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High Energy Booster Studies

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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

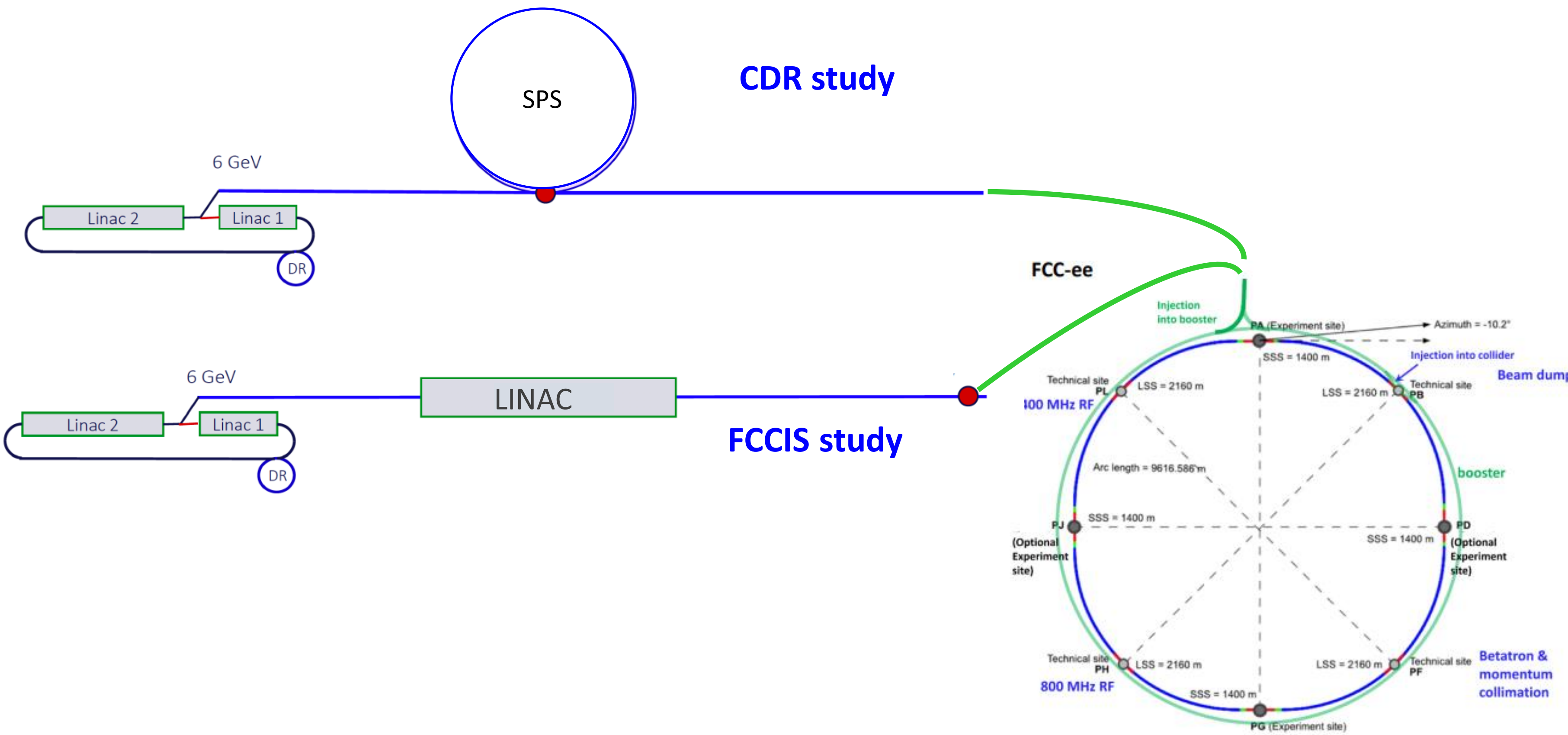
- The injector complex
  - Layout of the High Energy Booster (HEB)
- Optics design
  - Arcs
  - Insertions
- Injection energy and emittances
  - Dynamic Aperture (DA) and Momentum Acceptance (MA)
- Correction of imperfections and definitions of tolerances
- Emittance evolution and booster operations
- Perspectives

Injectors complex

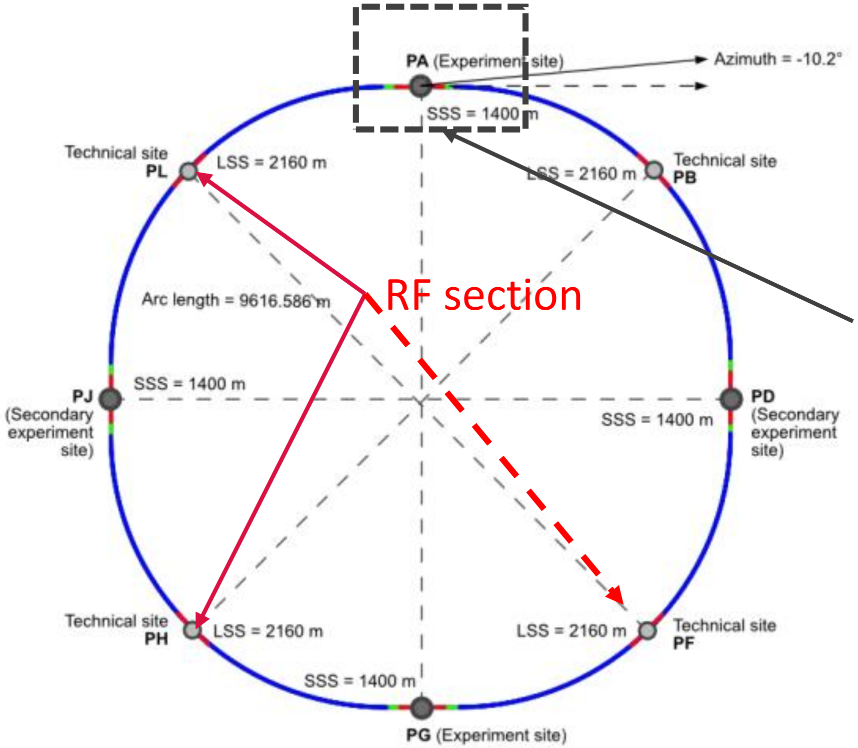
Injection energy into the booster **20 GeV** (or lower ?)

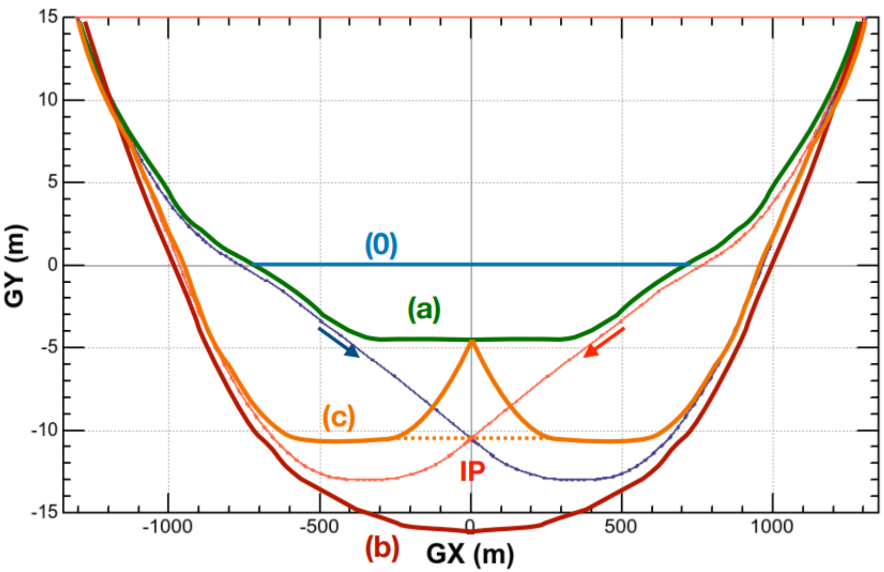
Ramping: **80-100 GeV / s (< 1 s)**

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

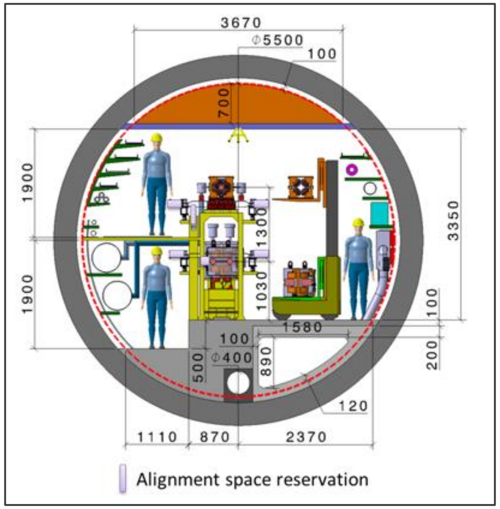


Booster layout (after CDR)





- Booster **layout updated** to follow the last collider survey version.
- In the current booster version, **cavities are located in sections H and L.** Alternative all **RF system** of the Booster placed in **L** or **F**.
  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)**
- **Bypass of the booster near the detector still under investigation.**
- Booster on top of the collider or on the outside.



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

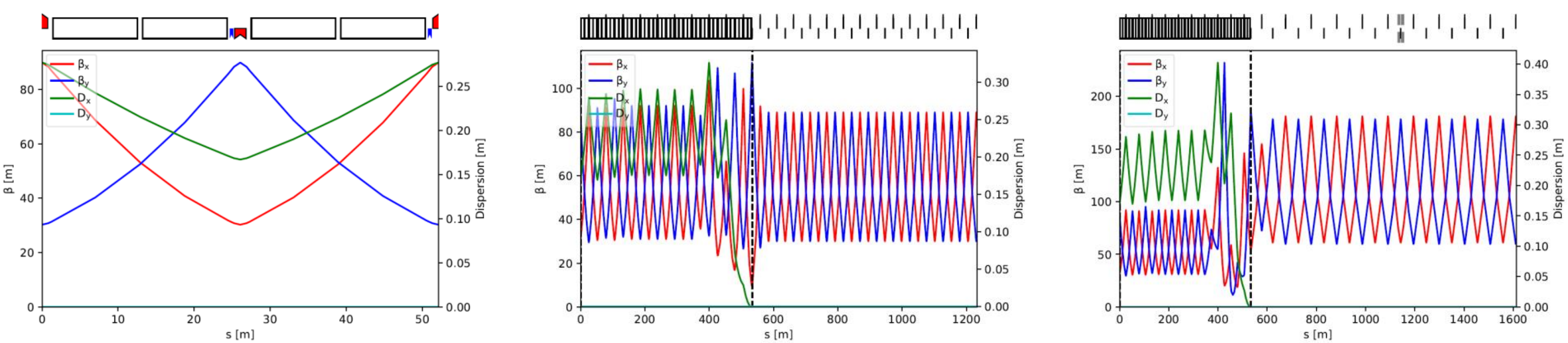
Distance between dipoles: 0.4 m
Distance between quadrupole and sextupole: 0.165 m
Distance between dipole and sextupole: 0. 504 m
Distance between quadrupole and dipole: 0.869 m
(it includes space for BPM and dipole correctors)

\# 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/m²	174
	Gradient at ttbar energy (182.5 GeV)	T/m²	1582
	Length	m	0.5

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

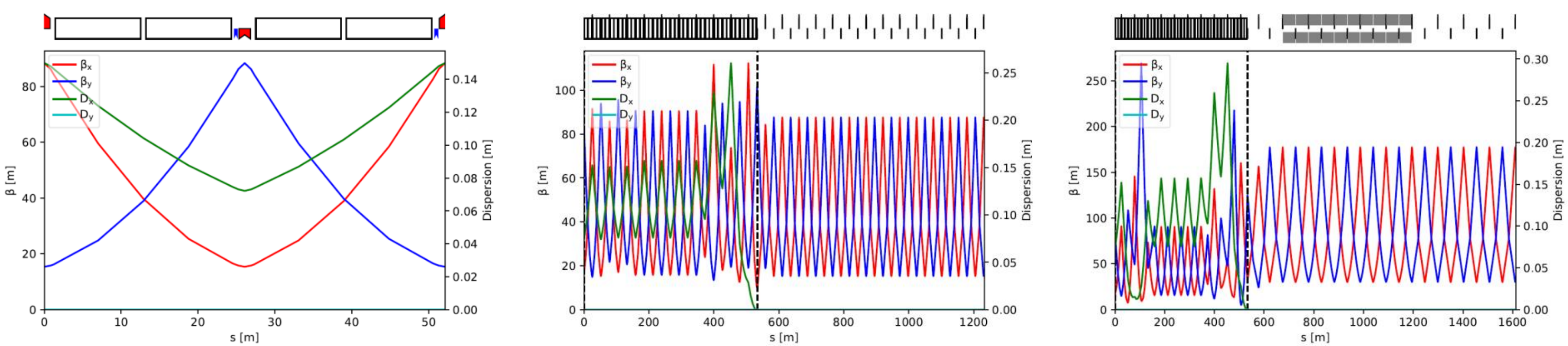
Distance between dipoles: 0.4 m
Distance between quadrupole and sextupole: 0.165 m
Distance between dipole and sextupole: 0. 504 m
Distance between quadrupole and dipole: 0.869 m
(it includes space for BPM and dipole correctors)

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/)

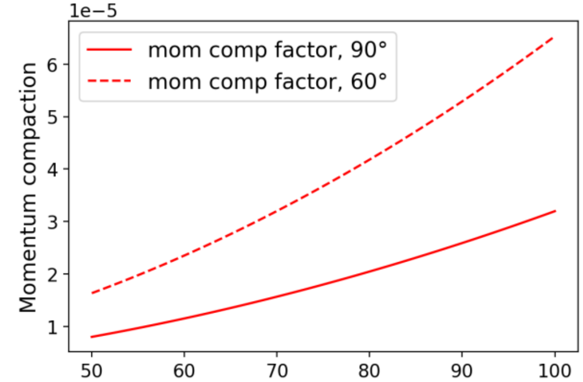


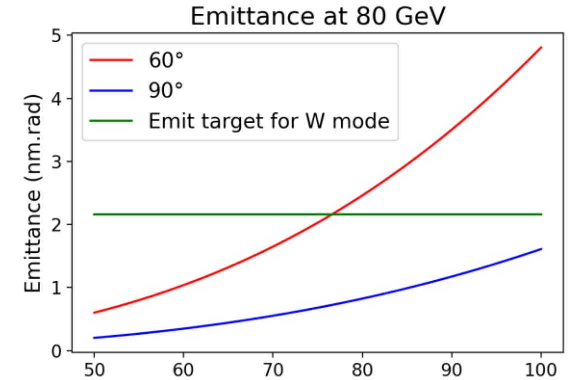
Equilibrium emittances

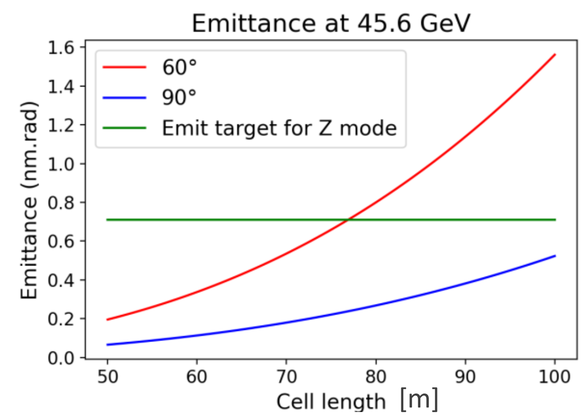
- Booster rms emittance at extraction ≤ collider

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





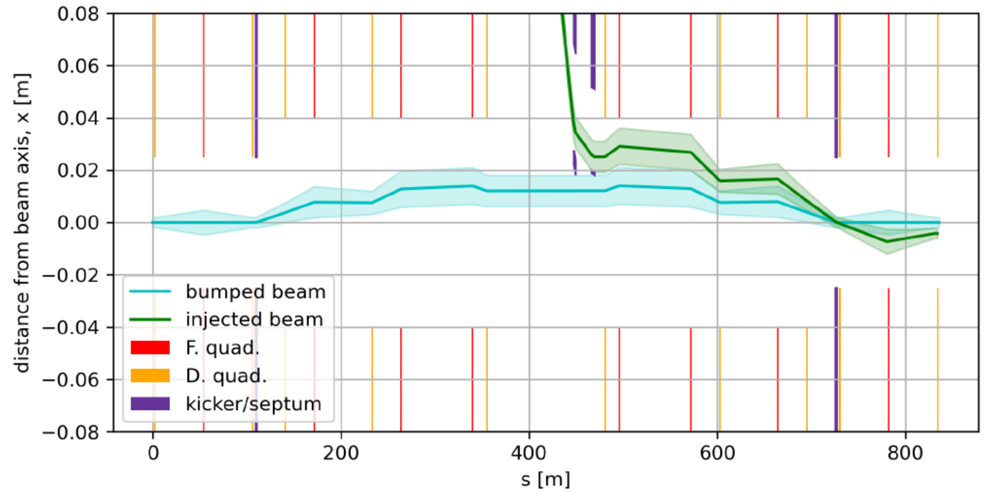


Injection/ extraction in the High Energy Booster

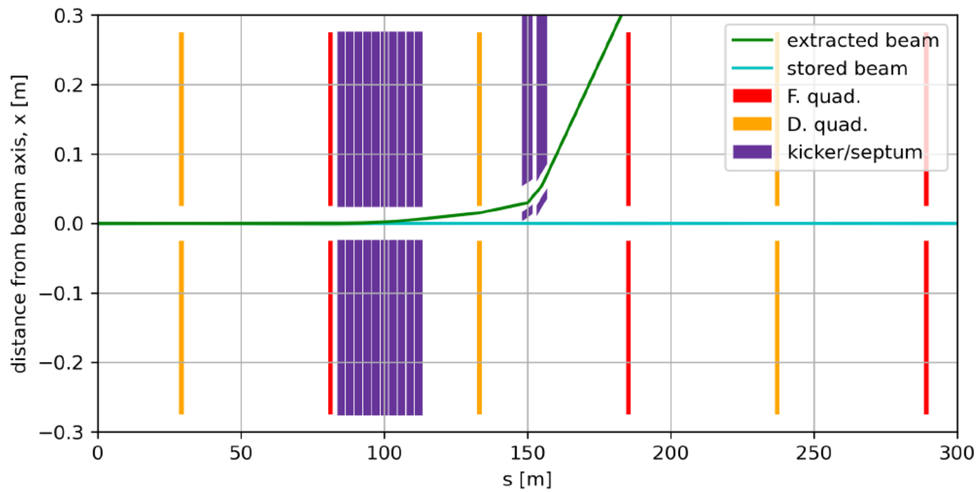
R. L. Ramjiawan & E. Howling

First optics design

- 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**

Dynamic Aperture defined as
Stable initial amplitude @ 4500 turns (~15% *tx* 20 GeV)

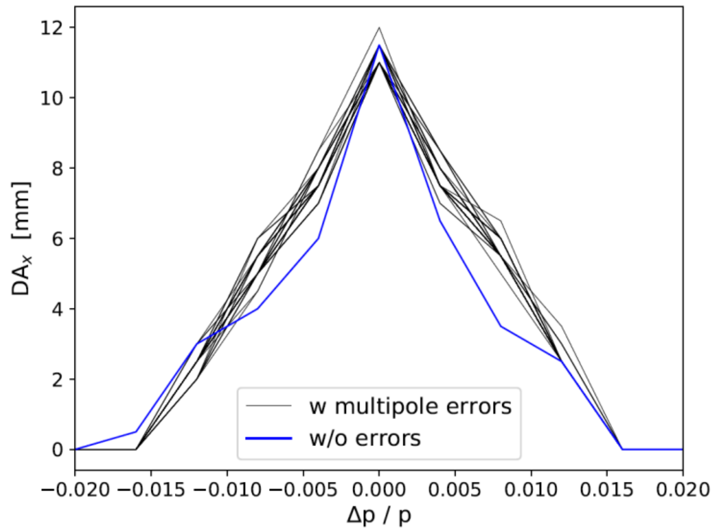
Courtesy of F. Zimmermann and Jie Gao

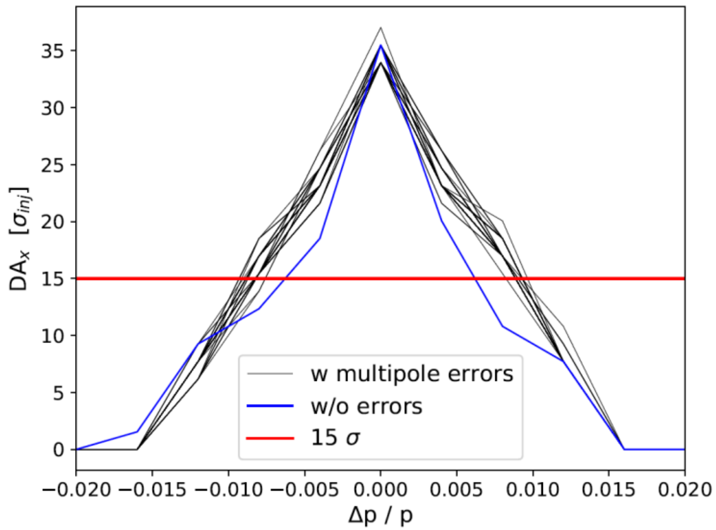
	CT dipole		Iron-core dipole	
GFR=R26	28Gs	56Gs	28Gs	56Gs
B1/B0	-5.20E-04	-1.04E-04	-1.56E-03	-2.60E-04
B2/B0	4.73E-04	5.41E-04	-2.03E-03	-2.03E-04
B3/B0	-7.03E-06	1.05E-04	3.52E-04	1.76E-04
B4/B0	-9.14E-04	-3.66E-04	4.57E-04	-1.83E-04
B5/B0	3.56E-05	-2.38E-05	-2.38E-05	-3.56E-05
B6/B0	6.18E-04	2.16E-04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

relative values @ R = 26 mm

91km 60°/60° optics

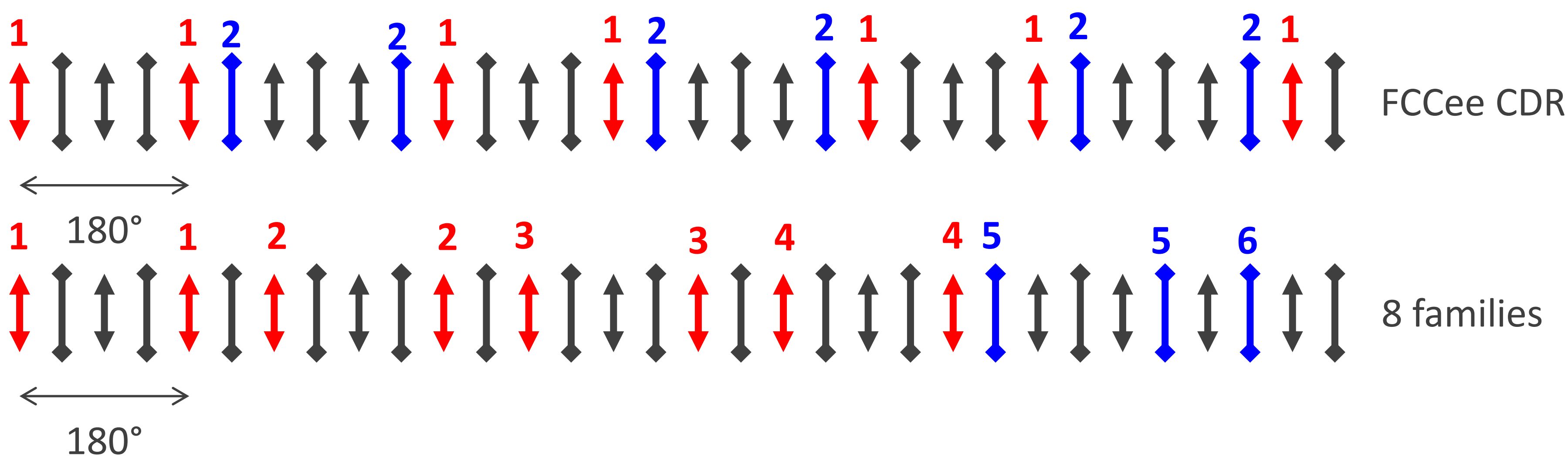
$\beta_x = 83.2$ m $\beta_y = 32.2$ m $D_x = 0$ m
Geometric emittance injected 1.27 nm





DA of 91km **90°/90° optics** is **~ 5mm** (due to synchro-betatron resonances)

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



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

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

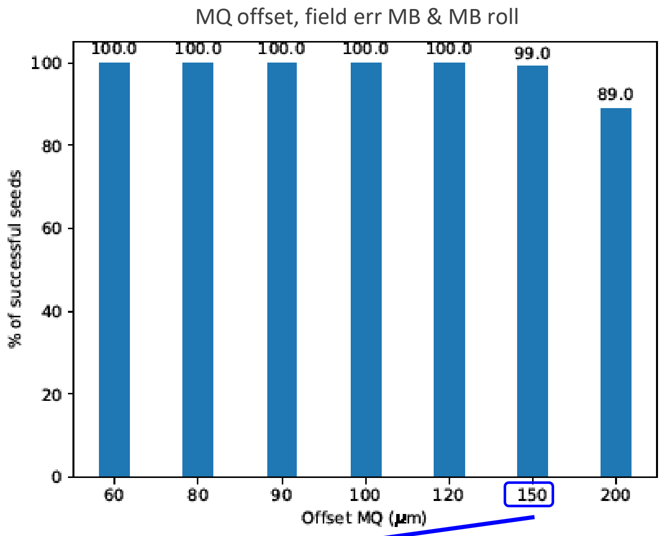
T. Da Silva

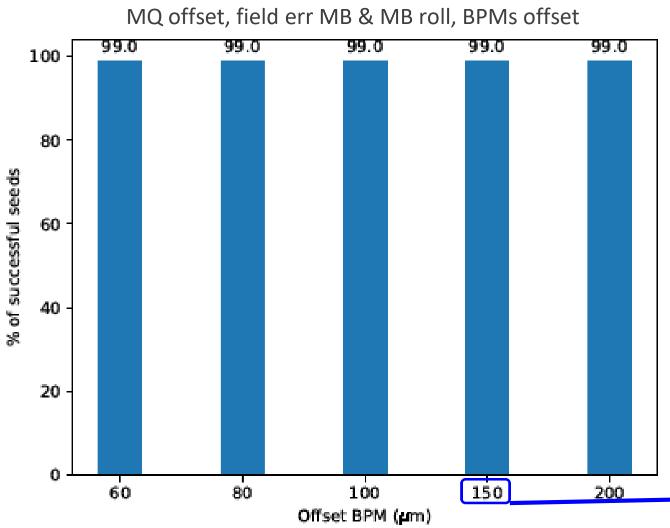
- Define pre-alignment tolerances of the elements and the orbit correctors specifications + establish a correction procedure for orbit correction for the FCC-ee high energy booster.

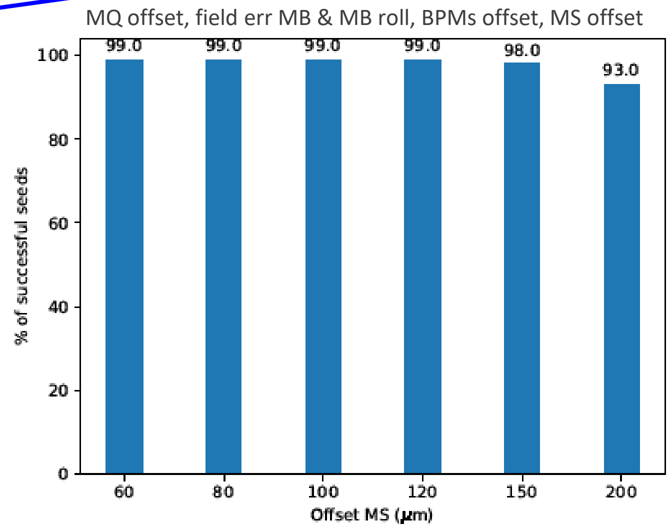
Orbit correction only

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

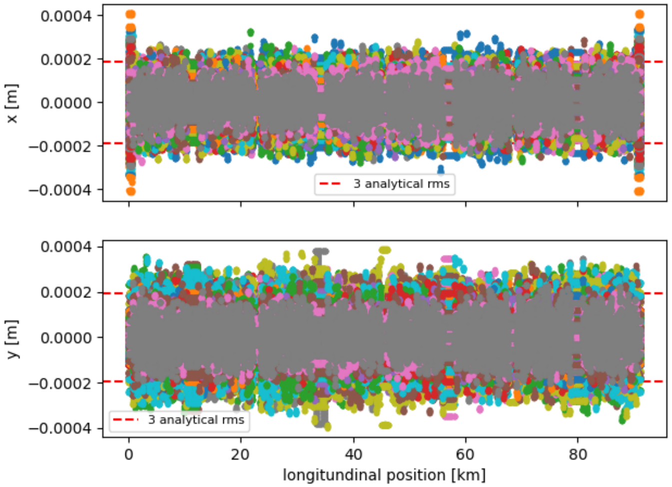




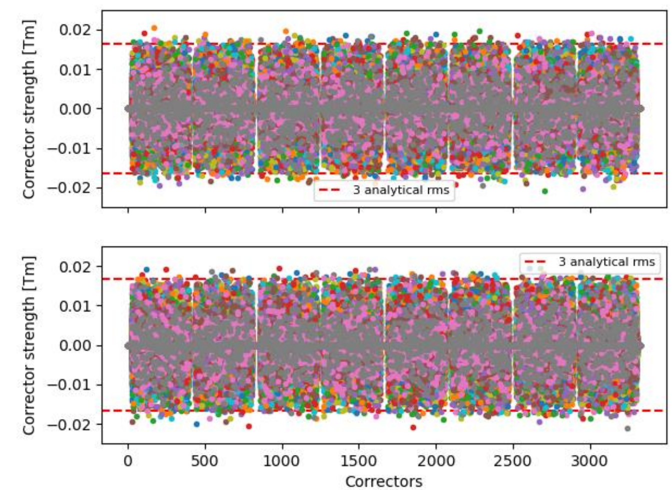


First pre-alignment and correctors specs

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 stenghts [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 also beta-beating, dispersion and coupling (**emittance tuning**)

T. Da Silva

Injectors parameters and Booster cycle time

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

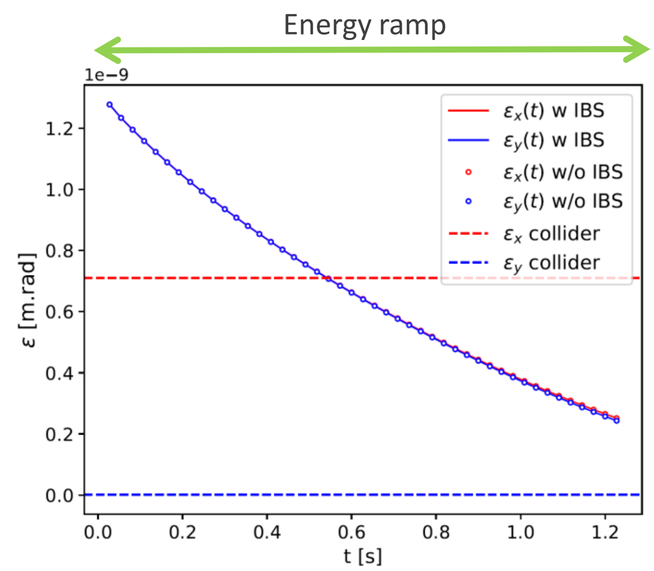
	Z	WW	ZH	tt
Collider energy [GeV]	45.6	80	120	182.5
Collider & BR bunches / ring	10000	880	248	40
Collider particles / bunch [10^{10}]	24.3	29.1	20.4	23.7
Injector particles / bunch [10^{10}]	≤ 3.0 *			
Bootstrap particles / bunch [10^{10}]	2.43	1.746	1.224	1.422
# of BR ramps (to 1/2 stored current)	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

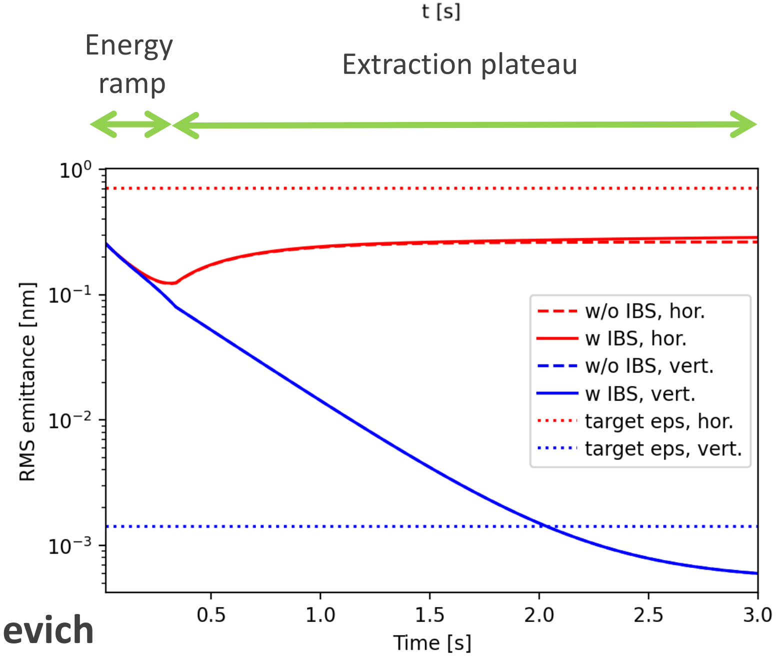
Sep 21, 2021
K. Oide

Emittance evolution and booster operation

The cycle time and emittance reach of the Booster depends on the beam emittance at injection in the booster ring, on the ramp time, on the ramp structure and on the lattice damping time

- At **Z mode**: optimization of cycle time to be able to reach target vertical emittance at extraction of the Booster
  - Solution with the wiggler discarded
  - Adding **extra time at extraction** preferred
  - Two dipoles families: under investigation
- To do:
  - Optimization of RF Voltage at injection and extraction
  - Impact of mis-matched bunch length at injection into the Booster (taking into account collective effects)
  - Impact on beam dynamics of the 800 MHz RF system vs 400 MHz + 800 MHz (baseline)





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

LINAC parameters: **S. Bettoni, A. Latina, A. Grudiev, P. Craievich**

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 Drivitng terms optimization
  - Optimisation strategy for sextupoles families (MOGA, ML,…) ?
  - Different Arc cell ?

- **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)**

Thank you for your attention

First requirements for beam instrumentation

- First tolerance studies for BPM **resolution** in the arcs

  ⇒ 50 µm rms distribution over ~3000 BPMs

- 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).

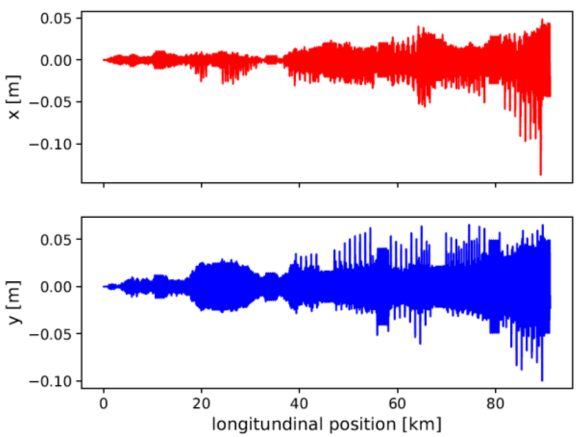
- We should be able **to measure the emittance of the bunches** at the extraction.
  - At extraction, we should be at equilibrium and bunch properties should be roughly the same from bunch to bunch (especially for other modes than Z).
  - Because of the interplay of damping and IBS during the accumulation, the bunch properties are not the same from bunch to bunch: beam emittance, beam size and bunch length vary from bunch to bunch.

Orbit correction procedure

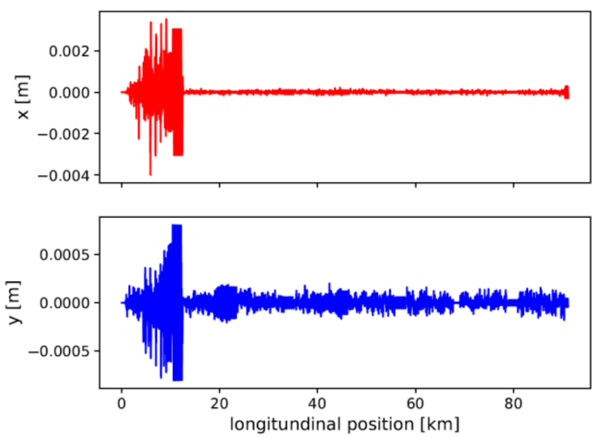
Mettere mie slides

1. Definition of CORRs and BPMs:
    1. If QP focusing → following BPM reads and CORR corrects in horizontal plane.
    2. If QP defocusing → following BPM reads and CORR corrects in vertical plane.
2. Choice CORRs and BPMs for the segment by segment (SbS):
    1. x plane: first BPM of the arc, the 2 CORRs before the beginning of the arc to the **3** BPMs and CORRs after the end of the arc.
    2. y plane: first BPM of the arc, the 2 CORRs before the beginning of the arc to the **2** BPMs and CORRs after the end of the arc.
3. Sextupoles are turned off. SbS correction and several SVD corrections behind.
4. Sextupoles are turned on. 1 final SVD corrections behind.

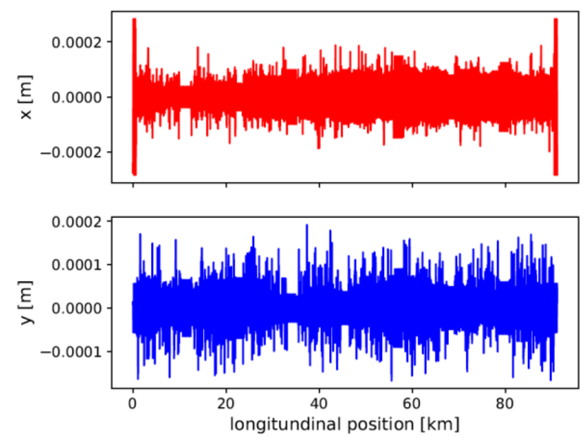
Orbit with errors (before correction)



Orbit after SbS correction



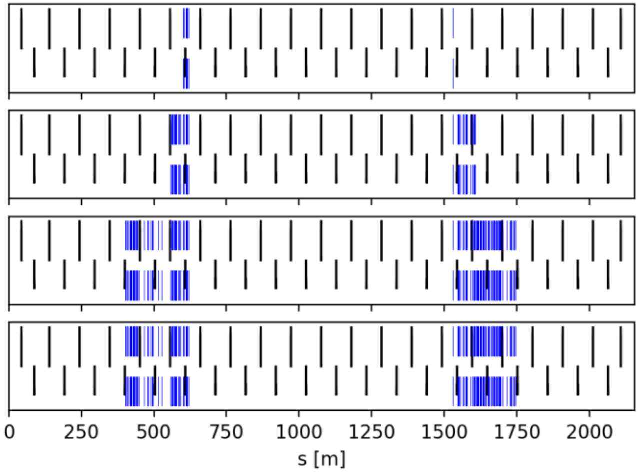
Orbit after final correction



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



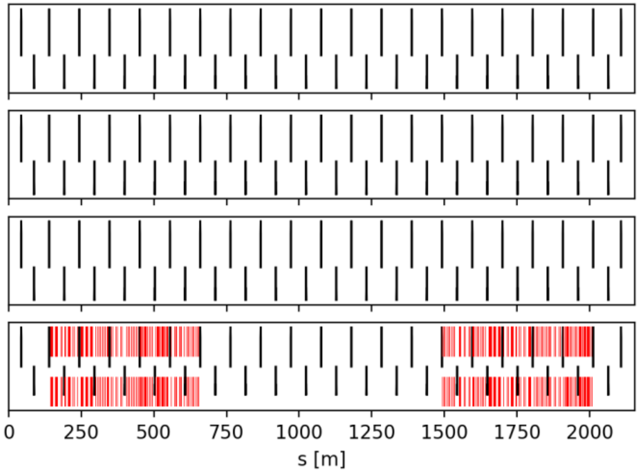
Z mode

W mode

H mode

tt mode

Insertion H

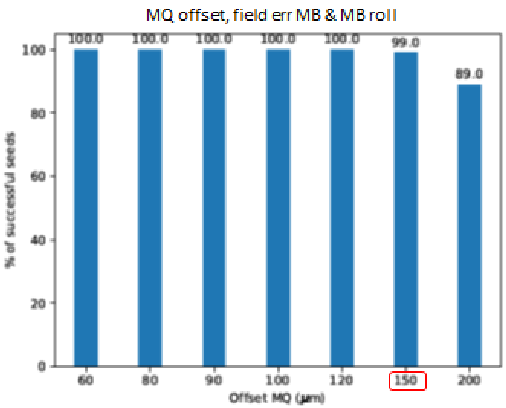


- Z mode: 2 CM left, 1 CM right of IPL
- W mode: 7 CM left, 6 CM right of IPL
- H mode: 17 CM left, 17 CM right of IPL
- tt mode: 17 CM left, 17 CM right of IPL

- tt mode: 60 CM left, 60 CM right

- All RF systems of the Booster installed in the same insertion (H or F)
  ⇒ optimize the cost of the infrastructures
- **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**)

Errors and statistic

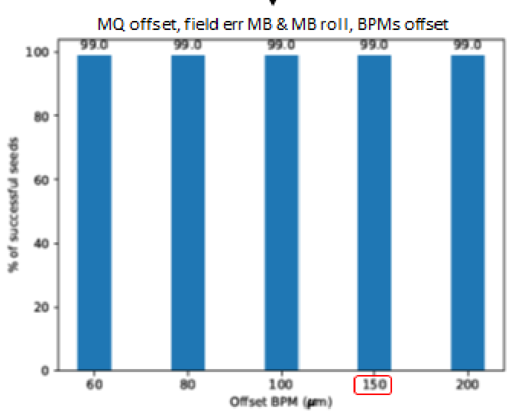


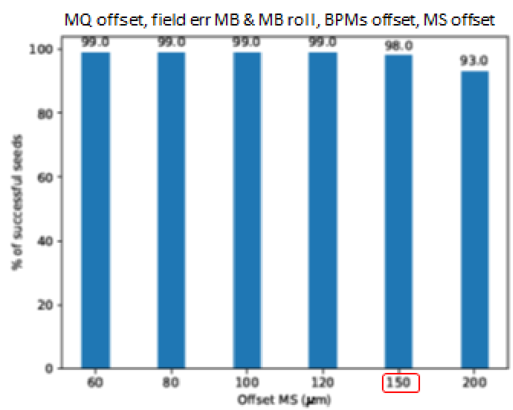
Error type	Value
Offset quadrupoles	60, 80, 90, 100, 120, 150 and 200 µm
Dipole relative field error	10^{-4}
Main dipole roll error	300 mrad
Offset BPMs	60, 80, 100, 150 and 200 µm
Offset sextupoles	60, 80, 100, 120, 150 and 200 µm
BPMs resolution error	10 and 50 µm

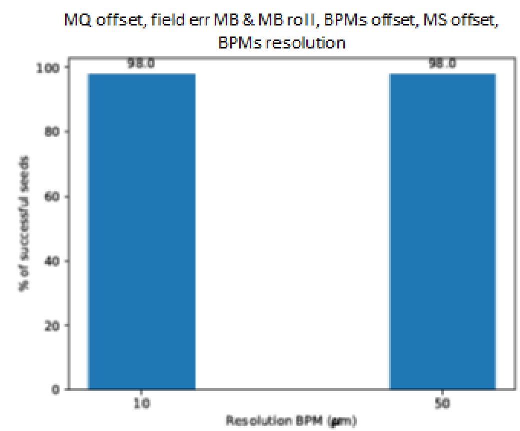
Offset BPMs → With MQ offset fixed to 150 µm

Offset sextupoles → With MQ & BPMs offset fixed to 150 µm

BPMs resolution error → With MQ, BPMs & MS offset fixed to 150 µm







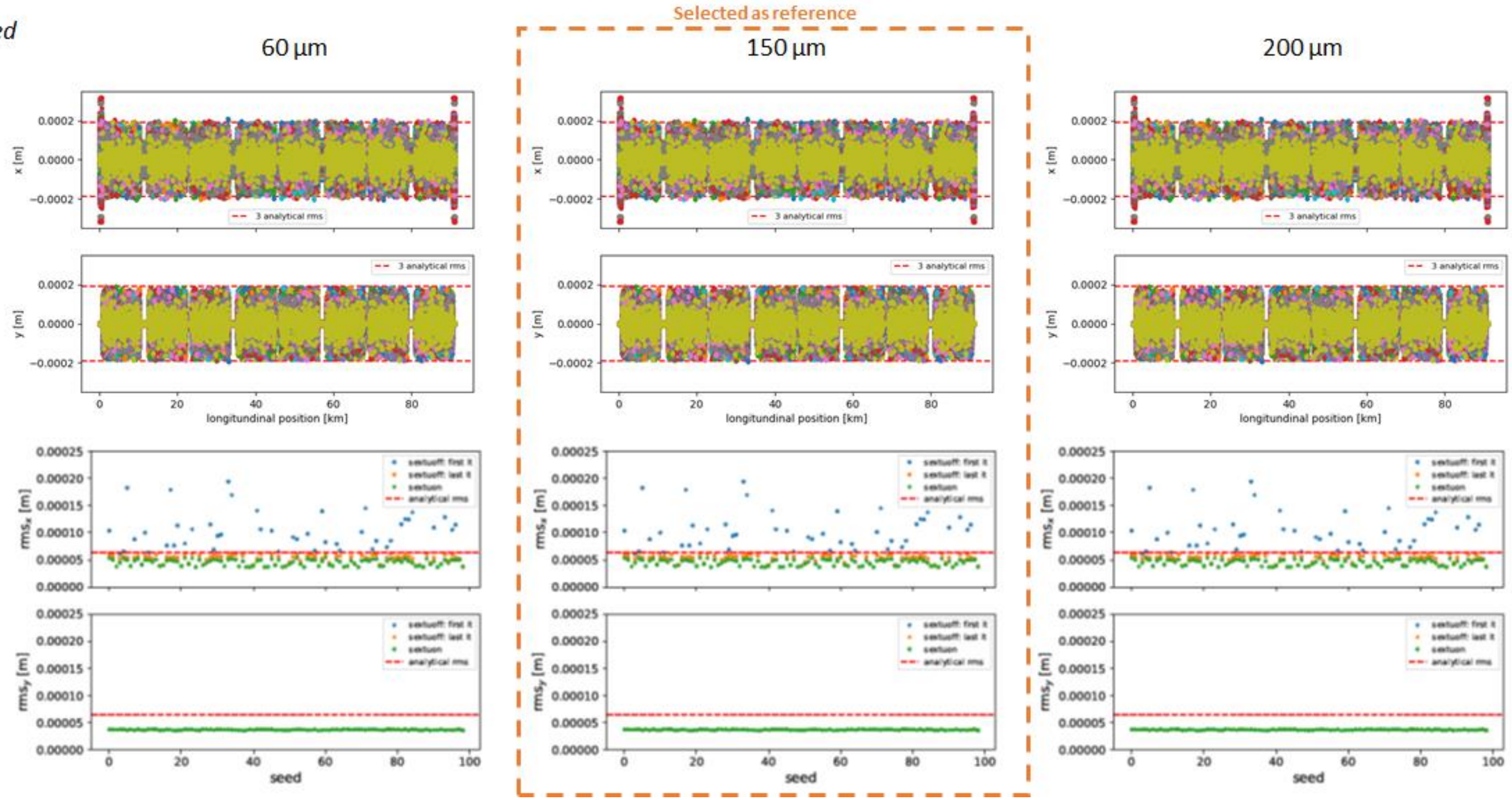
Mettere mie slides

Result Example Orbit:
offset quad, dipole field err & dipole roll, offset BPMs

One color = one seed

After SVD ring with MS on

RMS of the orbit



Mettere mie slides

Summary RMS

	Case	Plane	3 x Analytical RMS	3 x Mean RMS/seeds
MQ offset = 150 µm MB field err = 10^{-4} MB roll = 300 mrad	Orbit [m]	x	$189{,}6.10^{-6}$	$111{,}9.10^{-6}$
		y	$190{,}5.10^{-6}$	$109{,}8.10^{-6}$
	Correctors stengths [Tm]	x	$16{,}5.10^{-3}$	$10{,}8.10^{-3}$
		y	$16{,}5.10^{-3}$	$10{,}8.10^{-3}$
MQ offset = 150 µm MB field err = 10^{-4} MB roll = 300 mrad BPM offset = 150 µm MS offset = 150 µm	Orbit [m]	x	$188{,}4.10^{-6}$	$112{,}2.10^{-6}$
		y	$192{,}0.10^{-6}$	$109{,}8.10^{-6}$
	Correctors stengths [Tm]	x	$16{,}5.10^{-3}$	$10{,}8.10^{-3}$
		y	$16{,}8.10^{-3}$	$10{,}8.10^{-3}$
MQ offset = 150 µm MB field err = 10^{-4} MB roll = 300 mrad BPM offset = 150 µm MS offset = 150 µm BPM resolution = 50 µm	Orbit [m]	x	$188{,}4.10^{-6}$	$150{,}3.10^{-6}$
		y	$192{,}0.10^{-6}$	$153{,}3.10^{-6}$
	Correctors stengths [Tm]	x	$16{,}5.10^{-3}$	$10{,}8.10^{-3}$
		y	$16{,}8.10^{-3}$	$11{,}1.10^{-3}$

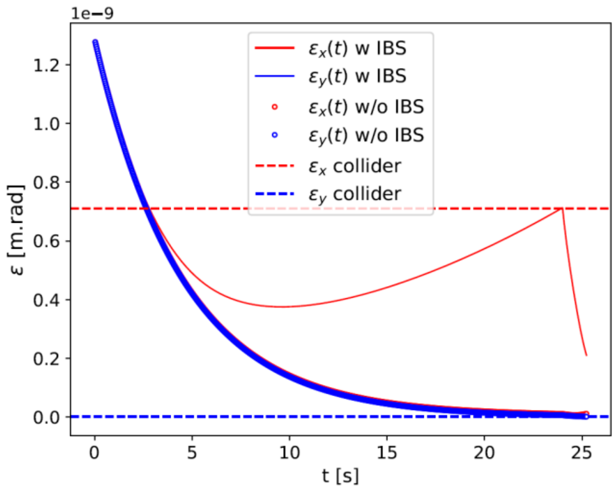
Mettere tabella piu’ beta-beat piu’ conclusion presentazione tatiana

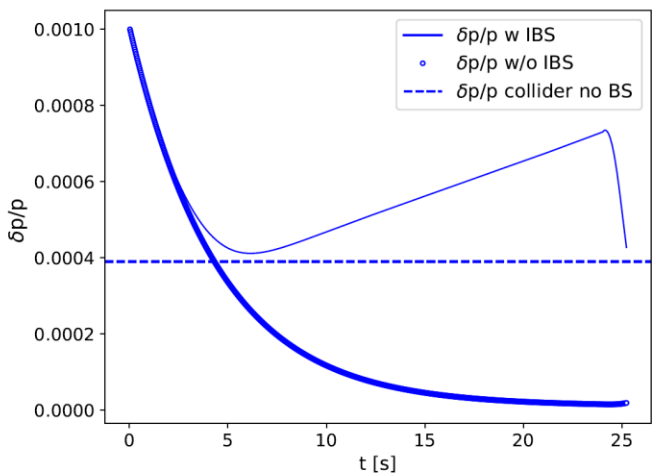
Emittances evolution: accumulation + ramp

- **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 **0.1%**
  - Bunch Length of **1 mm**
  - 2.53e+10 particles per bunch (**4 nC**)
- **The IBS is not negligible during accumulation process** (equilibrium emittance at 20 GeV not reached).
- The beam parameters **(emittance and energy spread)** vary from a bunch to another**.** The collider **energy spread might be not reached** at **extraction energy.**
  ⇒ **bunch length > 1 mm** from the LINAC preferred

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

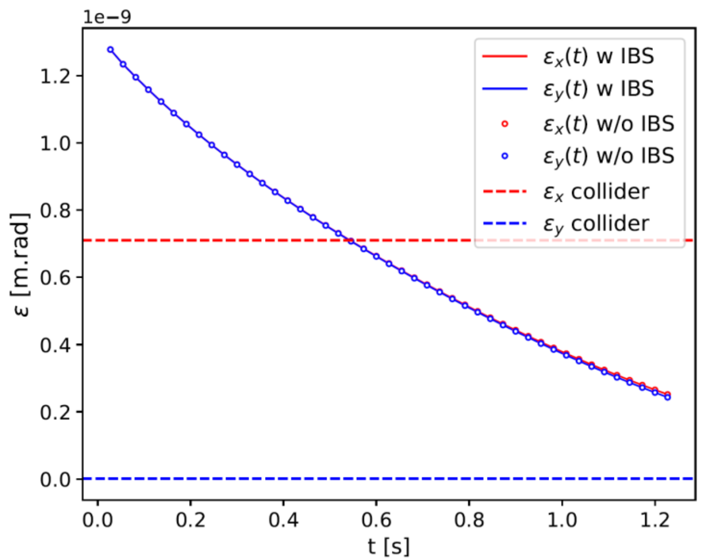
→ S. Bettoni, A. Latina, A. Grudiev

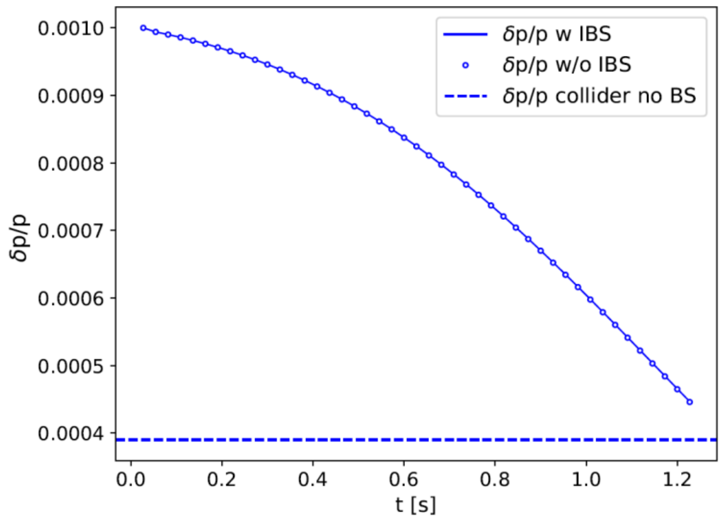




Emittances evolution: ramp

- **Z mode:**
  - No accumulation (i.e. last bunch injected)
  - 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 **0.1%**
  - Bunch length of **1 mm**
  - 2.53e+10 particles per bunch (**4 nC**)
- **Acceleration time is short enough to see no IBS effect.**
- **Synchrotron integral I2 is too small to reach collider parameters within 1.2 s.**





Possible solutions (1/3): Damping Wiggler

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

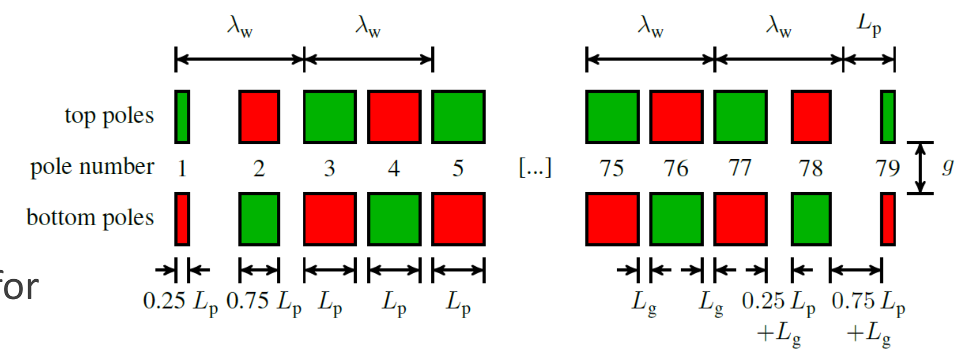
Target damping time 0.1 s (to fulfill cycle time)

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

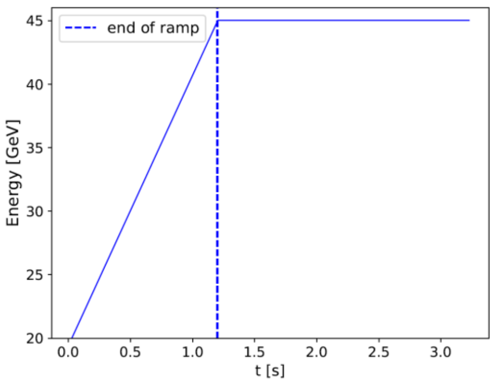
Possible solutions (2/3): 2s at extraction energy

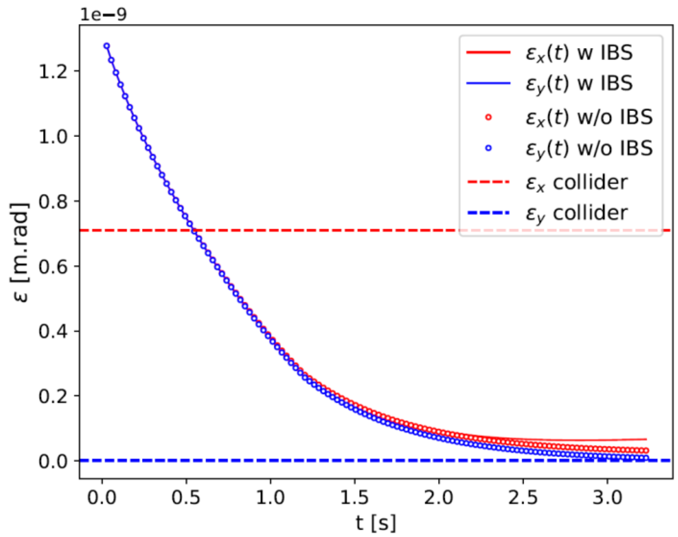
Tor Raubenheimer

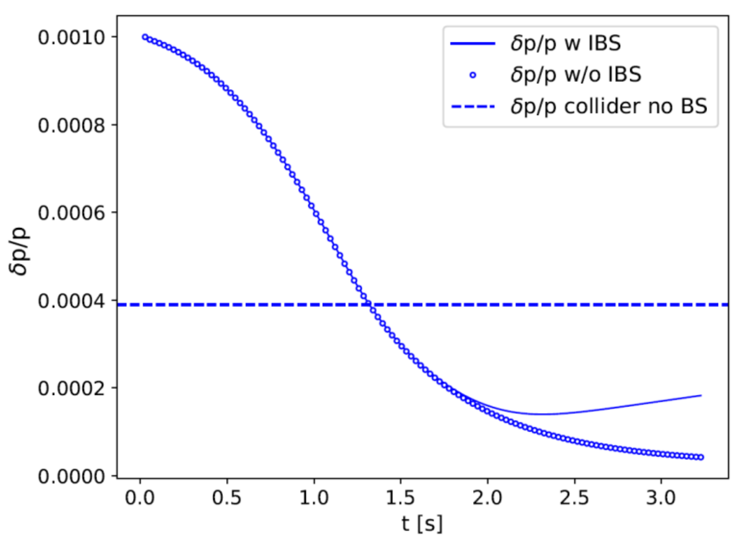
Add 2 seconds after the energy ramp at extraction energy

Pros: no change to the optics design

Cons: small increase Booster Cycle time







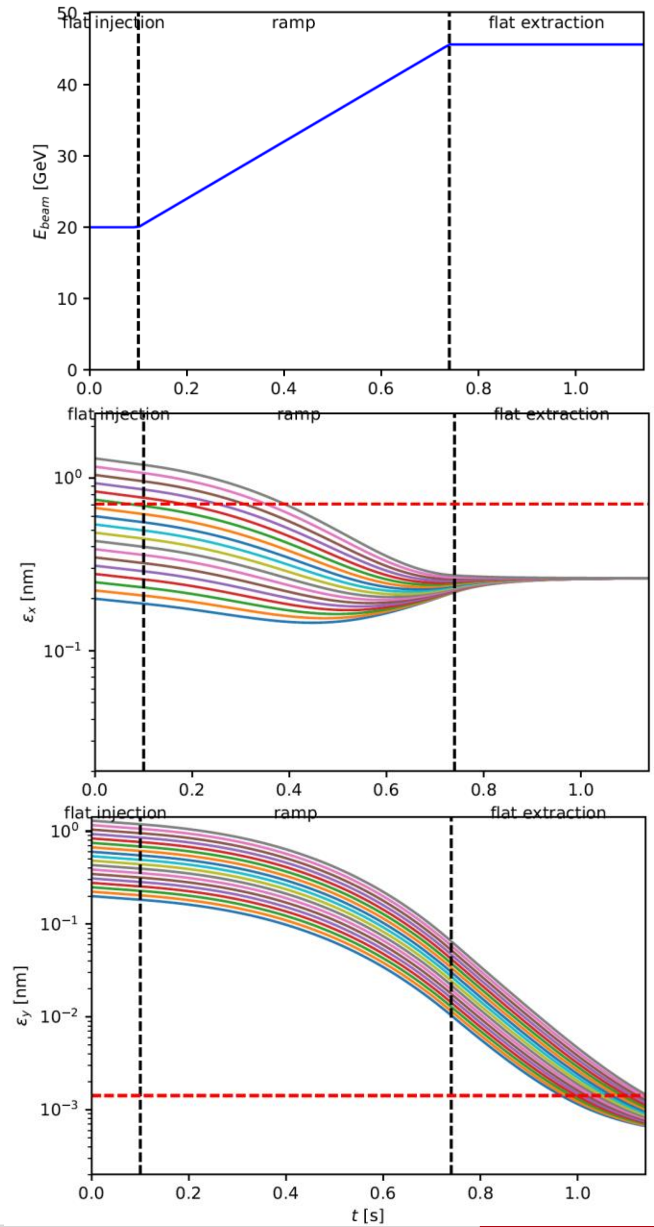
Possible solutions (3/3): change I2 integral & ramp time

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

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

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

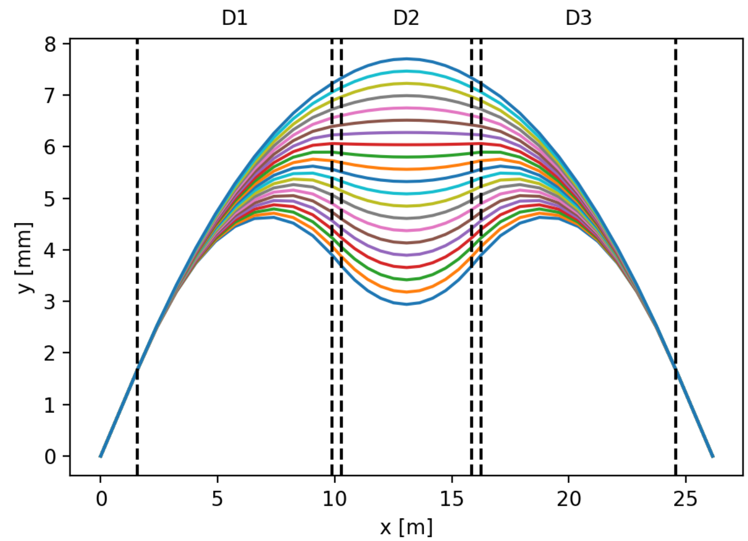


Possible solution :

- 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**