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

60°/60° Optics for Z and W modes

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

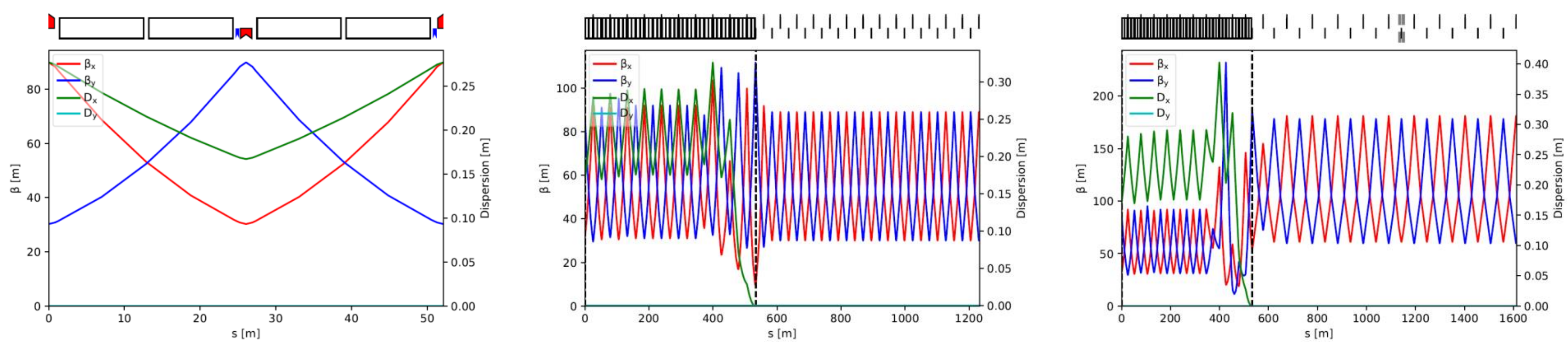
Distance between dipoles: 0.4 m
Distance between quadrupole and sextupole: 0.165 m
Distance between dipole and sextupole: 0. 504 m
Distance between quadrupole and dipole: 0.869 m
(it includes space for BPM and dipole correctors)

dipoles = 2×2944

quadrupoles = 2944

sextupoles = 2632/6

⇒ Very challenging **low** dipole field at injection



90°/90° Optics for H and ttbar modes

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

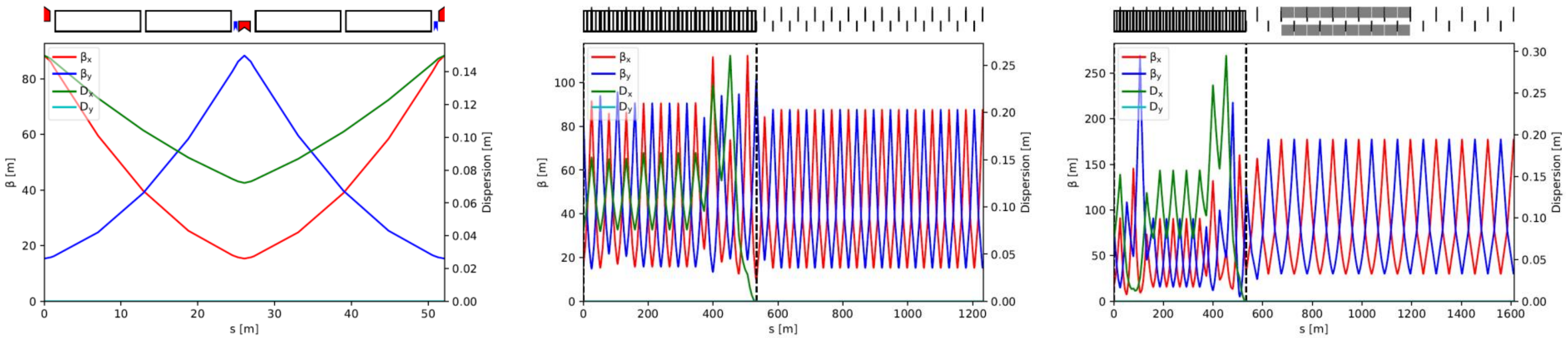
Distance between dipoles: 0.4 m
Distance between quadrupole and sextupole: 0.165 m
Distance between dipole and sextupole: 0. 504 m
Distance between quadrupole and dipole: 0.869 m
(it includes space for BPM and dipole correctors)

dipoles = 2×2944

quadrupoles = 2944

sextupoles = 2632/4

⇒ Very challenging **low** dipole field at injection (preliminary magnet design by **J. Bauche** @ FCC week 2022 https://indico.cern.ch/event/1064327/contributions/4888487/)

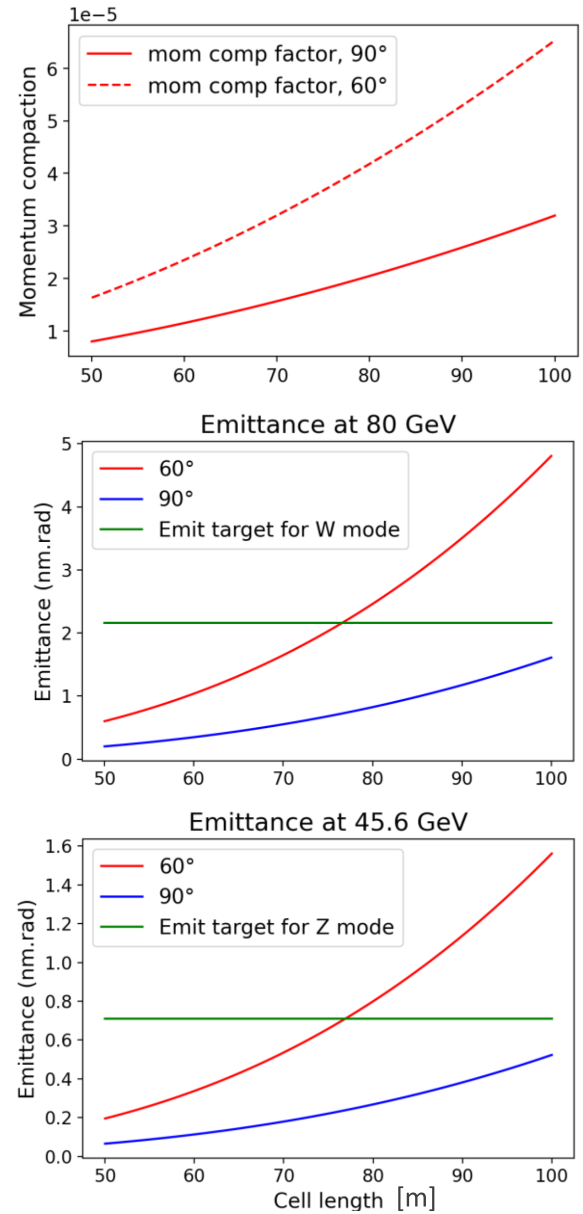


Equilibrium emittances

- Booster rms emittance at extraction ≤ collider

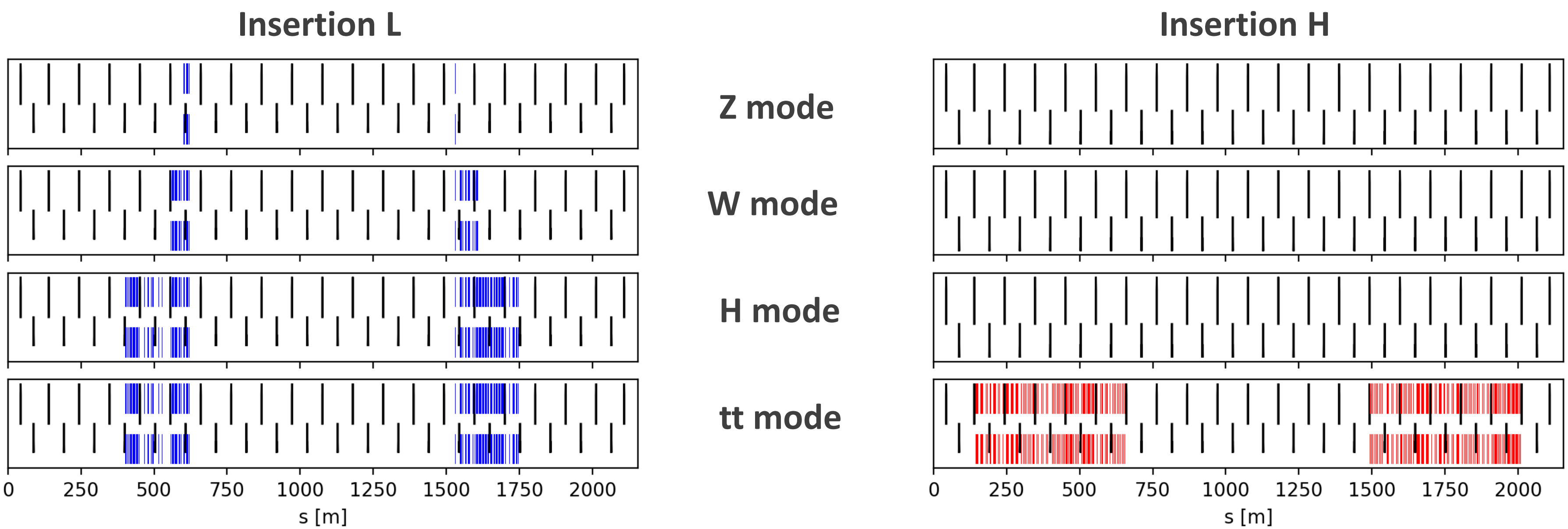
Beam Energy [GeV]	Eq. Emittance [nm rad] 60°/60°	Eq. Emittance [nm rad] 90°/90°	Eq. Emittance Collider [nm rad]	new Eq. emittance Collider new [nm rad]
45.6 (Z)	0.235	0.078	0.24	**0.71**
80 (W)	0.729	0.242	0.84	**2.16**
120 (H)	4.229	0.545	0.63	**0.64**
175 (tt)	3.540	1.172	1.48	**1.49**

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



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



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

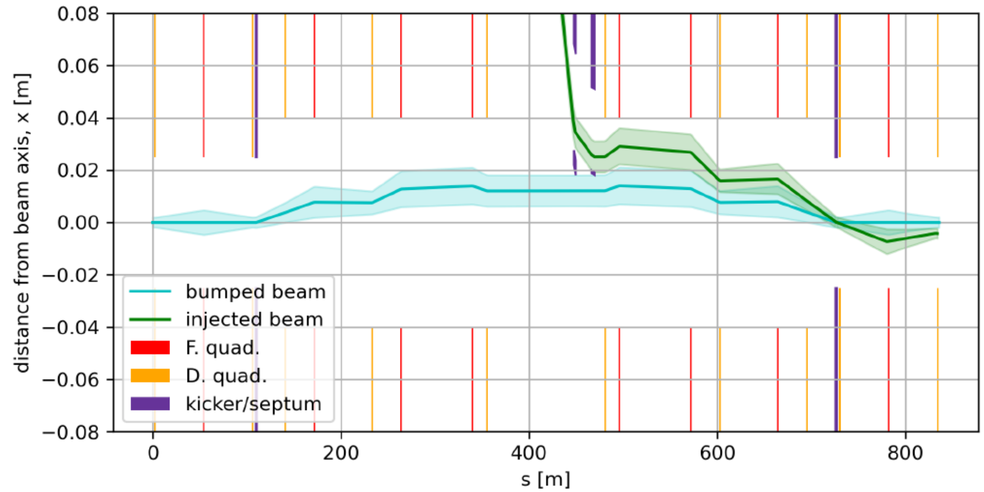
- tt mode: 60 CM left, 60 CM right

➢ **Proposal** of the **RF group** to use **800 MHz only** for all mode of the Booster: https://indico.cern.ch/event/1064327/contributions/4888581/ (**F. Peauger**)

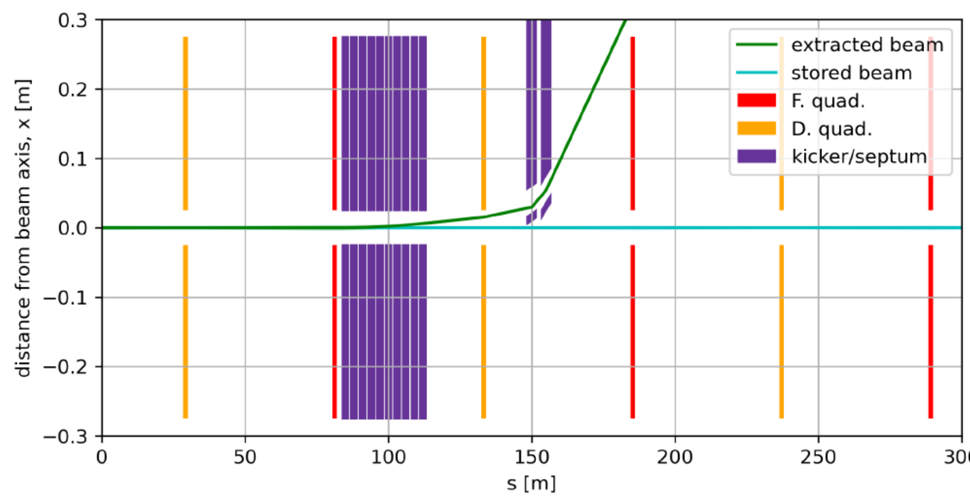
Injection/ extraction in the High Energy Booster

R. L. Ramjiawan & E. Howling

- Injection scheme with orbit bump and thin electrostatic septum
- Possibility to have vertical injection to be studied



- Extraction scheme with 10 kickers allows for some machine protection
- Room for optics optimization of both injection and extraction



DA at injection (20 GeV) 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}**

MadX Thin-Lens Tracking (60 seeds)

DA: Stable initial amplitude @ 4500 turns (~15% *tx* 20 GeV)

Courtesy of F. Zimmermann and Jie Gao

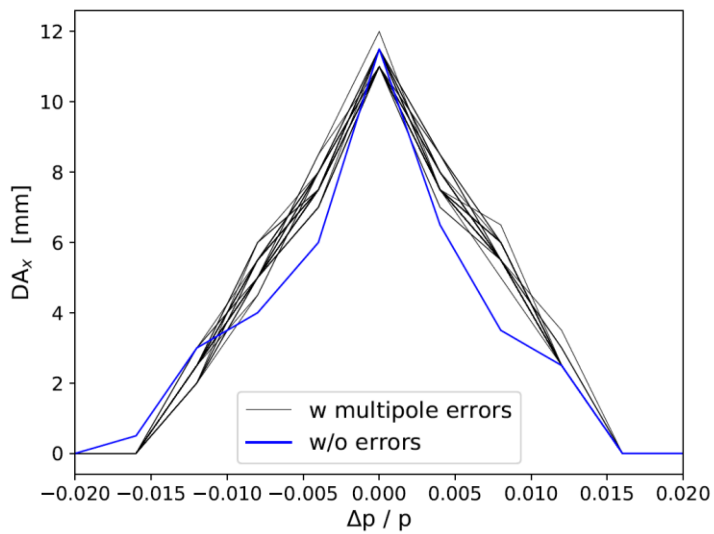
	CT dipole		Iron-core dipole	
GFR=R26	28Gs	56Gs	28Gs	56Gs
B1/B0	-5.20E-04	-1.04E-04	-1.56E-03	-2.60E-04
B2/B0	4.73E-04	5.41E-04	-2.03E-03	-2.03E-04
B3/B0	-7.03E-06	1.05E-04	3.52E-04	1.76E-04
B4/B0	-9.14E-04	-3.66E-04	4.57E-04	-1.83E-04
B5/B0	3.56E-05	-2.38E-05	-2.38E-05	-3.56E-05
B6/B0	6.18E-04	2.16E-04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

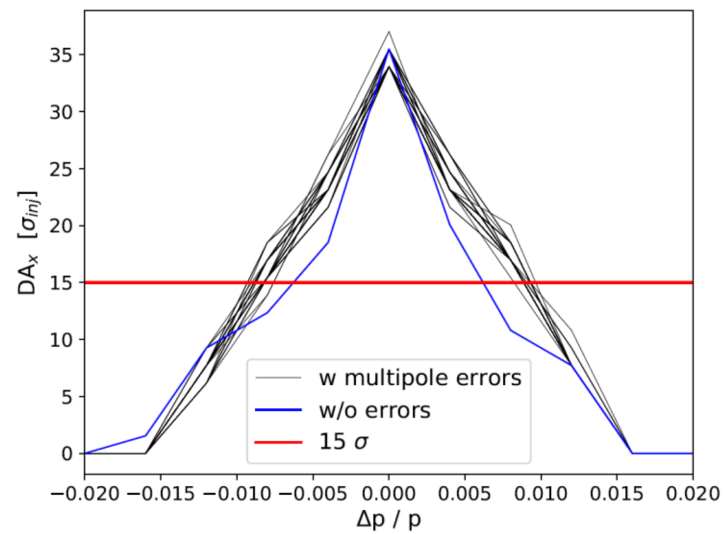
relative values @ R = 26 mm

91km 60°/60° optics

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

Geometric emittance injected 1.27 nm



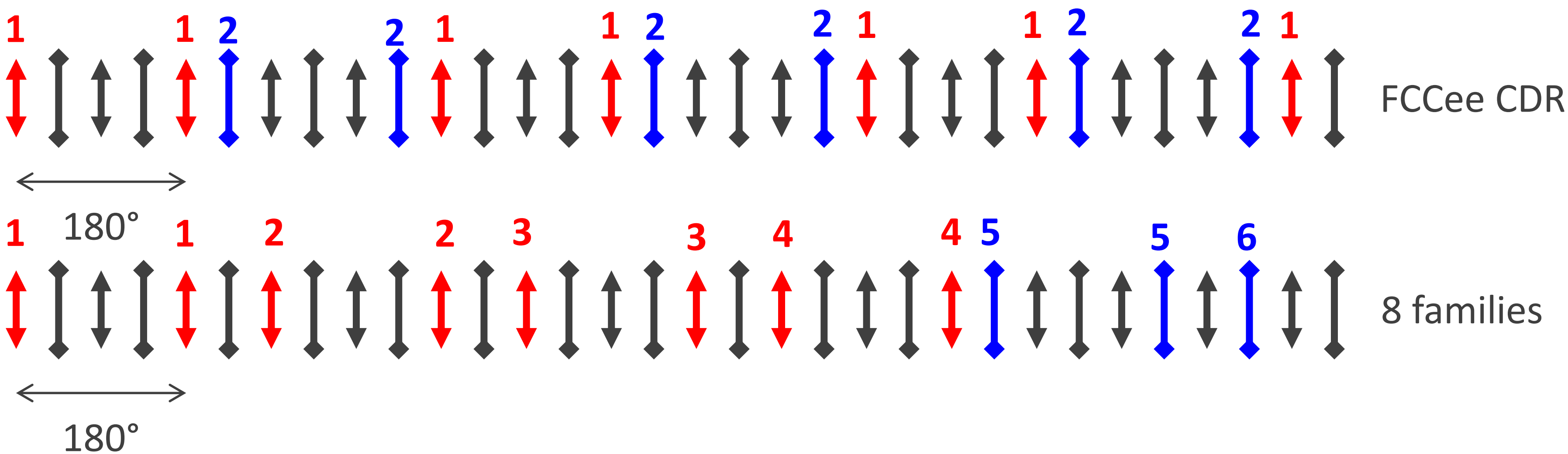


preliminary

DA of 91km **90°/90° optics** is **~ 5mm** (due to longitudinal motion)

Dynamic aperture and momentum acceptance improvement

- Investigating alternative sextupoles schemes with 4 non-inteleaved sextupole families. Better 2nd order chromaticity but higher anharmonicity.



- Using odd Defocusing Sextupoles families to optimize Resonance Driving Terms, in particular the candidate terms of driving synchro-betatron resonance.

RD Term	Before correction	After correction
h11001	-0.0597	-0.0585
h00111	0.0788	0.0776
h20001	**2.3321 - 5.9823i**	**-0.0000 - 0.9894i**
h00201	**-11.0933 - 0.1063i**	**0.0041 + 3.3608i**
h10002	-0.1846 + 0.0136i	-0.1846 + 0.0136i
h21000	1.4358e-04 - 6.5961e-04i	1.4451e-04 - 6.8774e-04i

A. Mashal

"latest" parameters

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Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.95 / 2.75
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.25
Lifetime (q + BS)	[sec]	–		1065	4062
Lifetime (lum)	[sec]	1129	1070	596	744

[a] incl. hourglass.

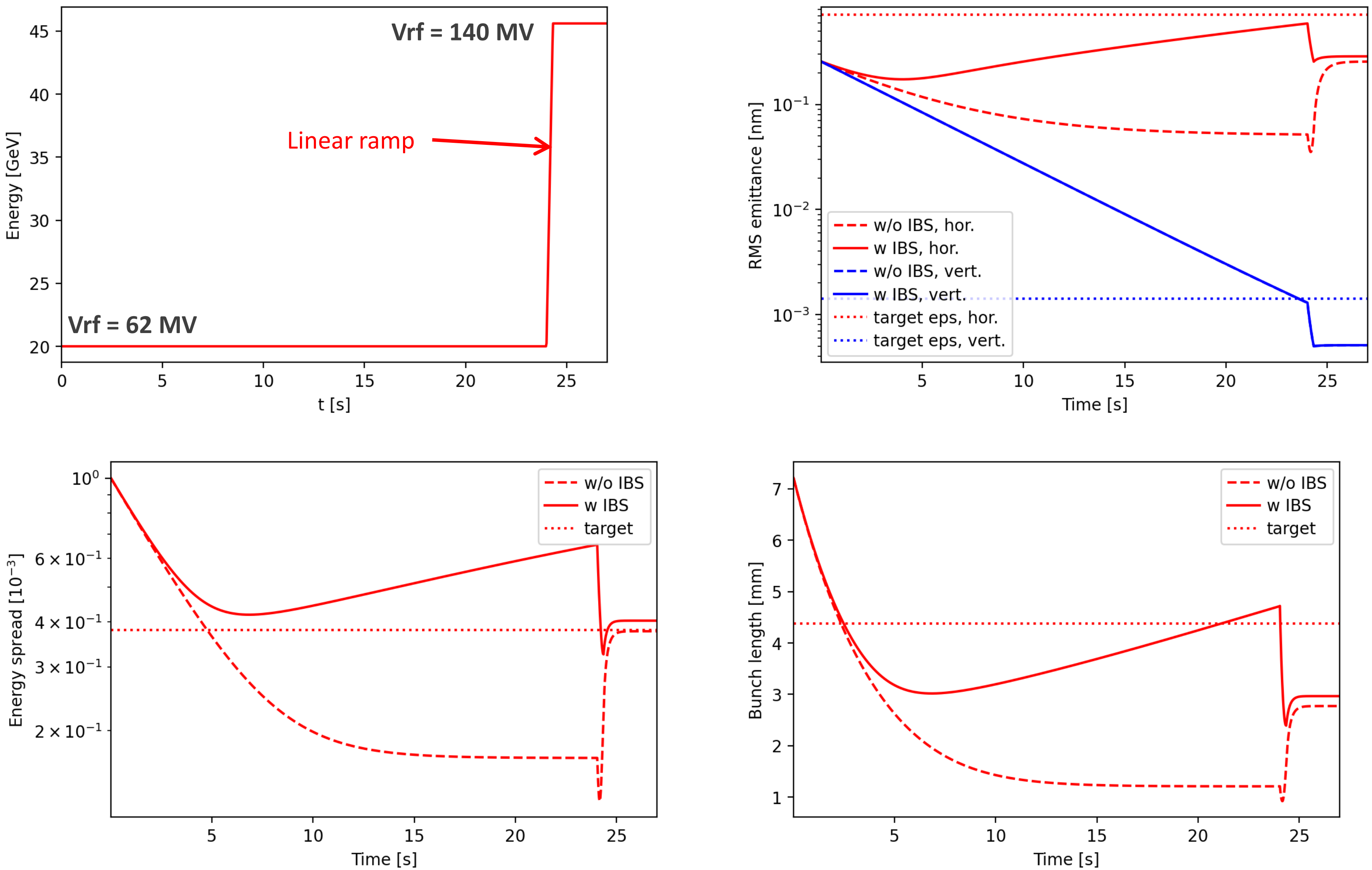
K. Oide, Aug. 4, 2022 1

Emittances evolution

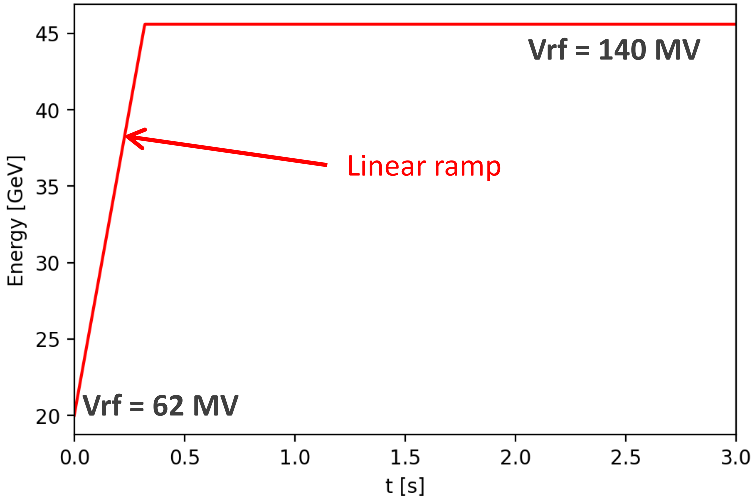
- **We consider the Z mode:**
  - We accumulate in the booster for 24 s: for the emittance evolution we consider 2 cases:
    - 1 fresh beam (the ramp begins directly after injection).
    - 1 accumulation time of 24 s before the ramp.
  - We ramp from 20 GeV to 45.6 GeV for 0.32 s.
  - We consider also a flat-top of 2.7 s (to get a total cycling time of 27 s) to evaluate the gain of damping at top energy.
- **The injection is from the LINAC at 20 GeV:**
  - Normalized emittance of **10 µm x 10 µm**. **S. Bettoni, A. Latina, A. Grudiev**
  - Energy spread of **0.1%**
  - 2.53e+10 particles per bunch (**4 nC**)
- We assume a matched beam: the bunch length is deduced from the total voltage, energy spread and momentum compaction.
- We consider the case with no IBS and with IBS.
- The IBS effect is calculated by using MAD-X routines. A benchmark with a tracking code will be performed when we converge on an injection parameter set.

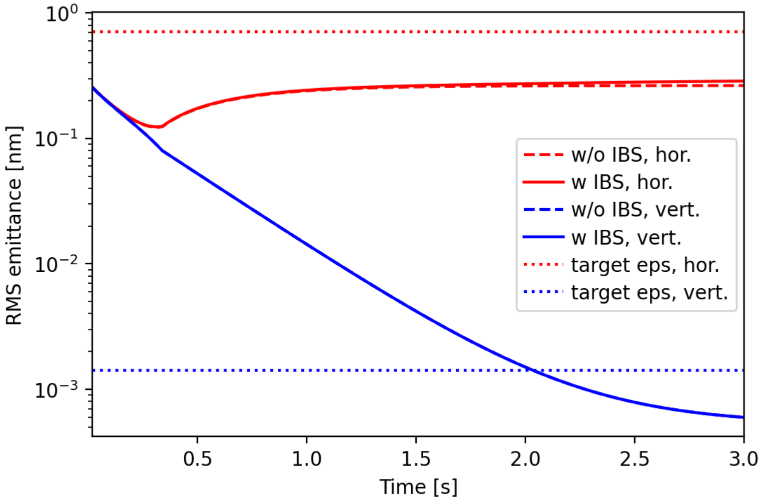
Thanks to M. Zampetakis, F. Antoniou, O. Etisken for IBS

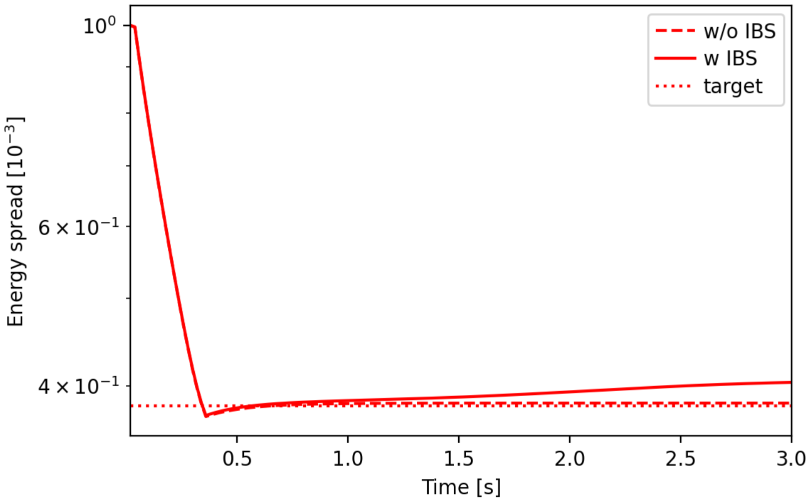
Emittance: accumulation + ramp
10µm x 10µm; 0.1%

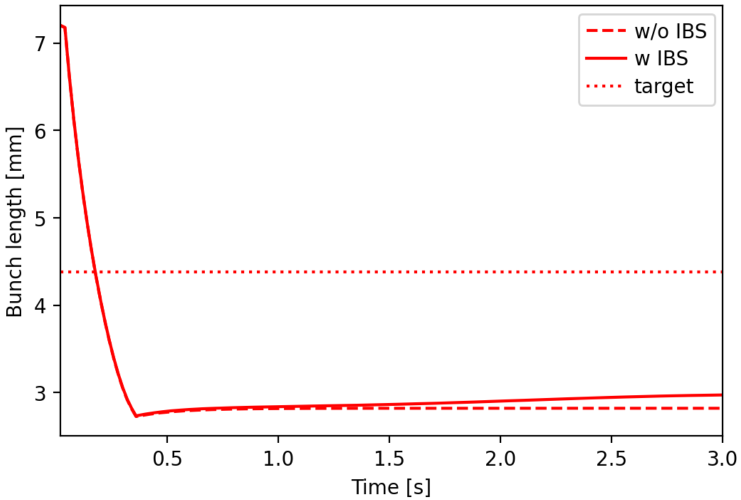


Emittance: ramp only 10µm x 10µm; 0.1%









Parameter variation during the cycling

- **During the accumulation process,**
  - IBS processes drive the emittance evolution.
  - The bunch parameters (length, emittance, size) vary from a bunch to another bunch. The instrumentation should enable to discriminate bunch properties between the different bunches (minimum bunch spacing of 25 ns).
- If we do not modify the I2 function (with different dipole families), **we should have a flat top of at least 2 seconds to damp the beam** with an initial round emittance of 10 µm**.**
- We can reduce a bit the duration of the flat top if we get smaller initial emittances.

- **We have assumed that the beam is matched at the entrance.** An initial energy spread of 0.1% gives a bunch length of 7.2 mm. We could reduce a bit the initial bunch length by increasing the initial RF voltage but we are quickly limited by the maximum total RF voltage.
- **If we do not match the longitudinal parameters, we will have some bunch length and momentum spread breathing.** We need to do tracking simulations to check that is not an issue.
- **We can lengthen the final bunch length** by adjusting the final total voltage**.**

Static magnets imperfections

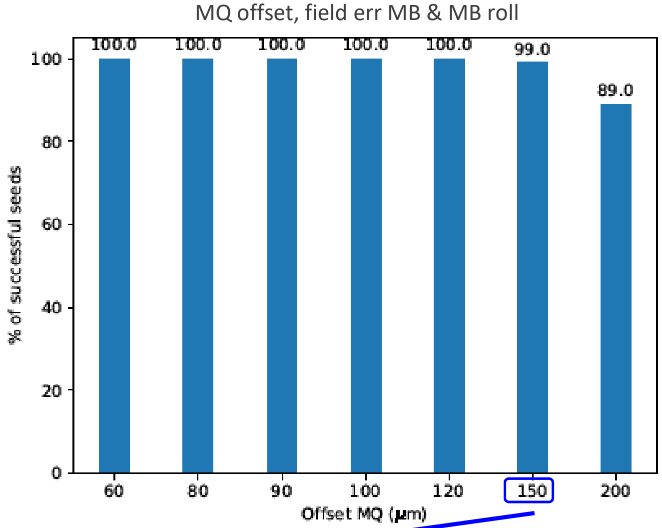
Tatiana Da Silva

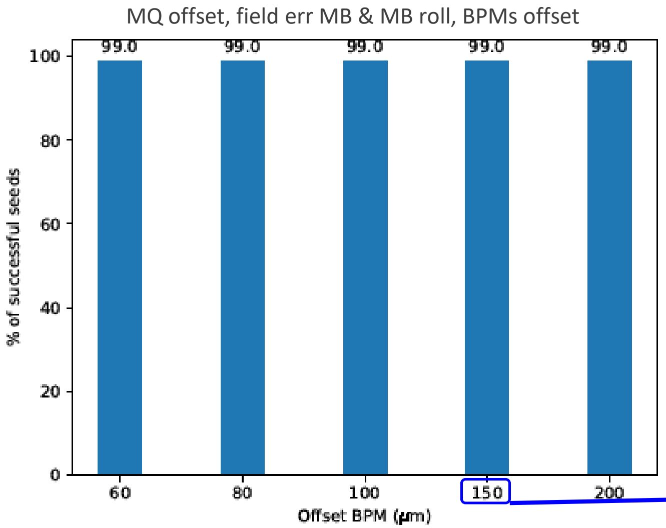
- Define pre-alignment tolerances of the elements and the orbit correctors specifications + establish a correction procedure for orbit correction for the FCC-ee high energy booster.

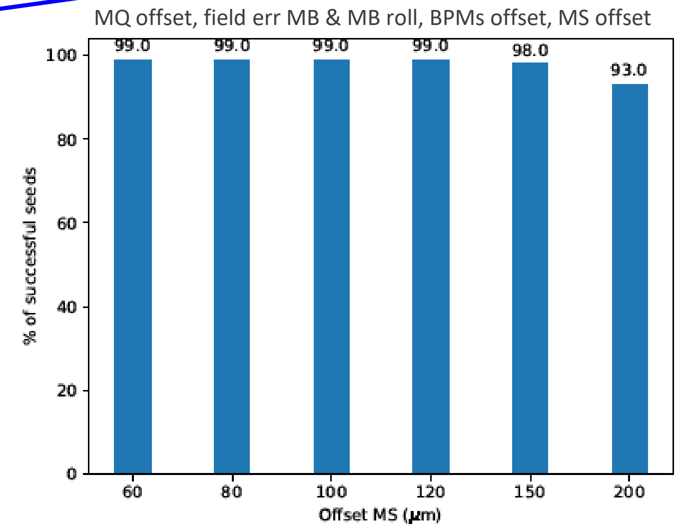
Orbit correction only

Statistics on 100 seeds

Error type	Value
Dipole relative field error	10^{-4}
Main dipole roll error	300 mrad
Offset quadrupoles	60, 80, 90, 100, 120, 150 and 200 µm
Offset BPMs	60, 80, 100, 150 and 200 µm
Offset sextupoles	60, 80, 100, 120, 150 and 200 µm





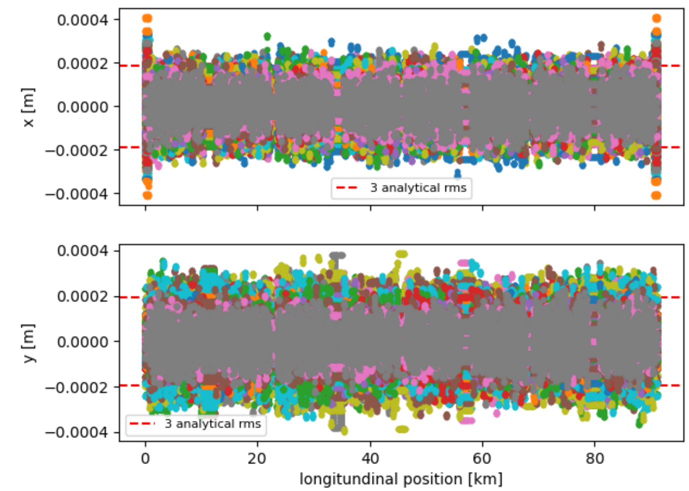


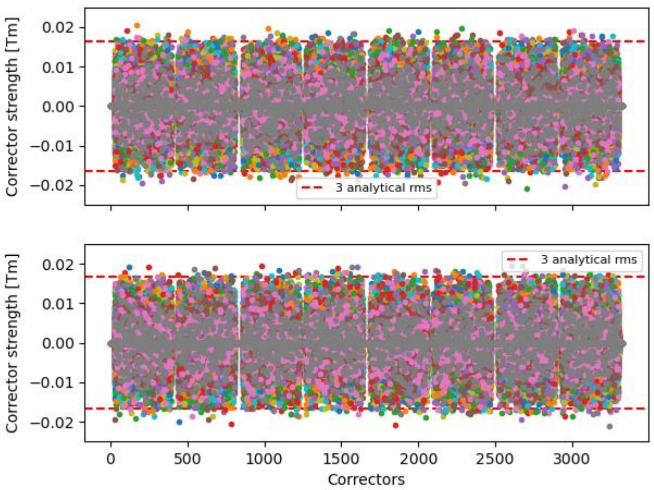
First pre-alignment and correctors specs

Imperfections rms value	Case	Plane	3 x Analytical RMS	3 x Mean RMS/seeds
MQ offset = **150 µm** MB field err = $\mathbf{10^{-4}}$ MB roll = **300 mrad** BPM offset = **150 µm** MS offset = **150 µm** BPM resolution = **50 µm**	Residual Orbit [10^{-6} m]	x	188.4	112.2
		y	192	109.8
	Correctors stengths [10^{-3} Tm]	x	**16.5**	10.8
		y	**16.8**	10.8

- First specifications of the main **magnets misalignment** of the High Energy Booster arcs cells **≃ 150 µm**
- First definition of the **orbit correctors** for the booster **≃ 20 mT**

- In order to preserve transverse emittances need to able to correct > 100% beta-beating, dispersion and coupling (**emittance tuning**)
  If not the case we will reduce misalignment specs





Tatiana Da Silva

Conclusions & Perspectives

- **Optics:**
  - Optimization of layout and booster positioning in the tunnel
  - Two options to bypass the experimental areas inside or outside detector

- **Improve DA and MA for the 90°/90° optics**
  - Resonance Driviting terms optimization
  - Optimisation strategy for sextupoles families (MOGA,…) ?
  - Improve optics design ?

- **HEB operation and emittance evolution**
  - Optimization of cycle time at Z
  - Effect of mis-matched beam at injection
  - Optimization of RF Voltage at injection and extraction
  - Study the 800 MHz RF system against 400 MHz + 800 MHz

- **First definition of the orbit correctors for the booster (≃ 20 mT) and orbit correction scheme. First specifications of elements misalignment (150 µm)**
  - Finalize the emittance tuning studies
  - Integration with DA and MA and Overall Design optimization (exploiting AI)

- **Finalize injection/extraction in the High Energy Booster (CERN)**

First requirements for beam instrumentation

- First tolerance studies require for 2944 BPMs in the arcs with a RMS resolution better than 50 µm.
- We should be able to measure the current of each bunch with a precision better than 20 pC (less than 1% of the bunch charge).
- We should be able to measure the emittance of the bunches at the extraction.
- Because of the damping during the accumulation, the bunch properties are not the same from bunch to bunch: beam emittance, beam size and bunch length vary from bunch to bunch.
- At extraction, we should be at equilibrium and bunch properties should be roughly the same from bunch to bunch (especially for other modes than Z).

Thank you for your attention

Possible solutions (1/3): Damping Wiggler

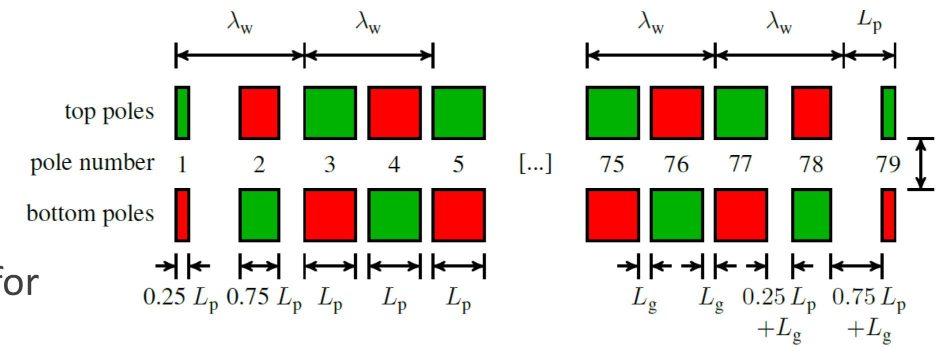
B. Haerer, T. Tydecks https://arxiv.org/abs/2111.14462

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

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

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

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

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
⇒ it **should be switched off** during acceleration or a parallel line with a fast kicker should be designed

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

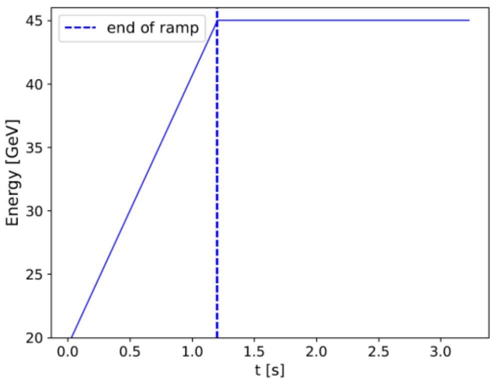
Possible solutions (2/3): 2s at extraction energy

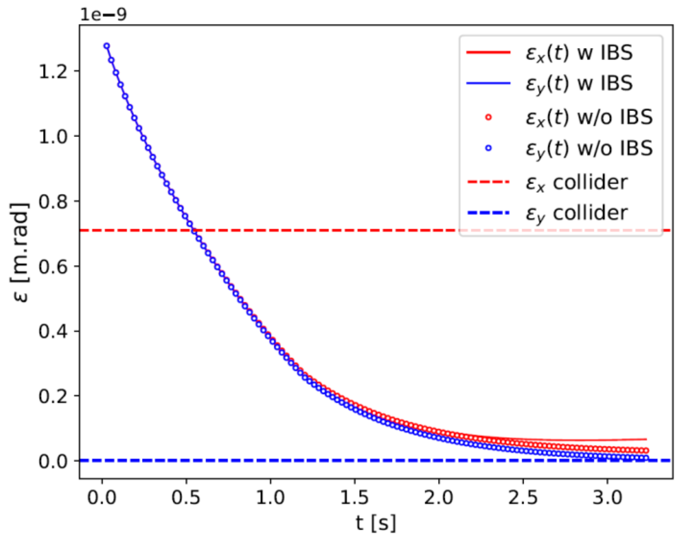
Tor Raubenheimer

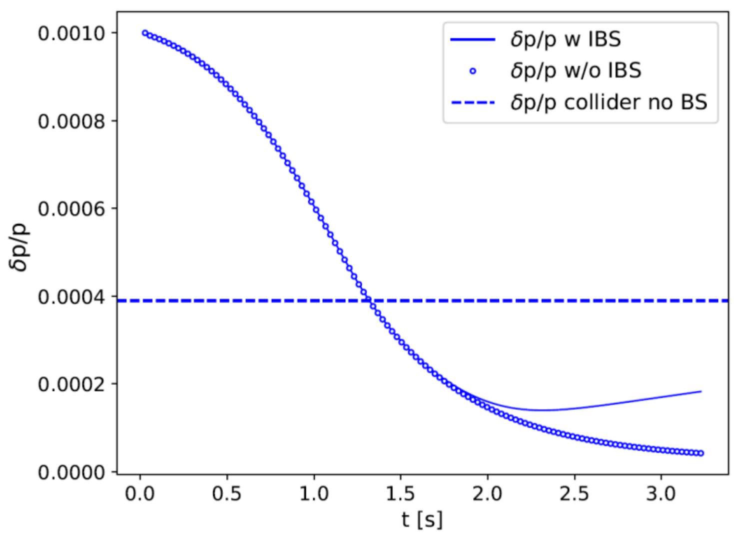
Add 2 seconds after the energy ramp at extraction energy

Pros: no change to the optics design

Cons: small increase Booster Cycle time







Possible solutions (3/3): change I2 integral & ramp time

Simple model with synchrotron radiation only

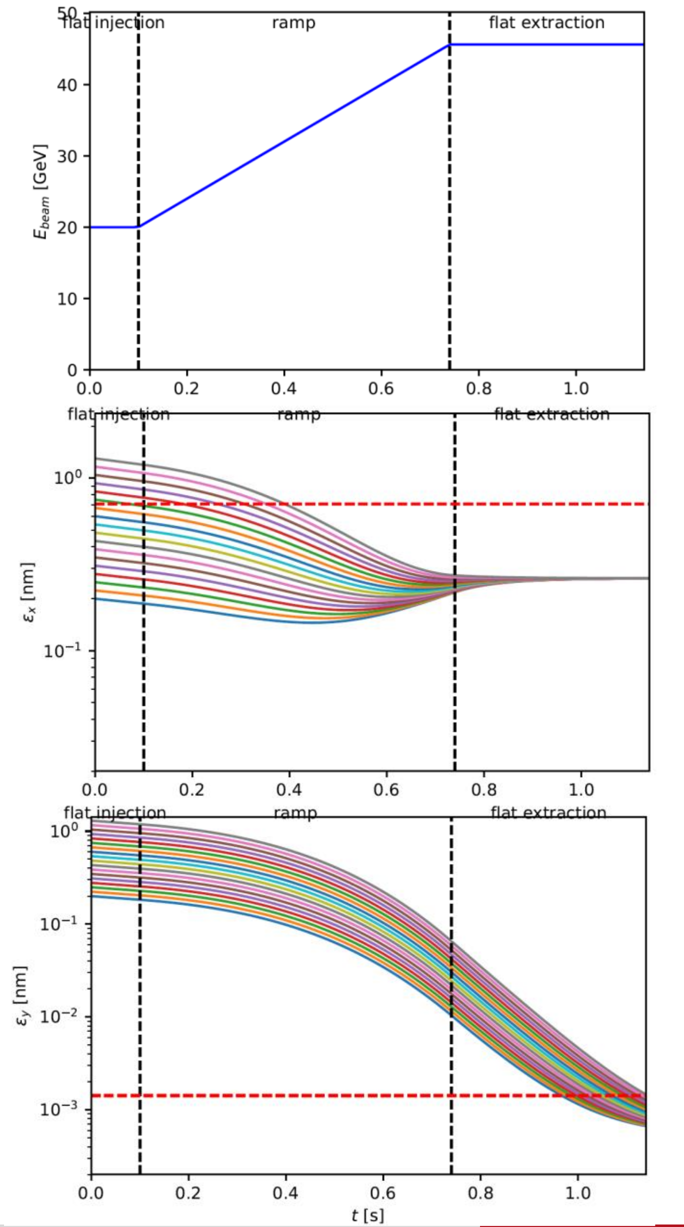
- Injection energy 20 GeV
- Injection rms emittance **0.2-1.3 nm**
- Energy injection + ramp + extraction ~**1.2 s**
- **4×I2 (4×I5)** synchrotron radiation integrals
- dE/dt = 40 GeV/s
- $k = 2\times10^{-3}$

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

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

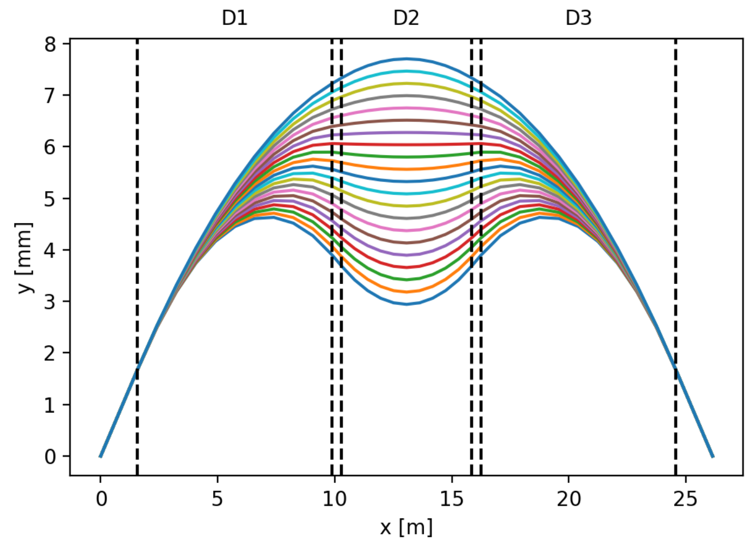
Possible solution :

- 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.



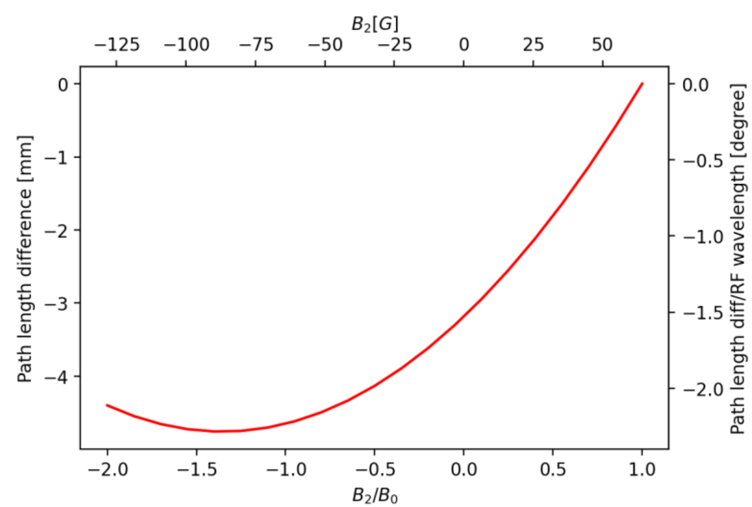
2 dipoles families optics

- 4 × I2 can be obtained with L2 ~5,5 m, B2~-128 G, B1 ~128 G at 20 GeV (to be compared with B~71 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



Advantages:

- Increase I2 without damping wigglers
- **Higher dipole field at injection** energy (useful for all modes and maybe possibility to lower injection energy)



Drawbacks:

- Different reference orbits ⇒ **reduction of beam stay clear?**
- **Change of path length should be followed by RF during acceleration…** (Oide)
- **More synchrotron** radiation and in **opposite direction** of foreseen absorber (at injection) ⇒ **vacuum quality to be investigated**