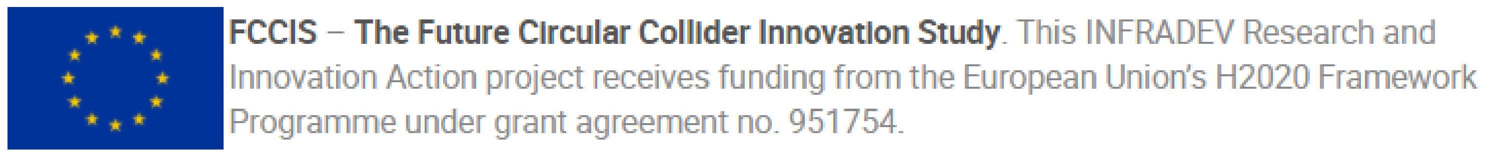
FCC BOOSTER DESIGN

A. Chance, B. Dalena, Q. Bruant (CEA), A Ghribi (CNRS)
A. Mashal (IPM), M. Migliorati (UniRoma), A. Rajabi (DESY)
F. Zimmermann (CERN)

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, T. Raubenheimer

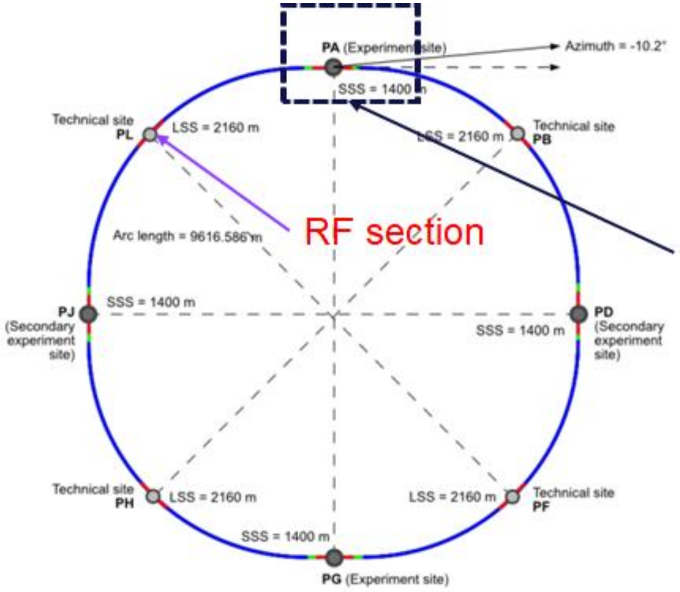

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

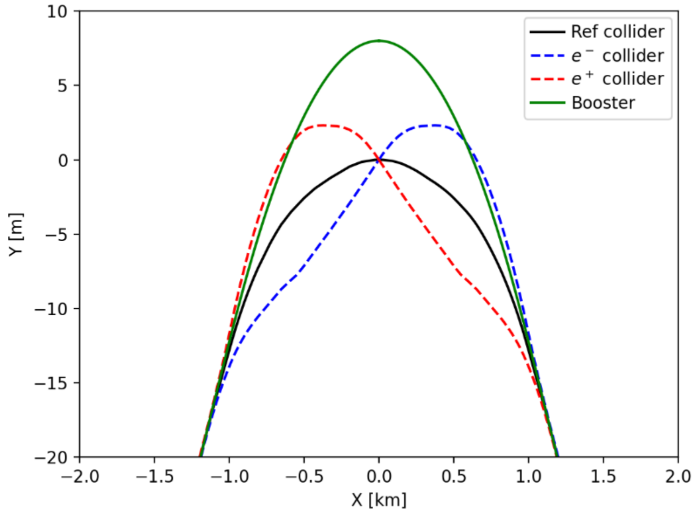
Major changes since FCC week 2023

- **Linac of 20 GeV as an injector + High-energy damping ring**
- **Same circumference as the collider**.
- **Better second order matching** in the insertions.
- **Reduced number of stored bunches** in the booster (safer injection to the collider).
    - Maximum number of stored bunches at Z/W/ZH/ttar operation: 1120/926/300/64.
    - Requires 10/2/1/1 booster cycles to give the total number of bunches to the collider.
    - Shorter accumulation time.
    - Enlarges the pressure tolerance and TCBI threshold (reduced average current).
- **Reduces maximum bunch charge** for **ZH/ttbar** operation: 4 nC → 1.6 nC.
    - Reduces the peak radiated power.
    - Enlarges the allowed impedance budget for ZH/ttbar operation.
- **Larger beam pipe** aperture: 50 mm → 60 mm (Copper).
  - Smaller contribution of the beam pipe to the impedance budget.
  - Enlarges the TMCI/TCBI threshold: same optics possible for all modes.
- **Larger misaligment errors** (150 um pre-alignment in the arcs → 200 um girder-to-girder + 50 um girder pre-alignement) and **orbit tuning procedures**

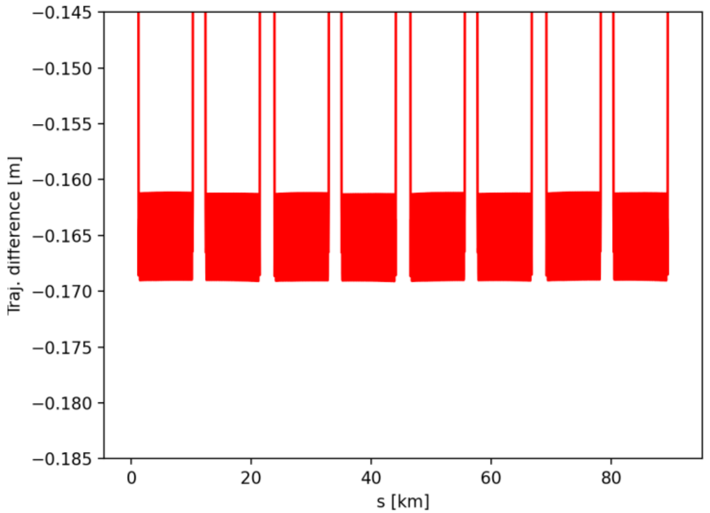
Layout status

October 2024

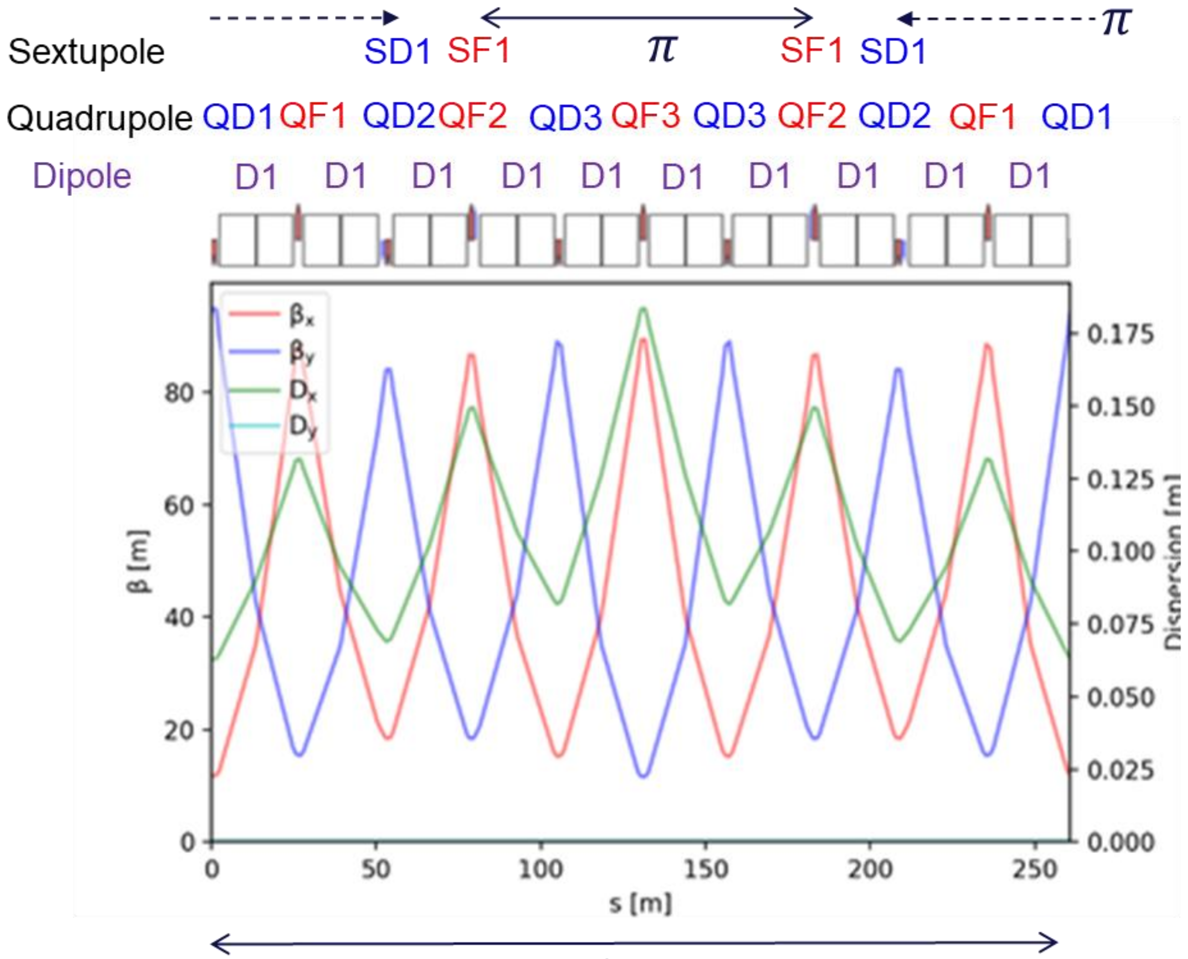




- 800 MHz cavities are located in section L.
- The booster is in the outer side of the collider with an offset at the IP of 8 m.
- The booster follows the geometry of the collider *V24.3_GHC*.
- The offset in the arcs has been adjusted according to get **the same circumference as the collider**:
  - Collider circumference: 90658.71376 m.
  - Booster circumference: 90658.713761 m
  - **The booster has an offset of -165 +/- 4 mm in the arcs.**



Baseline optics: V24.1_FODO

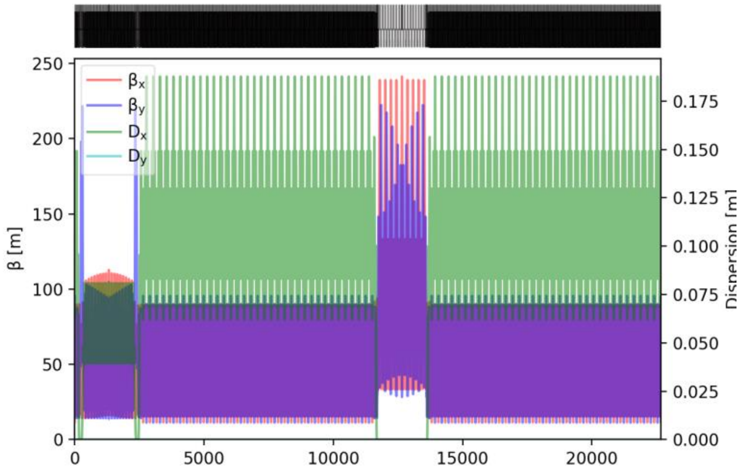


$$\frac{5\pi}{2} + \epsilon_{x,y}$$

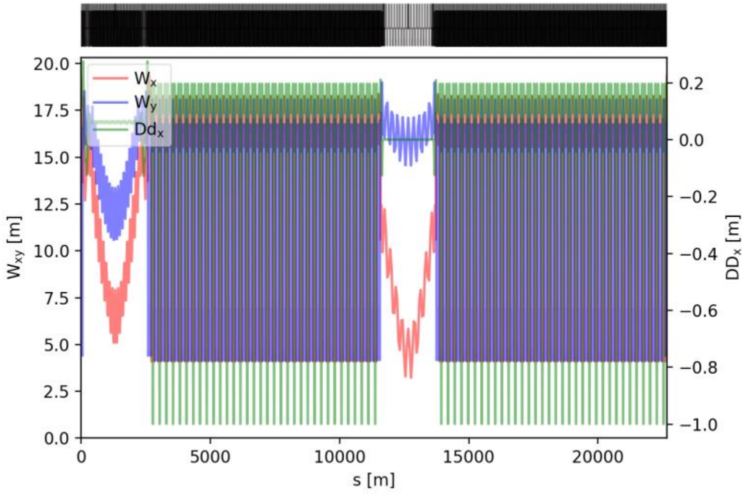
- Made of about 5 FODO cells of 52 m.
- 6 quadrupole families with about the same strength
  - to have a phase advance of π between the pair of sextupoles
  - To adjust the tune of the arc cell to get the target global tune.
- 1 dipole corrector + 1 BPM per quadrupole:
  - Horizontal when QF
  - Vertical when QD
- Cell length adjusted to follow the collider arc periodicity.
- Since V24_FODO, quadrupoles are a bit longer to reduce the power consumption: 1.3 m → 1.5 m.

Baseline optics: V24.1_FODO

Optical functions (1/4 of ring)



Montague functions (1/4 of ring)



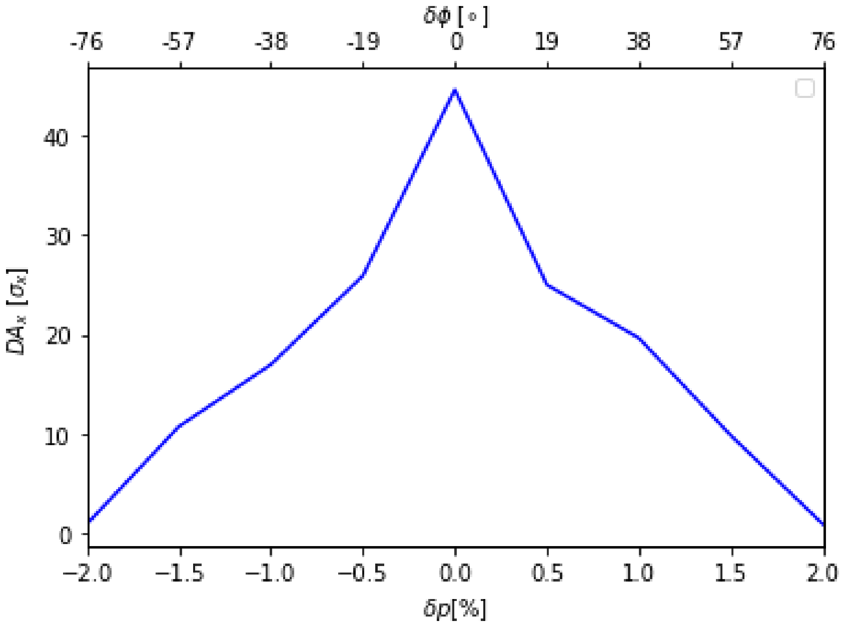
- Arc cell of 260 m with 5 quasi-FODO cells of 90° of 52 m each.
- Transparency conditions for the insertions:
  - Phase advance of π in both planes of between the focusing sextupoles in the dispersion suppressor to maximize the geometric aberration cancellation.
  - The angles of some dipoles in the dispersion suppressors have been matched to cancel the second-order dispersion.
  - Phase advance of the total insertion (including the dispersion suppressors) is equal to the phase advance of one arc cell (modulo 2 π).
  - Matching of the Montague and second-order dispersion.
- Tune Q_x/Q_y: **414**.225/**410**.29
- Momentum compaction: 7.13e-06; I5: 1.71e-11
- Cavities have been integrated to the lattice for the 4 modes.

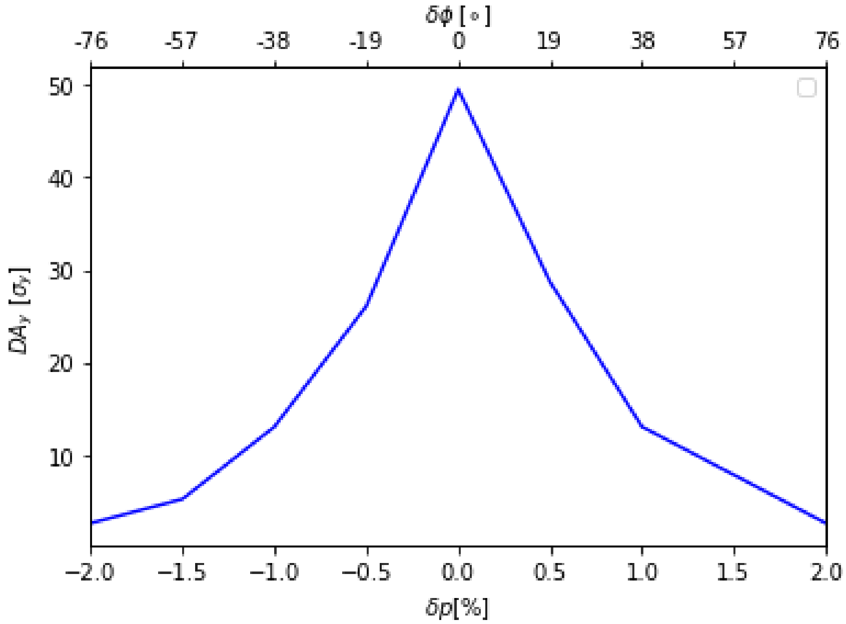
Magnet	Parameter	Unit	Value
Dipole	Min./Max. field	G	64 – 584
	Length	m	11.0
Quadrupole	Min./Max. gradient	T/m	0.5 – 23.2
	Length	m	1.5
Sextupole	Min./Max. gradient	T/m^2	35 – 1260
	Length	m	0.7 – 1.4

Dynamic aperture and momentum acceptance

Courtesy: B. Dalena, A. Mashal

- 6D Dynamic aperture calculated at IP2.
- Thanks to the transparency conditions, dynamic aperture and momentum acceptance stay quite large.
- We should be able to accept a phase jitter at injection up to 25°.
- In parallel, some work was done to enlarge the dynamic aperture of the baseline by using more sextupole families (criteria: enlarge the xi parameter linking the path length variation to the action).





Layout and constraints

Layout and geometry

- 8.5 degrees (~150 mrad) angle between transfer line and beam line
- Limited space between the wall and the booster beam line

Placement

- Fast rise of the kicker requires minimizing the distance between kicker and generator (alcove)
- Presently the injection line intersects to the booster ring is ~25m from the alcove

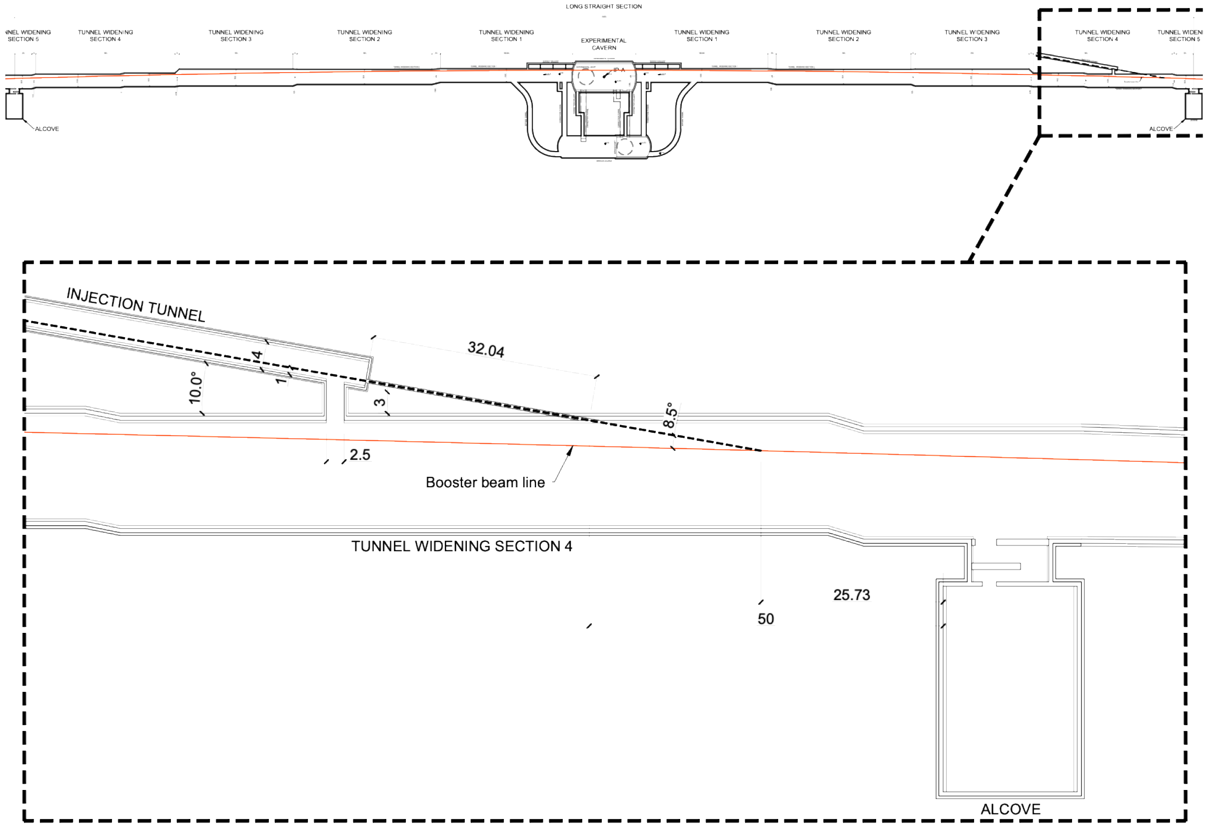
Solution

- Dipoles in the tunnel for a total of ~ 125 mrad
- Long septum system with 25 mrad cumulated angle
- 2 plane injection with small vertical angle of 90 µrad

Layout changes

- Present layout does not allow placement of septa at the intersect and kicker in front of the alcove
- 2 possible solutions
  - Moving the injection line intersect at least 25 m closer to the IP
  - Moving the Alcove at least 25 m further

Courtesy: Sen Yue

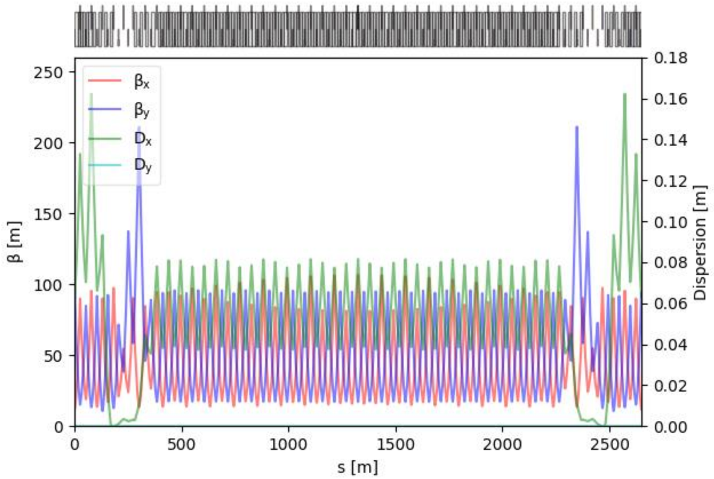


The detail information can be found in the ATDC meeting:
https://indico.cern.ch/event/1463503/

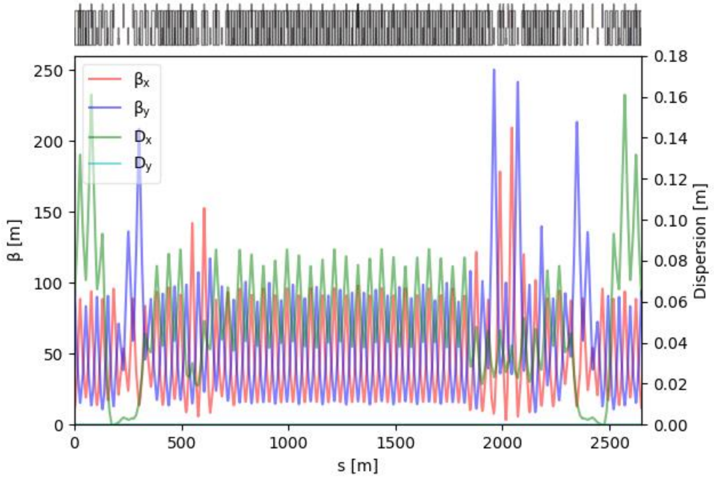
Optics design – positron V24_FODO

- A vertical defocusing quad is placed between septa and kicker
  - 2 additional quads are added for optics optimization.
  - 2*11 additional independent power supplies on quadrupoles
  - Minimal changes to the ring optics are expected.
- A global rematching of the insertion has been performed to get the matching conditions:
  - Global tune: **414**.225/**410**.29 → **415**.225/**410**.29
  - Dispersion bump near the electron injection to match the second-order dispersion.
- **Dynamic aperture and momentum acceptance to be evaluated.**
- **To be updated with V24.1_FODO.**

NO injection optics



WITH injection optics



Emittance evolution

We consider here the Z operation mode, which is the most demanding.

- The synchrotron radiation damping time at top energy is still quite large: 0.76 s.
  - **The total cycling time** (ramp-up + flat-top + ramp-down) **should be about 1 s**.
  - The time the beam spends in the booster is roughly the same as the damping time at Z energy: we have some SR damping but not so much.

→ The **final beam parameters will depend on the initial parameters**.

We have considered 2 initial beam parameters → **Injector complex: status and outlook by Paolo Craievich**

- Linac alone. $\epsilon_{xN} = 10\ \mu\text{m} \times \epsilon_{yN} = 10\ \mu\text{m} \times \sigma_{\Delta\text{p}/p} = 10^{-3}$
- High-energy damping ring. $\epsilon_{xN} = 20\ \mu\text{m} \times \epsilon_{yN} = 2\ \mu\text{m} \times \sigma_{\Delta\text{p}/p} = 10^{-3}$

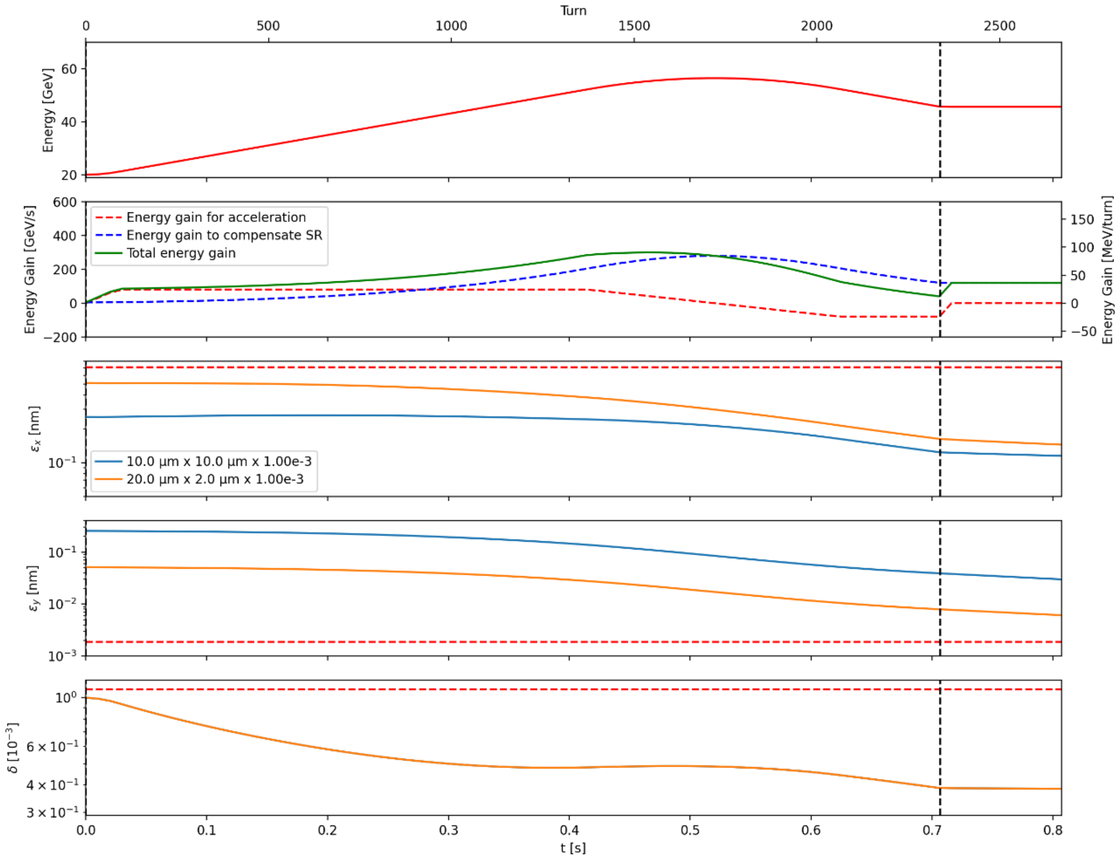
Collider acceptance allows a factor 1 on ϵ_{xRMS} and 5 on ϵ_{yRMS}. The target at extraction is:

Collider: $\boldsymbol{\epsilon_{xRMS} = 0.71\text{nm} \times \epsilon_{yRMS} = 1.9\ \text{pm} \times \sigma_{\Delta p/p} = 1.09\ 10^{-3}}$

Target: $\boldsymbol{\epsilon_{xRMS} < 0.71\text{nm} \times \epsilon_{yRMS} < 9.4\ \text{pm} \times \sigma_{\Delta p/p} = 1.09\ 10^{-3}}$

Emittance evolution Baseline (no accumulation)

Total cycling: 0.706 (ramp-up) +0.1 (flat-top) + 0.334 (ramp-down) = 1.14 s



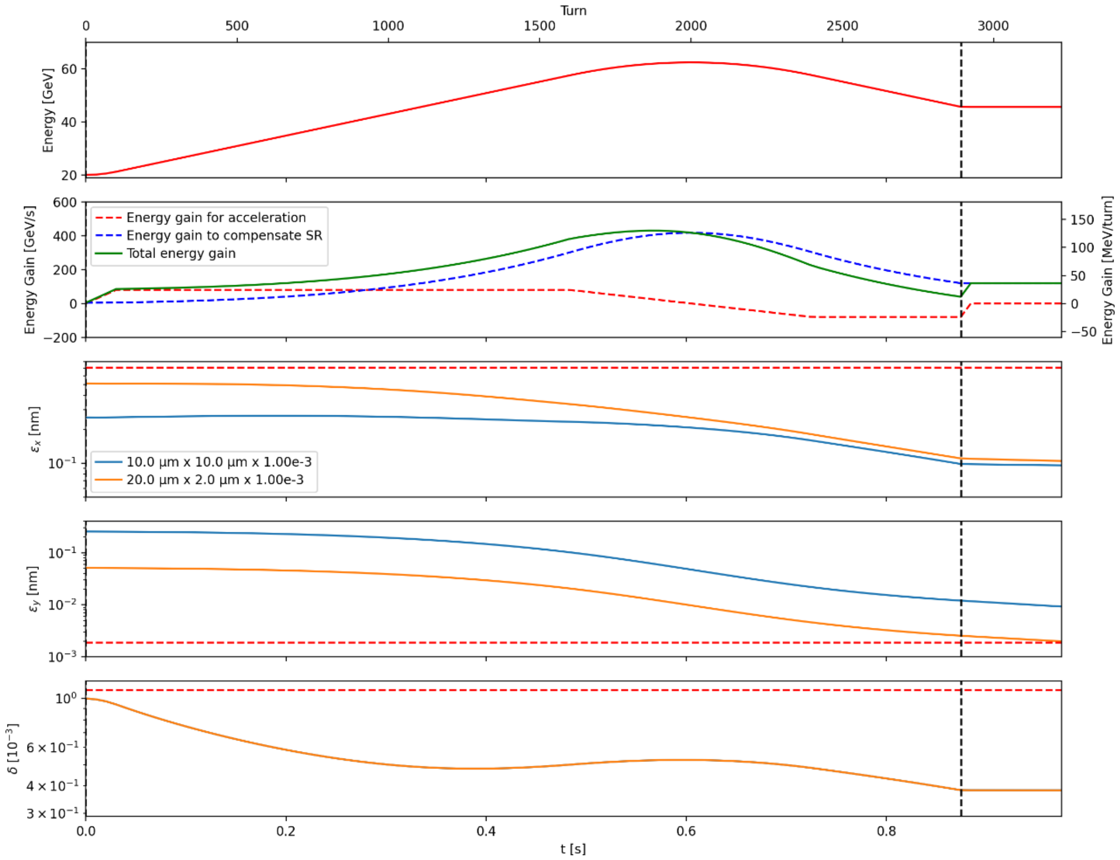
We use the double parabolic ramp + energy overshoot.

- Adiabatic start of the ramp (5% of initial energy gain)
- Steep linear energy ramp in the middle (80 GeV/s)
- Adiabatic approach of the flat top energy (80% of total gain)

- Linac alone: Initial beam parameters: 10 µm x 10 µm x 1e-3
  - Hor. Emittance: **0.122 nm**
  - Vert. Emittance: **30.0 pm**
  - Energy spread: **0.387e-3**
- High-energy DR: Initial beam parameters: 20 µm x 2 µm x 1e-3
  - Hor. Emittance: **0.159 nm**
  - Vert. Emittance: **6.12 pm**
  - Energy spread: **0.387e-3**

Emittance evolution
Shorter ramp-down by 170 ms

Total cycling: 0.876 (ramp-up) + 0.1 (flat-top) + 0.164 (ramp-down) = 1.14 s



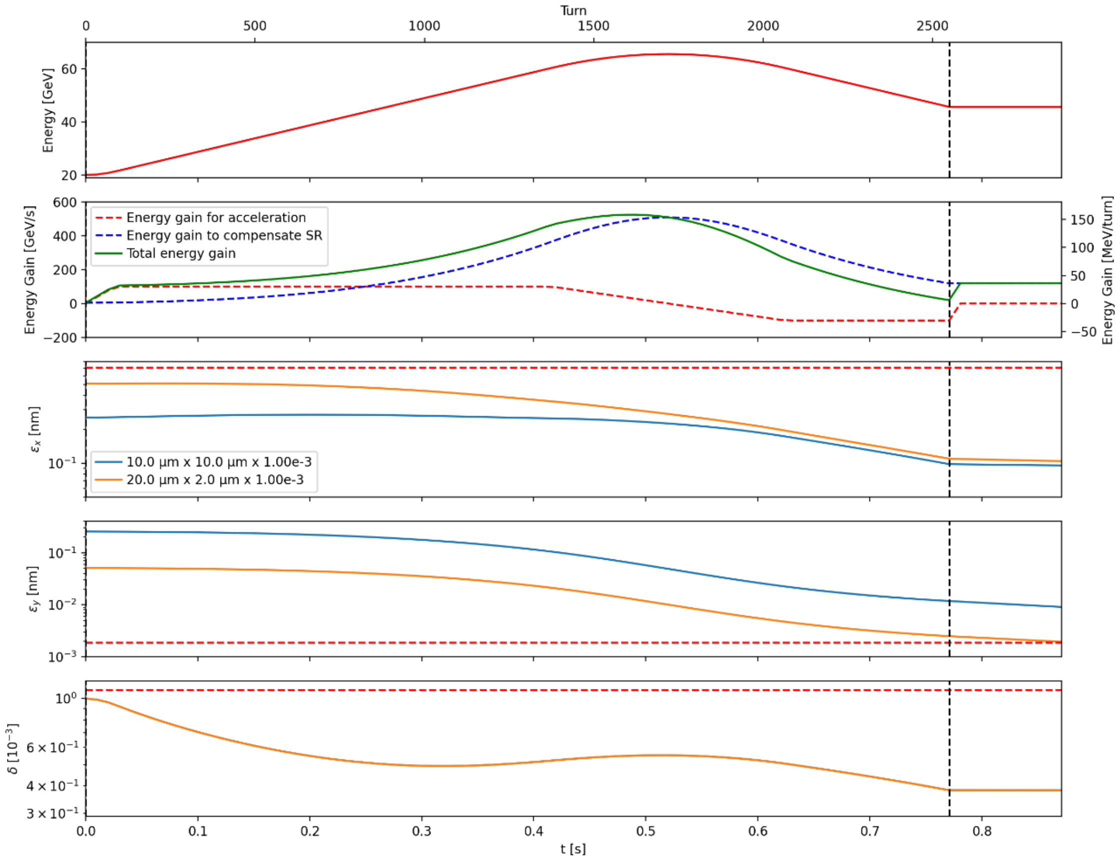
We use the double parabolic ramp + energy overshoot.

- Adiabatic start of the ramp (5% of initial energy gain)
- Steep linear energy ramp in the middle (80 GeV/s)
- Adiabatic approach of the flat top energy (80% of total gain)

- Linac alone: Initial beam parameters: 10 µm x 10 µm x 1e-3
  - Hor. Emittance: **0.096 nm**
  - Vert. Emittance: **9.27 pm**
  - Energy spread: **0.382e-3**
- High-energy DR: Initial beam parameters: 20 µm x 2 µm x 1e-3
  - Hor. Emittance: **0.105 nm**
  - Vert. Emittance: **1.99 pm**
  - Energy spread: **0.382e-3**

Emittance evolution
Higher maximum field slope in dipoles

Total cycling: 0.771 (ramp-up) +0.1 (flat-top) + 0.269 (ramp-down) = 1.14 s



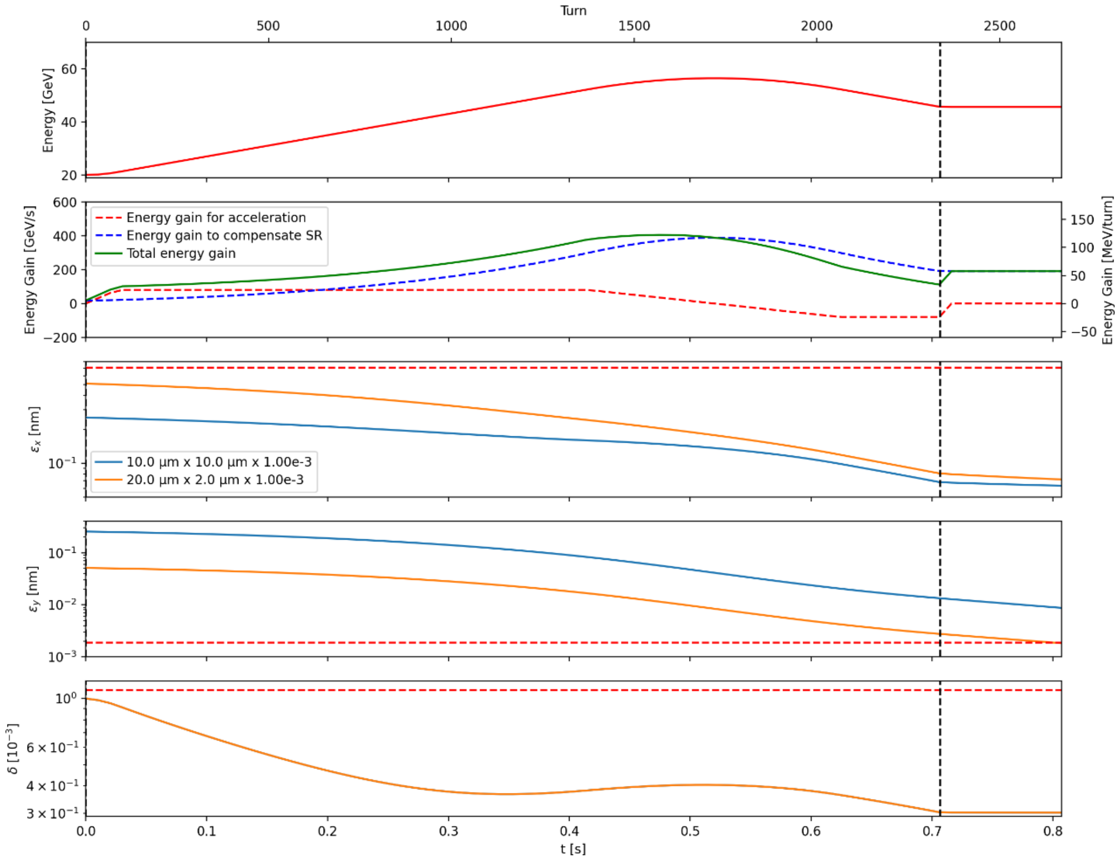
We use the double parabolic ramp + energy overshoot.

- Adiabatic start of the ramp (5% of initial energy gain)
- Steep linear energy ramp in the middle (**100 GeV/s**)
- Adiabatic approach of the flat top energy (80% of total gain)

- Linac alone: Initial beam parameters: 10 µm x 10 µm x 1e-3
  - Hor. Emittance: **0.096 nm**
  - Vert. Emittance: **9.1 pm**
  - Energy spread: **0.382e-3**
- High-energy DR: Initial beam parameters: 20 µm x 2 µm x 1e-3
  - Hor. Emittance: **0.105 nm**
  - Vert. Emittance: **1.96 pm**
  - Energy spread: **0.382e-3**

Emittance evolution
Wiggler: I_2 0.59 mm^{-1} → 2.43 mm^{-1} @20 GeV

Total cycling: 0.706 (ramp-up) +0.1 (flat-top) + 0.334 (ramp-down) = 1.14 s



We use the double parabolic ramp + energy overshoot.

- Adiabatic start of the ramp (5% of initial energy gain)
- Steep linear energy ramp in the middle (80 GeV/s)
- Adiabatic approach of the flat top energy (80% of total gain)

Wiggler 4.925 m, B_{gap}=1.45 T, L_{pole}=9.5 cm, L_{gap}=2cm, 43 poles

- Linac alone: Initial beam parameters: 10 µm x 10 µm x 1e-3
  - Hor. Emittance: **0.063 nm**
  - Vert. Emittance: **8.74 pm**
  - Energy spread: **0.303e-3**
- High-energy DR: Initial beam parameters: 20 µm x 2 µm x 1e-3
  - Hor. Emittance: **0.072 nm**
  - Vert. Emittance: **1.836 pm**
  - Energy spread: **0.303e-3**

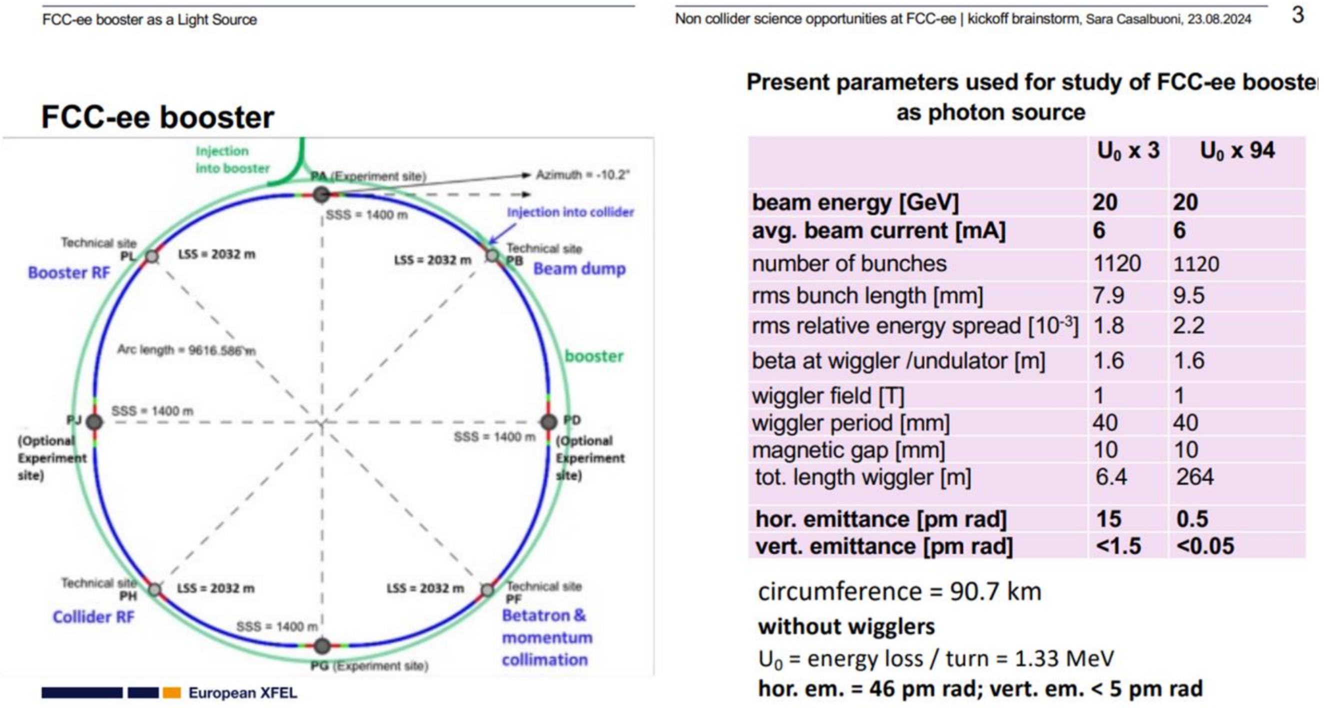
Emittance evolution summary

- **Going through higher energy** than the target during the ramp **speeds up the emittance damping** and gives a **smaller final vertical emittance**.
  - That requires a **higher voltage** (possible for Z operation since the required voltage is smaller than for the other modes) and **higher consumption**.
- **Still a lot of room for optimization** to get the target emittance:
  - The down ramp can be faster (hysteresis and Eddy losses to be optimized).
  - Maximum beam energy variation and Eddy currents in the dipoles to be evaluated.
  - Use of an additional wiggler.
- The **high-energy damping ring helps a lot** thanks to an initial smaller vertical emittance.
- Ramp is under optimization to integrate RF operations considerations.

	Case1: Linac alone	**Case 2, Linac + High-energy DR**
Baseline: cycle of 1.14 s	**30.0 pm**	**6.12 pm**
Shorter ramp-down by 170 ms	**9.27 pm**	**1.99 pm**
Higher max field slope 100 GeV/s	**9.1 pm**	**1.96 pm**
With a wiggler of 4.925 m	**8.74 pm**	**1.836 pm**

Proposal of to use the booster as a light source

Courtesy: Sara Casalbuoni



FCC-ee booster as a Light Source

Non collider science opportunities at FCC-ee | kickoff brainstorm, Sara Casalbuoni, 23.08.2024 3

FCC-ee booster

European XFEL

Present parameters used for study of FCC-ee booster as photon source

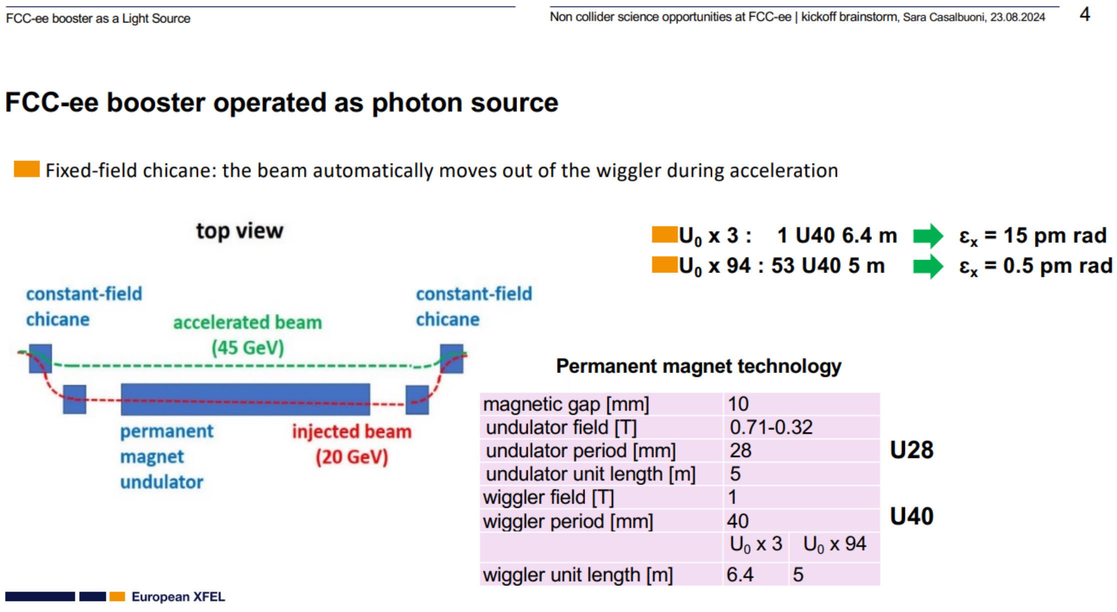
	U_0 x 3	U_0 x 94
beam energy [GeV]	**20**	**20**
avg. beam current [mA]	**6**	**6**
number of bunches	1120	1120
rms bunch length [mm]	7.9	9.5
rms relative energy spread [10^{-3}]	1.8	2.2
beta at wiggler /undulator [m]	1.6	1.6
wiggler field [T]	1	1
wiggler period [mm]	40	40
magnetic gap [mm]	10	10
tot. length wiggler [m]	6.4	264
hor. emittance [pm rad]	**15**	**0.5**
vert. emittance [pm rad]	**<1.5**	**<0.05**

circumference = 90.7 km

without wigglers

U_0 = energy loss / turn = 1.33 MeV

hor. em. = 46 pm rad; vert. em. < 5 pm rad



FCC-ee booster as a Light Source

Non collider science opportunities at FCC-ee | kickoff brainstorm, Sara Casalbuoni, 23.08.2024 4

FCC-ee booster operated as photon source

■ Fixed-field chicane: the beam automatically moves out of the wiggler during acceleration

■ **U_0 x 3 : 1 U40 6.4 m ➡ ε_x = 15 pm rad**

■ **U_0 x 94 : 53 U40 5 m ➡ ε_x = 0.5 pm rad**

Permanent magnet technology

magnetic gap [mm]	10		
undulator field [T]	0.71-0.32		
undulator period [mm]	28		**U28**
undulator unit length [m]	5		
wiggler field [T]	1		
wiggler period [mm]	40		**U40**
	U_0 x 3	U_0 x 94	
wiggler unit length [m]	6.4	5	

European XFEL

Status and plans

- The photon beam is parasitic: should not change the booster operation.
- The damping time at the injection energy should be short enough to reach the equilibrium emittance.
  - $\tau_x \ll \tau_{flatbottom} = 2s \Rightarrow 2\tau_x < 200\text{ ms} \Rightarrow I_2 > 0.054\, m^{-1} \Rightarrow U_0 > 91 U_{0,no\ wiggler}$.
- Let us take $U_0 = 94 U_{0,no\ wiggler} = 126 \frac{MeV}{turn}$
- We could locate most of the damping undulators in one of the dispersion free straight sections and add a dedicated undulator for the the light source in the cavern. Needs for lattice modifications.
  - We need more RF power and RF voltage:
    - 50.1 MV/0.020 MW → 206 MV/1.86 MW at injection.
    - How to switch off the undulators/use a chicane during the ramp is still to be discussed.
  - Mechanical integration to be evaluated (weight…).
  - **Needs for Mad-X/X-Suite development to have the undulator element** for a more accurate calculation of the equilibrium emittance.

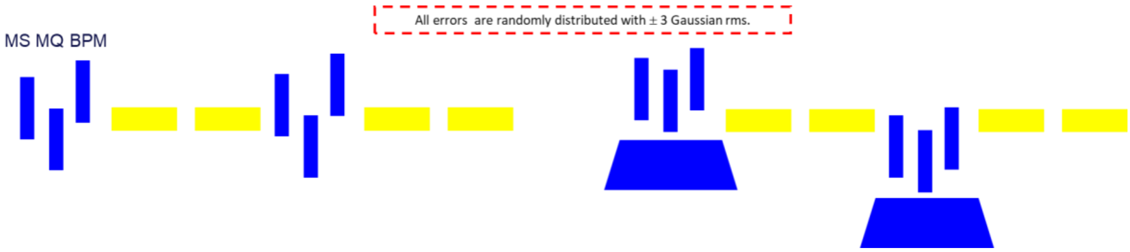
Correction strategy

Courtesy: B. Dalena, Q. Bruant

Similar to SuperKEKB commissioning

All orbit correctors are individually powered and located near one BPM at each quadrupole.
The correction strategy has two main sections:

1. With the sextupoles turned off (or very low strength).
    - Segment-by-Segment (SbS) correction *i.e.* arc by arc; which is similar to the LHC commissioning.
    - Two Singular Value Decompositions (SVD) on all arcs and in line, in order to get a small enough residual orbit for finding the closed orbit.
    - Multiple iterations of SVD in ring.
2. With the sextupoles turned on (full strength).
    - One iteration of SVD in ring.
    - Matching of the tunes and the chromaticity to nominal values, using the quadrupoles and sextupoles in the dispersion suppression and matching regions.
    - Orbit correction, tune and chromaticity.

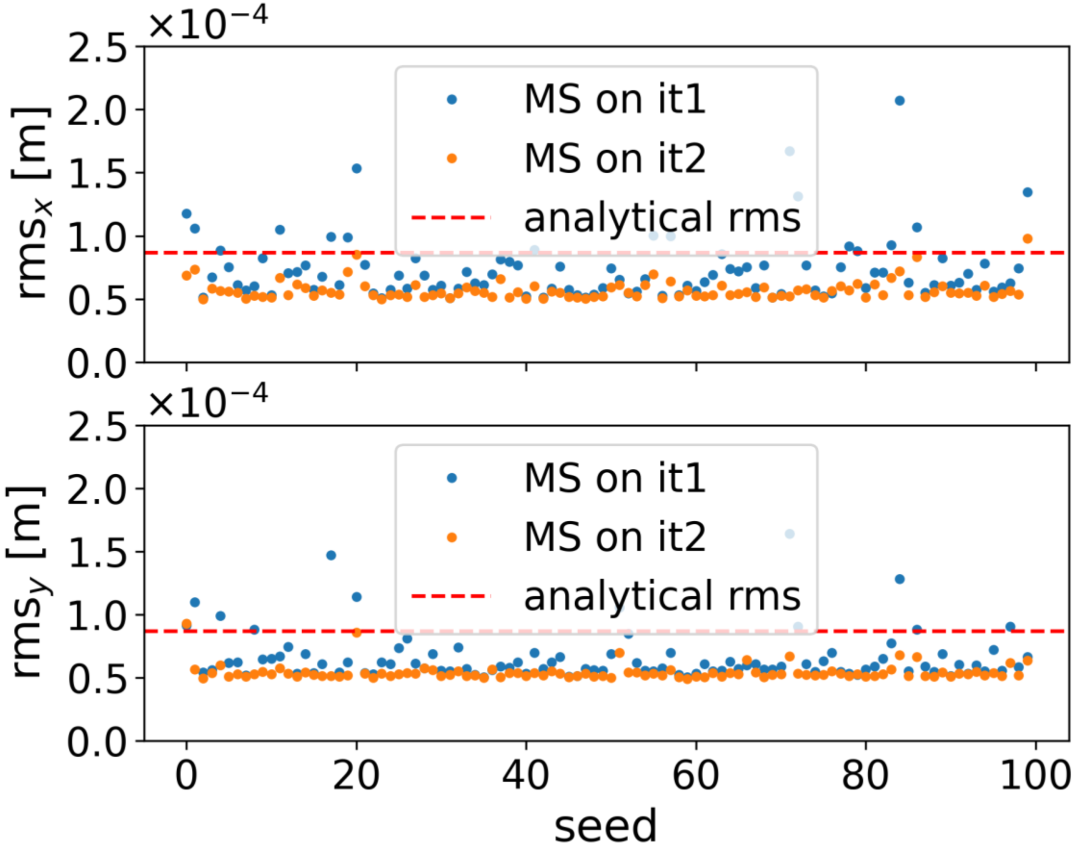


Error type (Gaussian ± 3 RMS)	RMS Value	Unit
MB relative field error	10^{-3}	-
MB main dipole roll error	300	µrad
MQ offset (respect to the girder)	50	µm
MQ roll error	100	µrad
MS offset (respect to the girder)	50	µm
BPM offset (respect to the girder)	50	µm
BPM resolution	50	µm
Girder-to-girder offset	200	µm

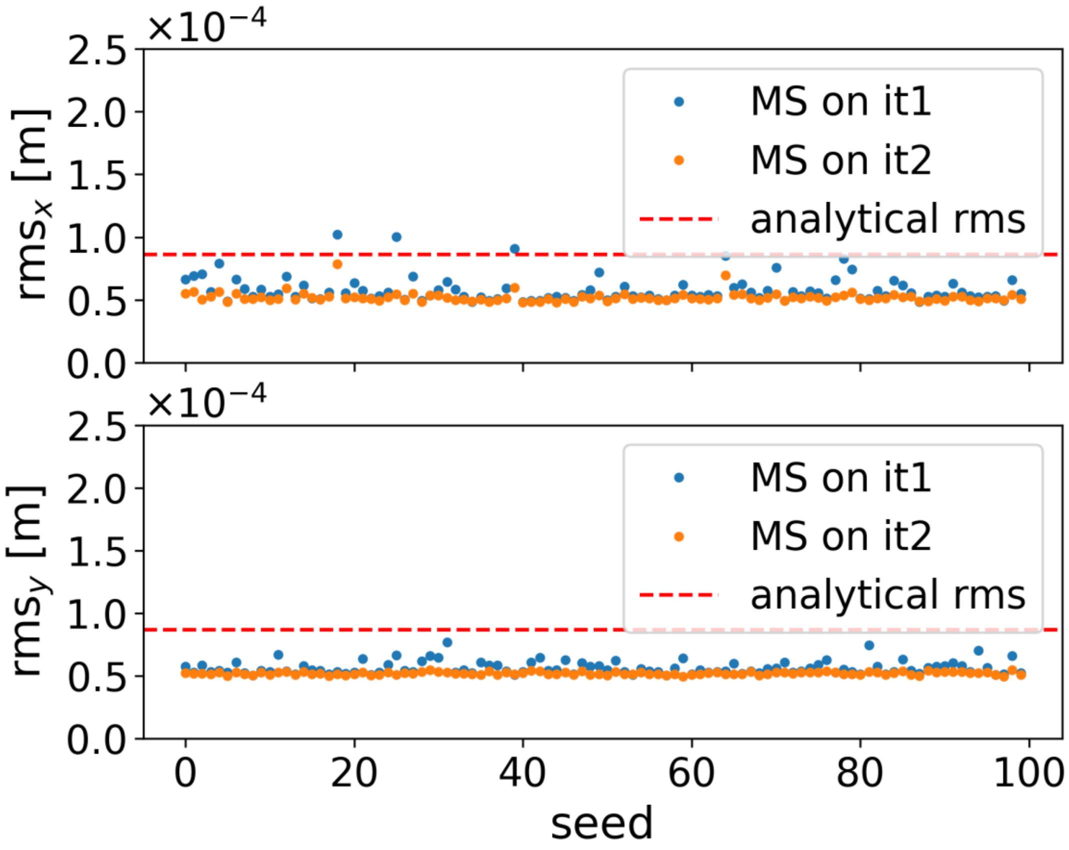
Residual orbit

Courtesy: B. Dalena, Q. Bruant

V24_FODO



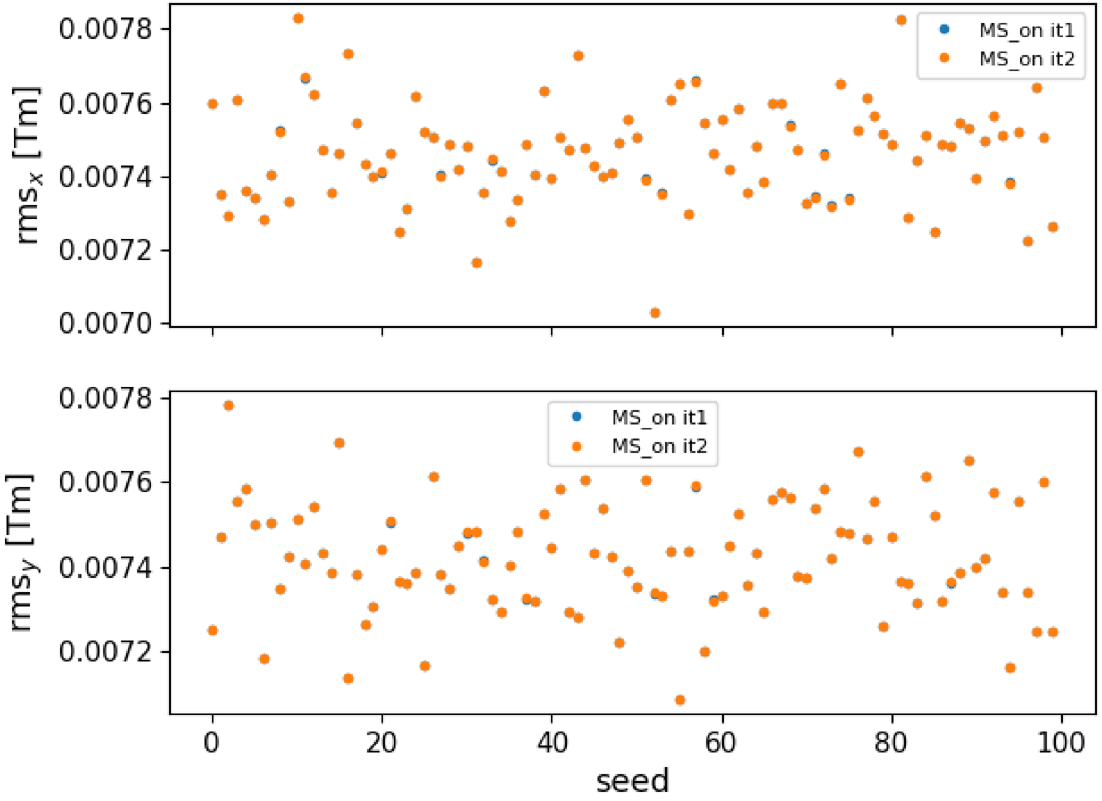
V24_HFD



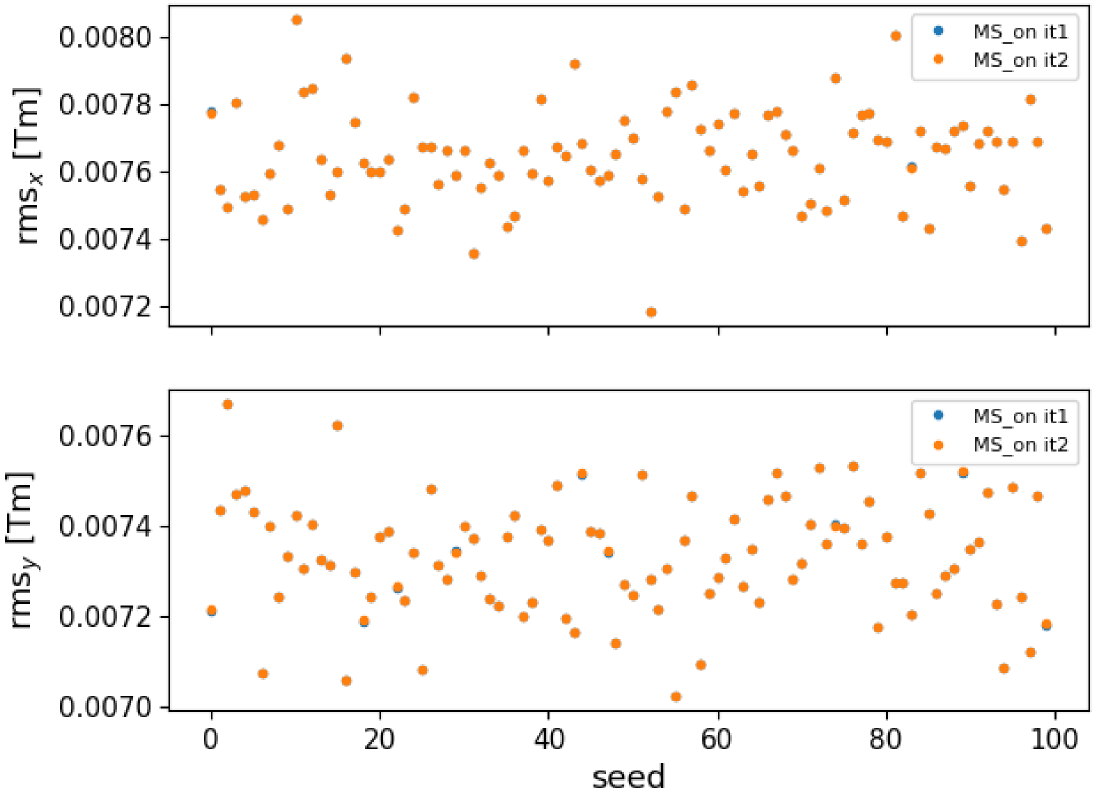
Corrector strength

Courtesy: B. Dalena, Q. Bruant

V24_FODO



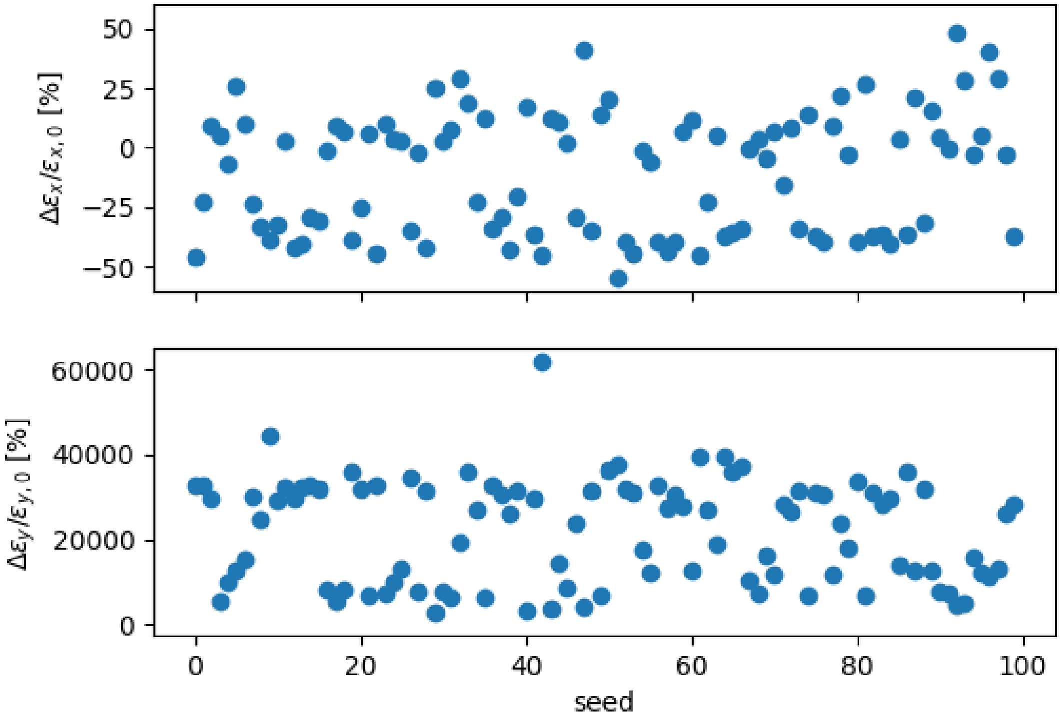
V24_HFD



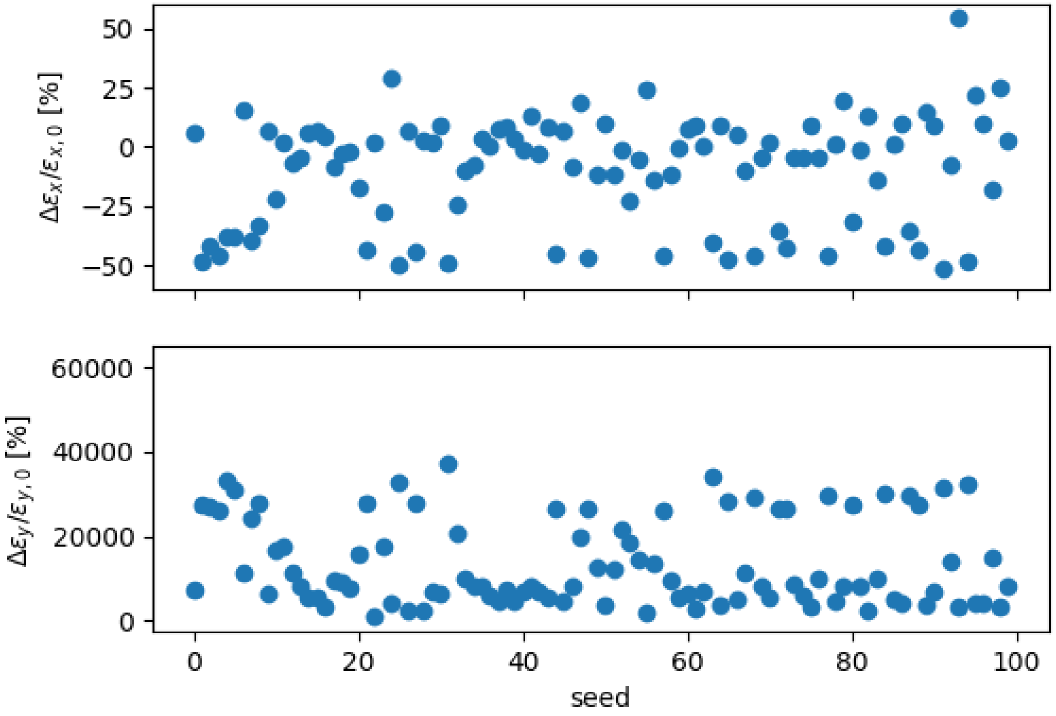
Emittance variation at Z energy

Courtesy: B. Dalena, Q. Bruant

V24_FODO



V24_HFD



Tuning summary

- **Both optics** have **similar final residual orbit** and **corrector values**, even if in the case of the HFD optics, the results are less spread out.
- **Important value of the relative emittance** in vertical transverse plane very strongly coupled (~ 100 %) to a very volatile behavior in horizontal transverse plane in both lattices. One can also consider that the HFD lattice seems to be more stable.
- **Needs of for a dedicated correction** to achieve the target extraction emittance in both transverse planes.

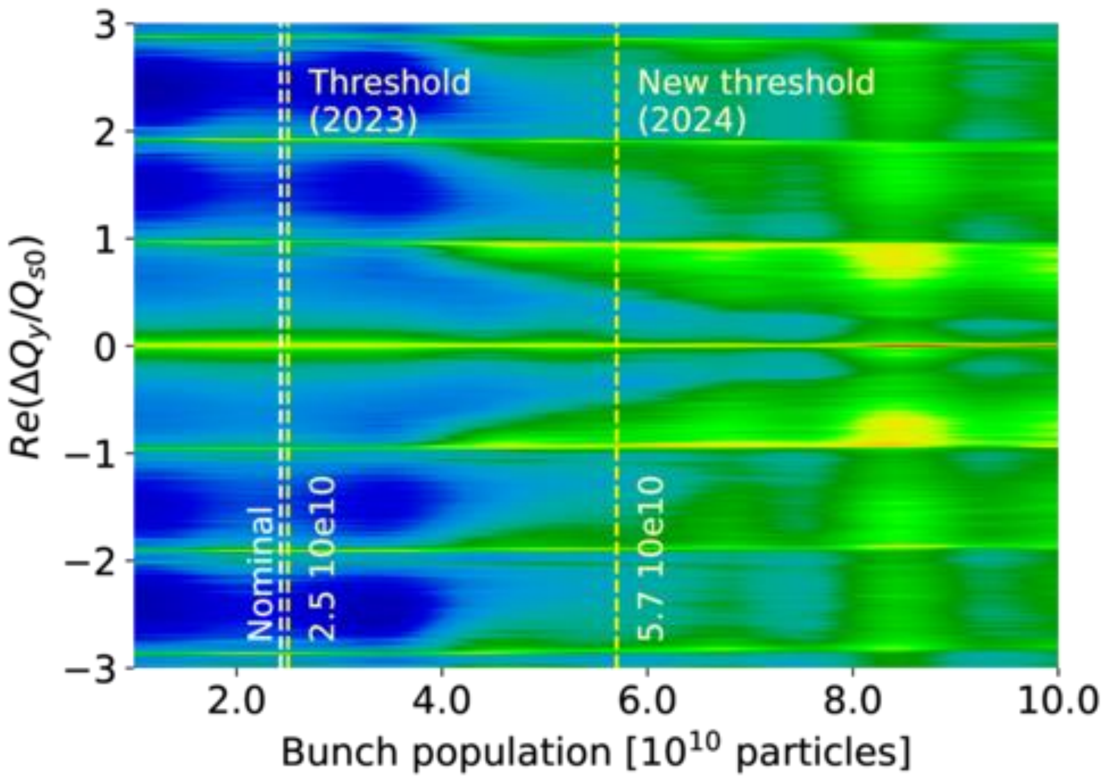
	Unit		**Lattice**	**$3 \times$ RMS Analytic**	**$3 \times$ RMS Seeds**
Residual orbit	µm	x	V24_FODO	252	171
			V24_HFD	251	156
		y	V24_FODO	253	163
			V24_HFD	253	156
Corrector strength	mT.m	x	V24_FODO	23	24
			V24_HFD	-	24
		y	V24_FODO	22	24
			V24_HFD	-	24

Tuning perspectives

- The alignment tuning procedures are validated and work for most cases.
- Some developments with cpymad were done to integrate tuning procedures with quadrupoles and skew quadrupoles to correct the phase advances, beta and dispersion beating, and coupling.
  - Response matrix is calculated.
  - First results are encouraging for the beta-beating correction.
  - Still debugging phase for the coupling correction.

Collective effects
Bunch population scan @ injection energy

Courtesy: A. Ghribi

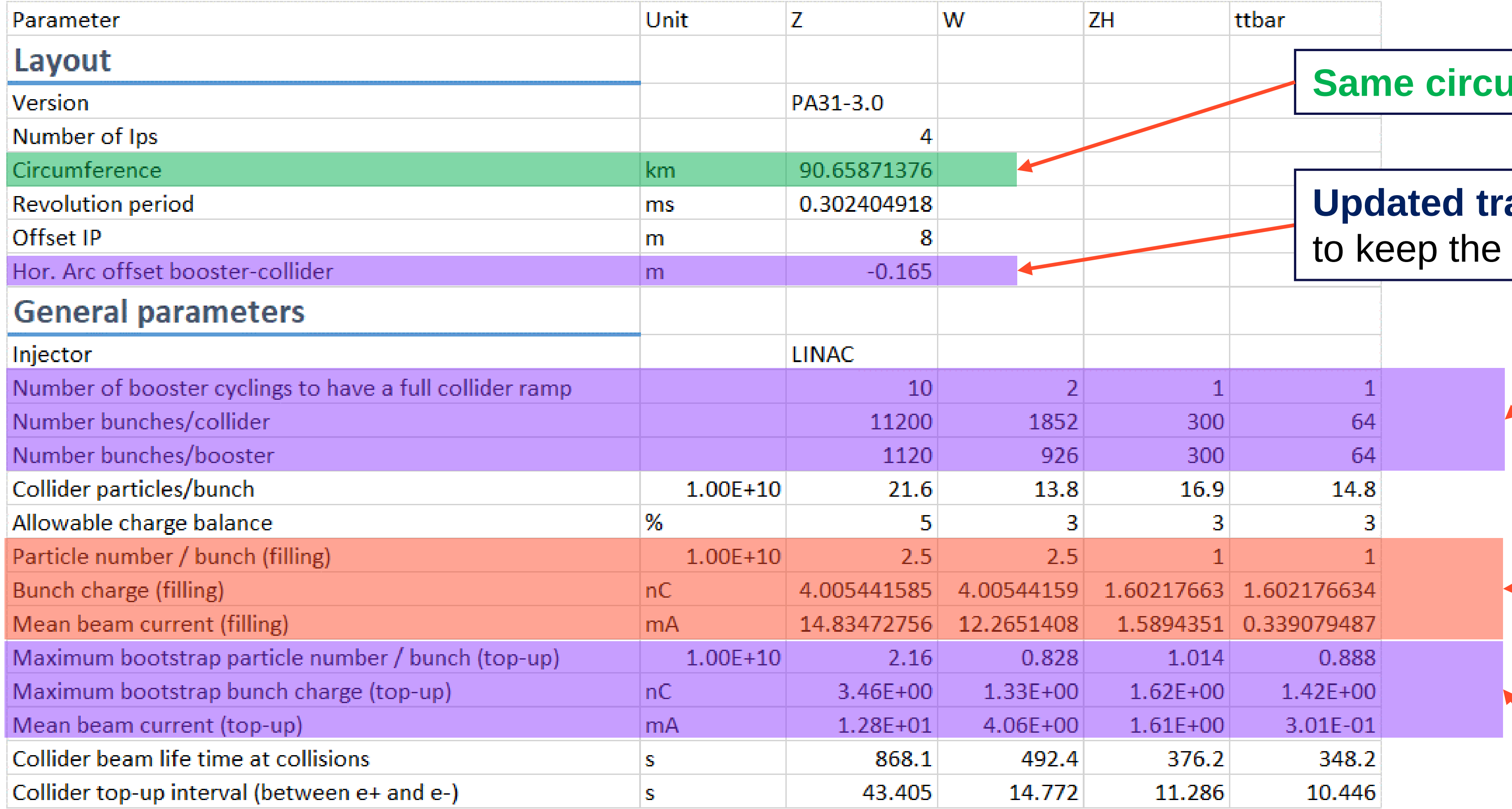


Growth rate as a function of the mode number for the PA31.3 baseline (2024), Z operation, E =20 GeV, σz =4 mm, Nb = 15880, Cu beam pipe (R=30 mm).

- **Going** from a radius of 25 mm **to 30 mm** for the vacuum chamber **cures the Transverse Mode Coupling Instabilies**.
- We can **use the same optics** for all modes.
- We **need a total impedance budget** to fully validate the stability at injection.
- Needs for a feedback system with a damping time of 310 turns.

Parameter summary (1): layout + filling

https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb (access with a CERN account).



Parameter	Unit	Z	W	ZH	ttbar
Layout					
Version		PA31-3.0			
Number of Ips		4			
Circumference	km	90.65871376			
Revolution period	ms	0.302404918			
Offset IP	m	8			
Hor. Arc offset booster-collider	m	-0.165			
General parameters					
Injector		LINAC			
Number of booster cyclings to have a full collider ramp		10	2	1	1
Number bunches/collider		11200	1852	300	64
Number bunches/booster		1120	926	300	64
Collider particles/bunch	1.00E+10	21.6	13.8	16.9	14.8
Allowable charge balance	%	5	3	3	3
Particle number / bunch (filling)	1.00E+10	2.5	2.5	1	1
Bunch charge (filling)	nC	4.005441585	4.00544159	1.60217663	1.602176634
Mean beam current (filling)	mA	14.83472756	12.2651408	1.5894351	0.339079487
Maximum bootstrap particle number / bunch (top-up)	1.00E+10	2.16	0.828	1.014	0.888
Maximum bootstrap bunch charge (top-up)	nC	3.46E+00	1.33E+00	1.62E+00	1.42E+00
Mean beam current (top-up)	mA	1.28E+01	4.06E+00	1.61E+00	3.01E-01
Collider beam life time at collisions	s	868.1	492.4	376.2	348.2
Collider top-up interval (between e+ and e-)	s	43.405	14.772	11.286	10.446

Same circumference as the collider.

Updated transverse offset between booster/collider to keep the same circumference.

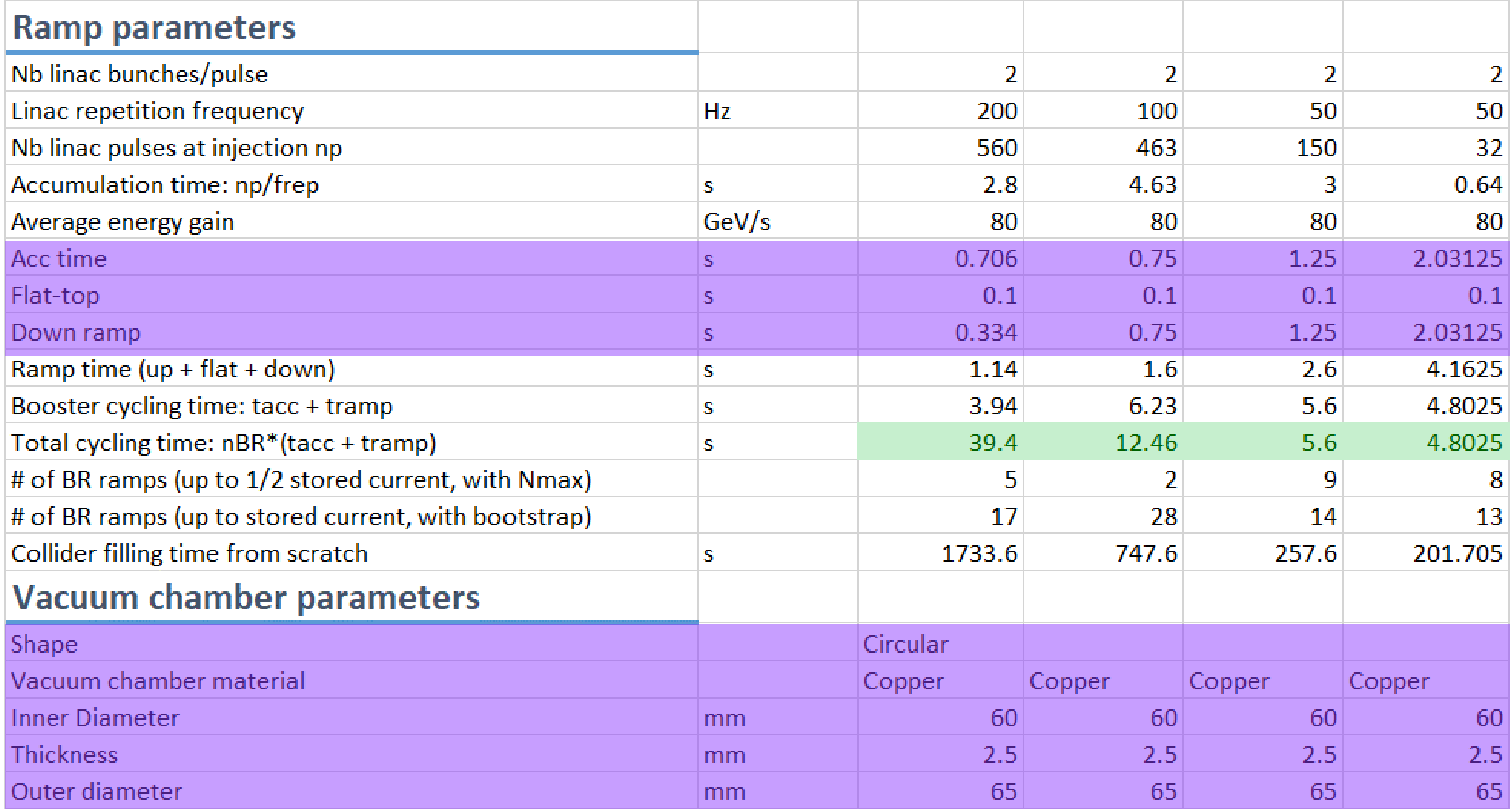
Several booster cyclings in top-up to fill the collider → Less stored bunches in the booster.

Reduced max bunch charge for the filling at tt and ZH operation modes

In top-up injection the charge bunch-to-bunch can vary from 0 to 100% of the bootstrap bunch charge

Parameter summary (2): ramp + beam-pipe

https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb (access with a CERN account).



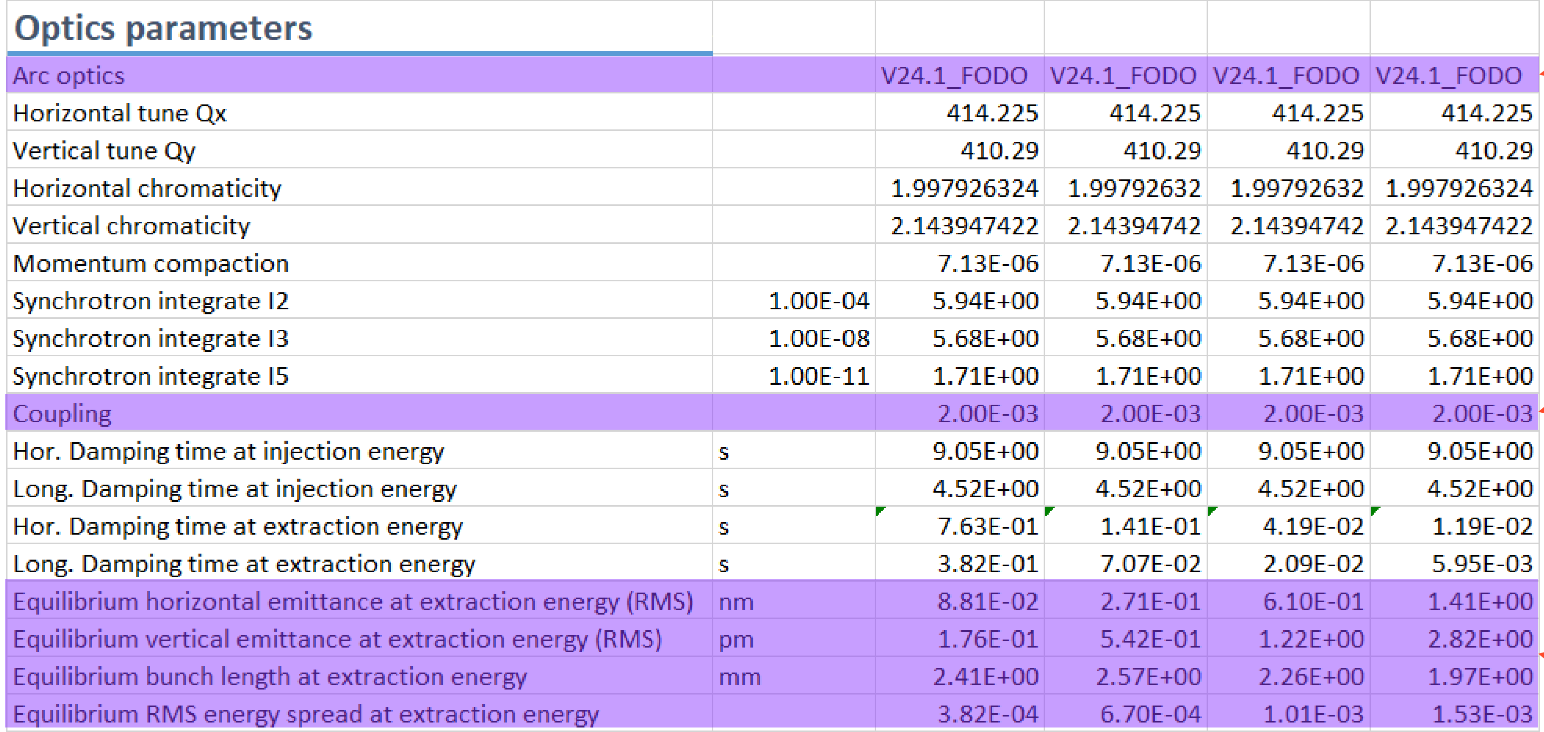
Ramp parameters					
Nb linac bunches/pulse		2	2	2	2
Linac repetition frequency	Hz	200	100	50	50
Nb linac pulses at injection np		560	463	150	32
Accumulation time: np/frep	s	2.8	4.63	3	0.64
Average energy gain	GeV/s	80	80	80	80
Acc time	s	0.706	0.75	1.25	2.03125
Flat-top	s	0.1	0.1	0.1	0.1
Down ramp	s	0.334	0.75	1.25	2.03125
Ramp time (up + flat + down)	s	1.14	1.6	2.6	4.1625
Booster cycling time: tacc + tramp	s	3.94	6.23	5.6	4.8025
Total cycling time: nBR*(tacc + tramp)	s	39.4	12.46	5.6	4.8025
# of BR ramps (up to 1/2 stored current, with Nmax)		5	2	9	8
# of BR ramps (up to stored current, with bootstrap)		17	28	14	13
Collider filling time from scratch	s	1733.6	747.6	257.6	201.705
Vacuum chamber parameters					
Shape		Circular			
Vacuum chamber material		Copper	Copper	Copper	Copper
Inner Diameter	mm	60	60	60	60
Thickness	mm	2.5	2.5	2.5	2.5
Outer diameter	mm	65	65	65	65

The **ramp is under evolution** (especially for the Z-mode).
We keep a flat-top of 0.1 s for all modes for operation considerations.
The down ramp could be faster (less limitations for Eddy currents): under investigation.

Enlarged inner diameter of the pipe.
→ **Smaller beam-pipe impedance**
→ We can use the **same optics** for all operation modes.

Parameter summary (3): optics

https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb (access with a CERN account).



Optics parameters					
Arc optics		V24.1_FODO	V24.1_FODO	V24.1_FODO	V24.1_FODO
Horizontal tune Qx		414.225	414.225	414.225	414.225
Vertical tune Qy		410.29	410.29	410.29	410.29
Horizontal chromaticity		1.997926324	1.99792632	1.99792632	1.997926324
Vertical chromaticity		2.143947422	2.14394742	2.14394742	2.143947422
Momentum compaction		7.13E-06	7.13E-06	7.13E-06	7.13E-06
Synchrotron integrate I2	1.00E-04	5.94E+00	5.94E+00	5.94E+00	5.94E+00
Synchrotron integrate I3	1.00E-08	5.68E+00	5.68E+00	5.68E+00	5.68E+00
Synchrotron integrate I5	1.00E-11	1.71E+00	1.71E+00	1.71E+00	1.71E+00
Coupling		2.00E-03	2.00E-03	2.00E-03	2.00E-03
Hor. Damping time at injection energy	s	9.05E+00	9.05E+00	9.05E+00	9.05E+00
Long. Damping time at injection energy	s	4.52E+00	4.52E+00	4.52E+00	4.52E+00
Hor. Damping time at extraction energy	s	7.63E-01	1.41E-01	4.19E-02	1.19E-02
Long. Damping time at extraction energy	s	3.82E-01	7.07E-02	2.09E-02	5.95E-03
Equilibrium horizontal emittance at extraction energy (RMS)	nm	8.81E-02	2.71E-01	6.10E-01	1.41E+00
Equilibrium vertical emittance at extraction energy (RMS)	pm	1.76E-01	5.42E-01	1.22E+00	2.82E+00
Equilibrium bunch length at extraction energy	mm	2.41E+00	2.57E+00	2.26E+00	1.97E+00
Equilibrium RMS energy spread at extraction energy		3.82E-04	6.70E-04	1.01E-03	1.53E-03

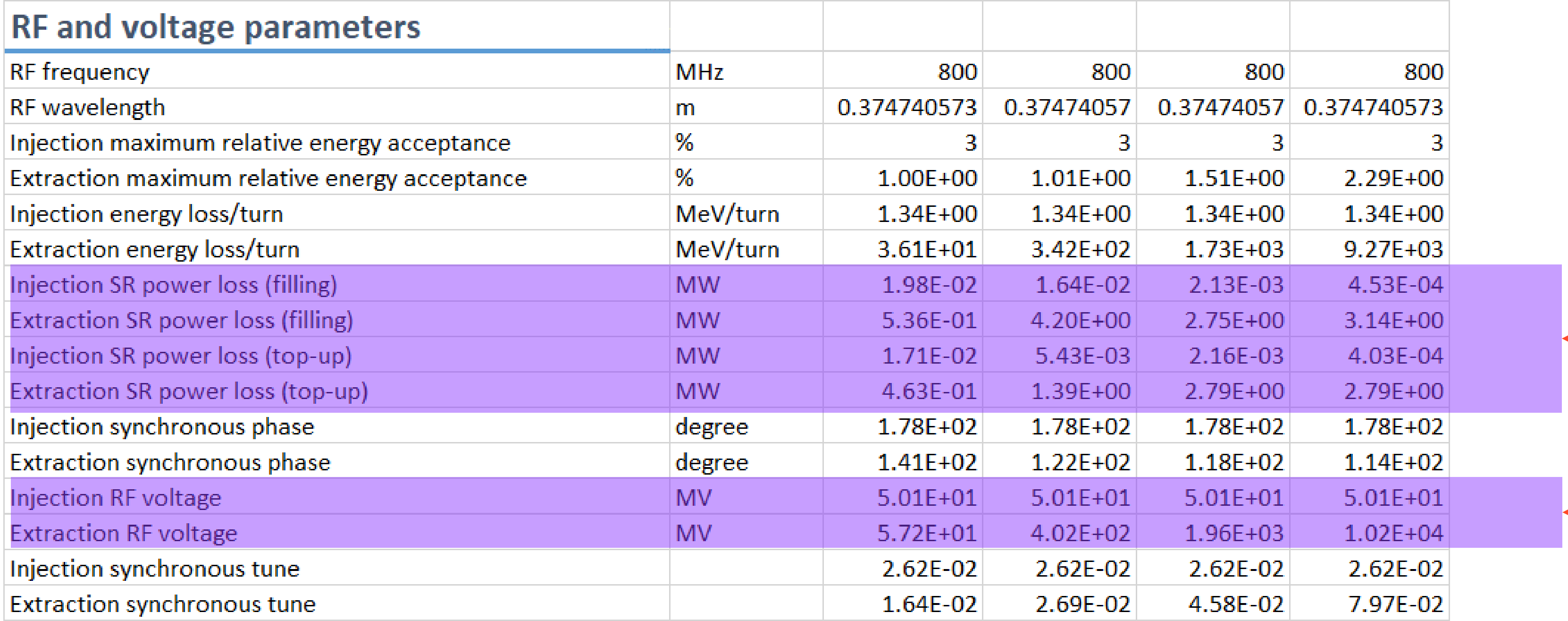
The optics files can be found here: https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb
Dynamic aperture, momentum acceptance, tuning similar between FODO and HFD.

This parameter needs to be reviewed: no need for a so small value to inject into the collider.

Extraction beam parameters (emittances and energy spread) are different from the collider and equilibrium (especially for Z-mode). At Z-mode, ramp optimisation is necessary to get a vertical emittance within the requirements.

Parameter summary (4): RF

https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb (access with a CERN account).



RF and voltage parameters					
RF frequency	MHz	800	800	800	800
RF wavelength	m	0.374740573	0.37474057	0.37474057	0.374740573
Injection maximum relative energy acceptance	%	3	3	3	3
Extraction maximum relative energy acceptance	%	1.00E+00	1.01E+00	1.51E+00	2.29E+00
Injection energy loss/turn	MeV/turn	1.34E+00	1.34E+00	1.34E+00	1.34E+00
Extraction energy loss/turn	MeV/turn	3.61E+01	3.42E+02	1.73E+03	9.27E+03
Injection SR power loss (filling)	MW	1.98E-02	1.64E-02	2.13E-03	4.53E-04
Extraction SR power loss (filling)	MW	5.36E-01	4.20E+00	2.75E+00	3.14E+00
Injection SR power loss (top-up)	MW	1.71E-02	5.43E-03	2.16E-03	4.03E-04
Extraction SR power loss (top-up)	MW	4.63E-01	1.39E+00	2.79E+00	2.79E+00
Injection synchronous phase	degree	1.78E+02	1.78E+02	1.78E+02	1.78E+02
Extraction synchronous phase	degree	1.41E+02	1.22E+02	1.18E+02	1.14E+02
Injection RF voltage	MV	5.01E+01	5.01E+01	5.01E+01	5.01E+01
Extraction RF voltage	MV	5.72E+01	4.02E+02	1.96E+03	1.02E+04
Injection synchronous tune		2.62E-02	2.62E-02	2.62E-02	2.62E-02
Extraction synchronous tune		1.64E-02	2.69E-02	4.58E-02	7.97E-02

Reduction by a factor 2 of the maximum radiated power

Cavity voltage under review (in agreement with ramp update).

Conclusions and perspectives (1)

Optics

- Main changes of the **parameter table** within 1 year.
  - Same circumference as the collider
  - Different filling scheme (Z and W operation).
  - Change of the beam-pipe diameter.
  - New ramp parameters.
- **Better second-order** matching conditions have **improved** the **dynamic aperture** and **momentum acceptance**.
- The injection section has been included for V24_FODO. Cavities are included in V24.1_FODO.
- **Tuning strategies** for the orbit correction have been **improved**.
- We are **below the threshold of the TMCI** with the new parameter table.

Conclusions and perspectives (2)

General

- **Alternative optics** based on HFD has to be updated with new geometry.
- Dynamic aperture calculations to give the tolerances on b_3 and thus Eddy currents.
- Improve the ramping strategy.

Optics tuning

- Emittance growth due to misalignement and errors is not negligible. Ongoing activity:
  - Coupling and vertical dispersion correction algorithms based on the same scheme as for the collider and SuperKEK-B: a skew quadrupole nested with main sextupole.
  - Tune and phase advance: use of trim quadrupoles.
  - Go further in emittance tuning and refine algorithms.

Collective effects

- Refine the impedance budget (include RF contributions, bellows,…).
- Include dampers in stability correction

Longer term:

- Tapering (including the ramp), emittance measurement at least at extraction, beam loss monitors
- Evaluate the booster as a light source.

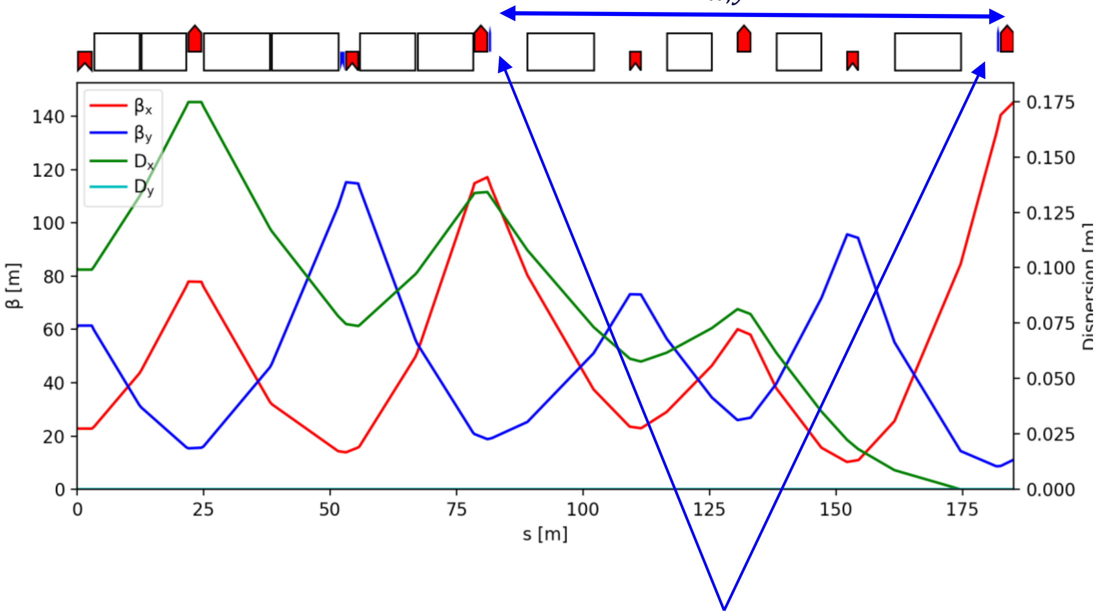
Thank you for your attention

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.

Transparency + dispersion suppressor

Dispersion suppressor

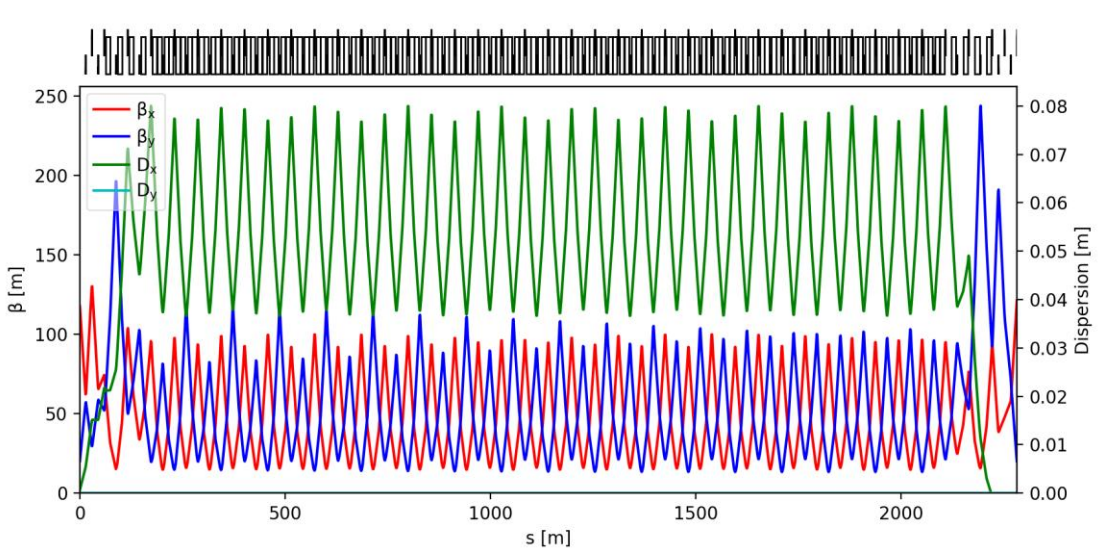
$\Delta\mu_{x,y} \approx \pi$



Sextupole pair used to correct 2^{nd} order chromaticity

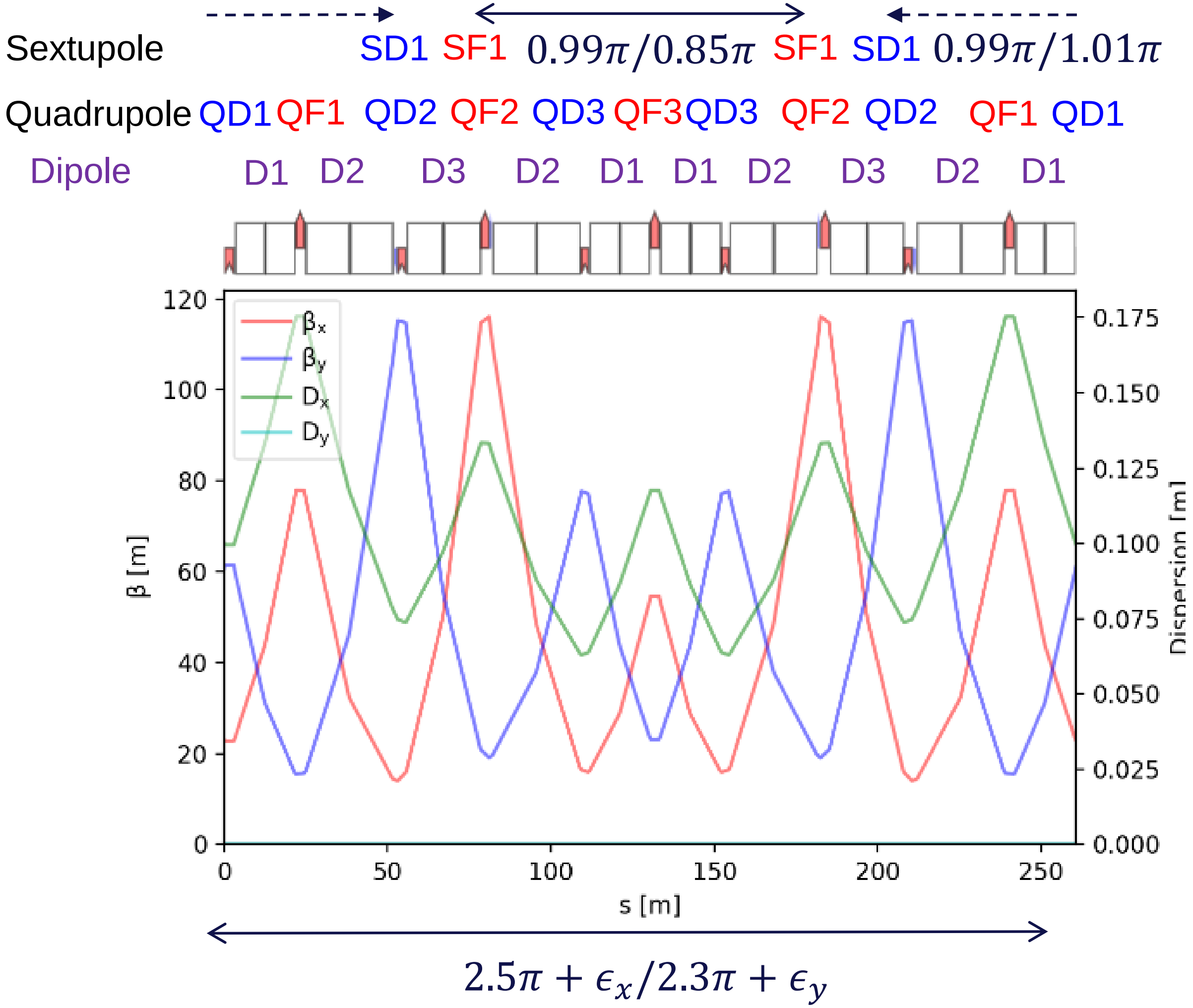
Insertion 1

$\Delta\mu_{x,y} = 2\,n\,\pi + \mu_{x,y\ cell}$



Matching quadrupoles are used to match the Montague functions between the arcs

HFD



Sextupole SD1 SF1 $0.99\pi/0.85\pi$ SF1 SD1 $0.99\pi/1.01\pi$

Quadrupole QD1 QF1 QD2 QF2 QD3 QF3 QD3 QF2 QD2 QF1 QD1

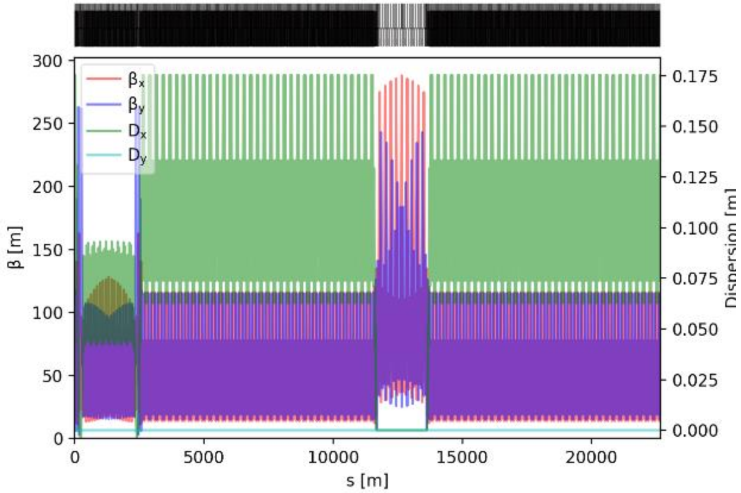
Dipole D1 D2 D3 D2 D1 D1 D2 D3 D2 D1

$2.5\pi + \epsilon_x/2.3\pi + \epsilon_y$

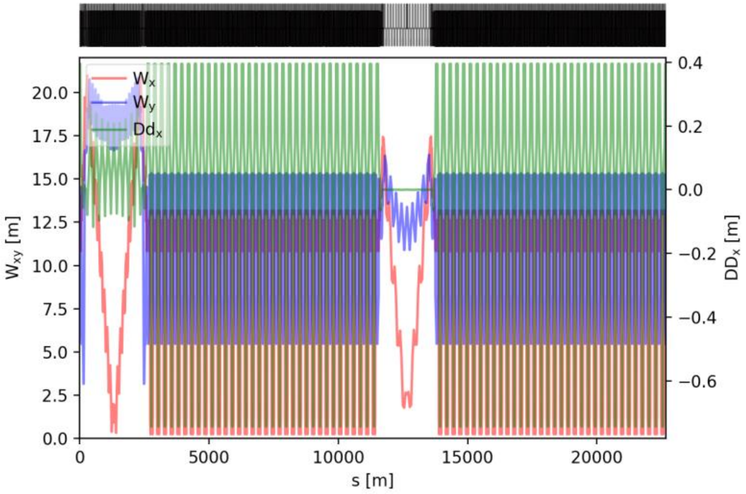
- Variation of the dipole length: 3 families BUT same field (no need of additional powering).
- 6 families
  - to have an optimum phase advance between the pair of sextupoles to minimize anharmonicity
  - To adjust the tune of the arc cell to get the target global tune.
  - The horizontal and vertical tunes are slightly different.
- 1 dipole corrector + 1 BPM per quadrupole:
  - Horizontal when QF
  - Vertical when QD
- Cell length adjusted to follow the collider arc periodicity.

HFD

Optical functions (1/4 of ring)



Montague functions (1/4 of ring)



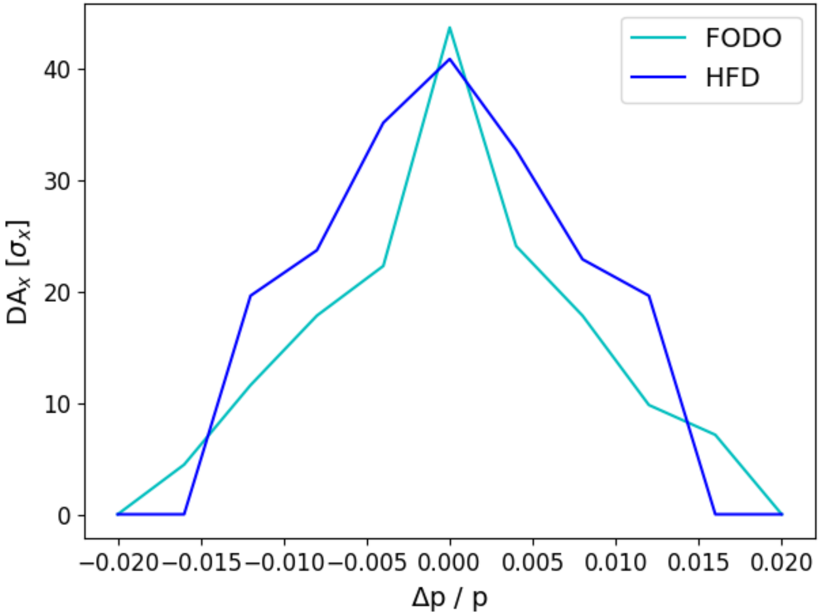
- Modulation of the dipole length to get a better high-order chromaticity.
- Transparency conditions for the insertions:
  - Phase advance of π in both planes of between the focusing sextupoles in the dispersion suppressor to maximize the geometric aberration cancellation.
  - The angles of some dipoles in the dispersion suppressors have been matched to cancel the second-order dispersion.
  - Phase advance of the total insertion (including the dispersion suppressors) is equal to the phase advance of one arc cell (modulo 2 π).
  - Matching of the Montague and second-order dispersion.
- Tune Q_x/Q_y: **411**.225/**382**.29
- Momentum compaction: 7.1**55**e-06; I5: 1.7**8**e-11
- Needs to refine the magnet length to balance the fields

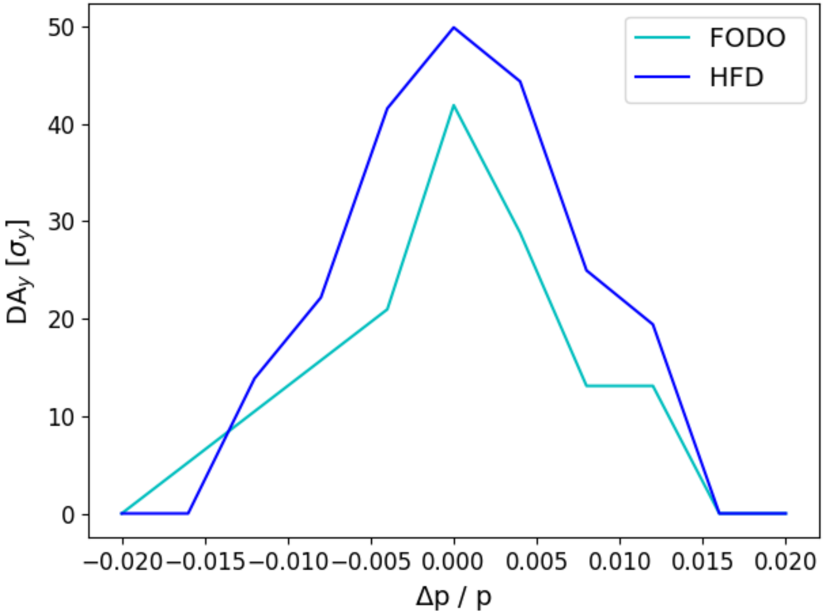
Magnet	Parameter	Unit	Value
Dipole	Min./Max. field	G	64 – 584
	Length	m	11.0
Quadrupole	Min./Max. gradient	T/m	1.42 – 14.7
	Length	m	2.18 – 2.76
Sextupole	Min./Max. gradient	T/m^2	128 – 1340
	Length	m	0.438 – 0.86

Dynamic aperture and momentum acceptance

Courtesy: B. Dalena, A. Mashal

- 6D Dynamic aperture calculated at IP2.
- Thanks to the transparency conditions, dynamic aperture and momentum acceptance for both lattices quite similar.
- In parallel, some work was done to enlarge the dynamic aperture of the baseline by using more sextupole families (criteria: enlarge the xi parameter).

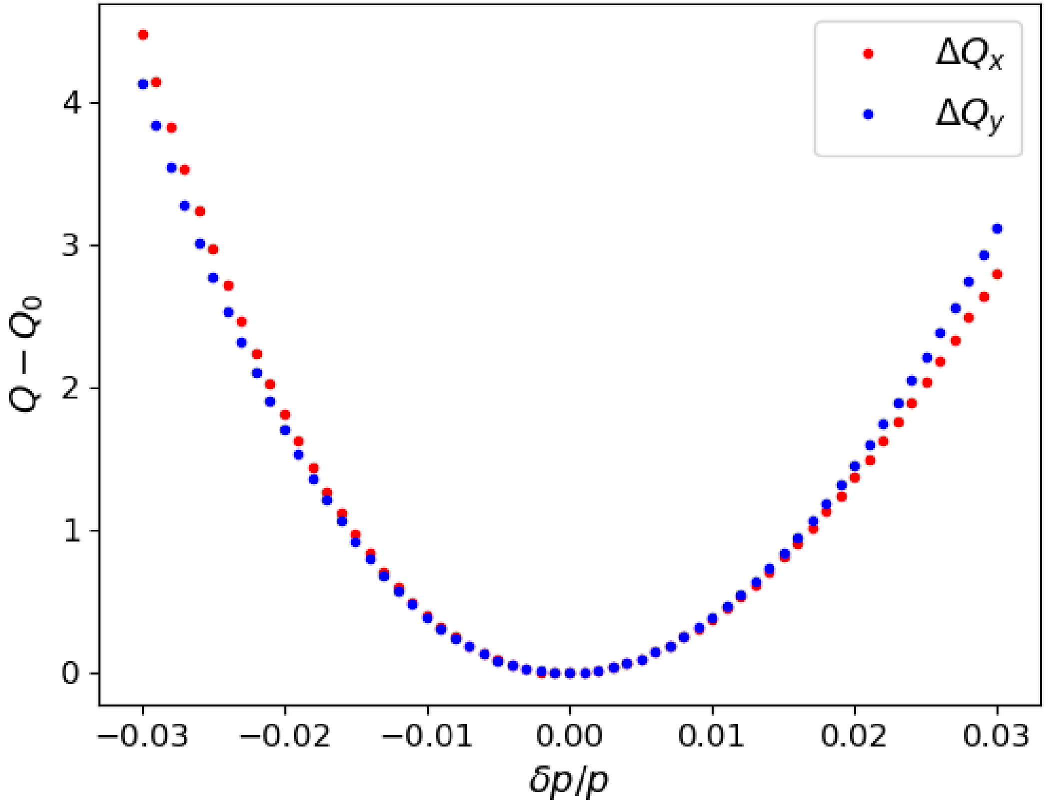


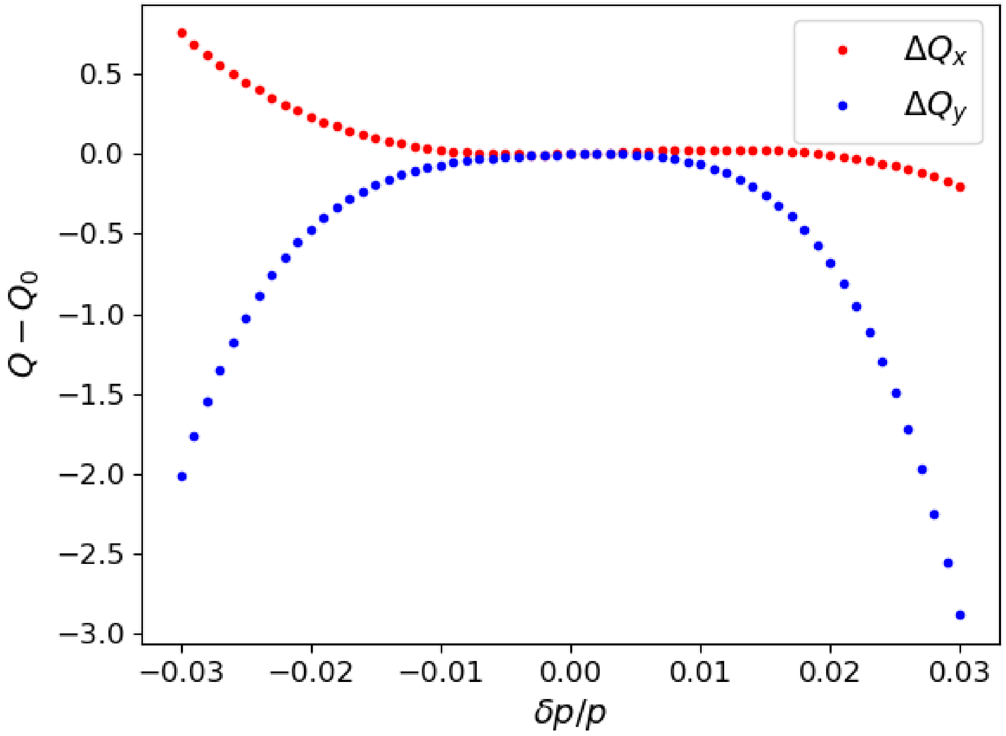


Comparison detuning with energy

FODO Baseline

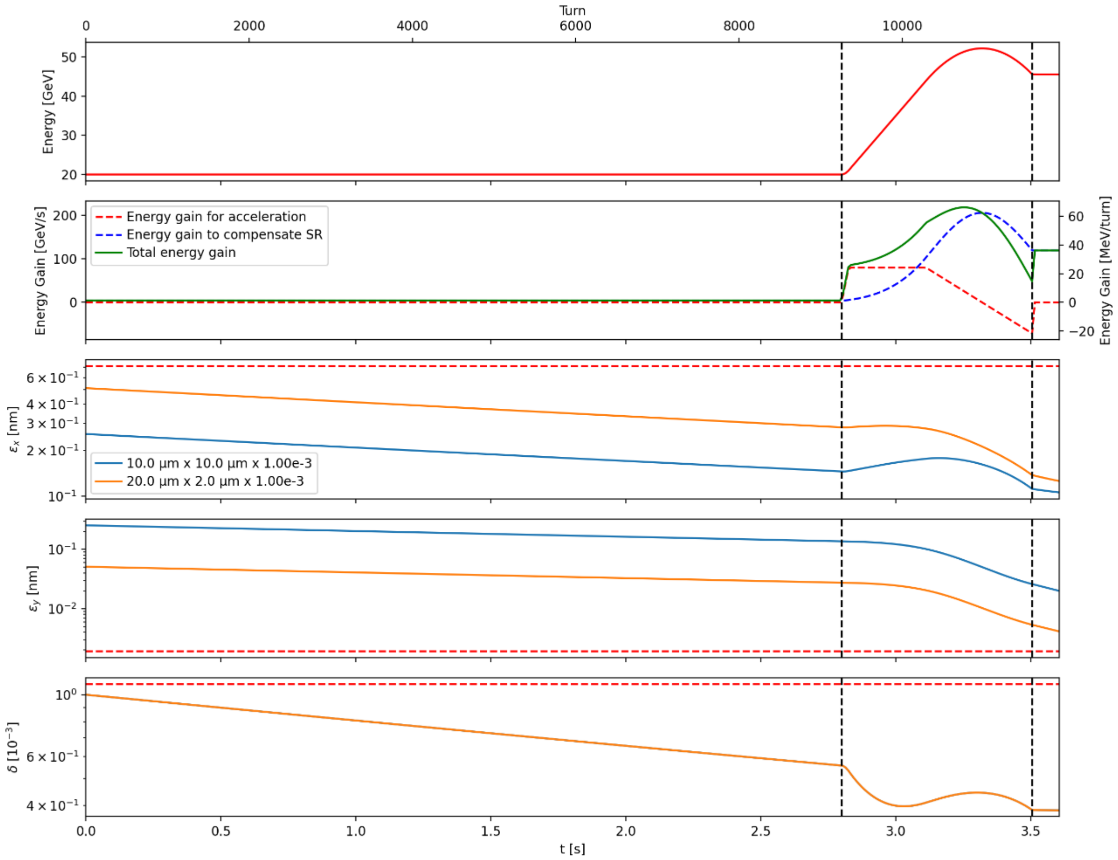
HFD





Emittance evolution
Baseline (accumulation of 2.8 s)

Total cycling: 0.706 (ramp-up) +0.1 (flat-top) + 0.334 (ramp-down) = 1.14 s



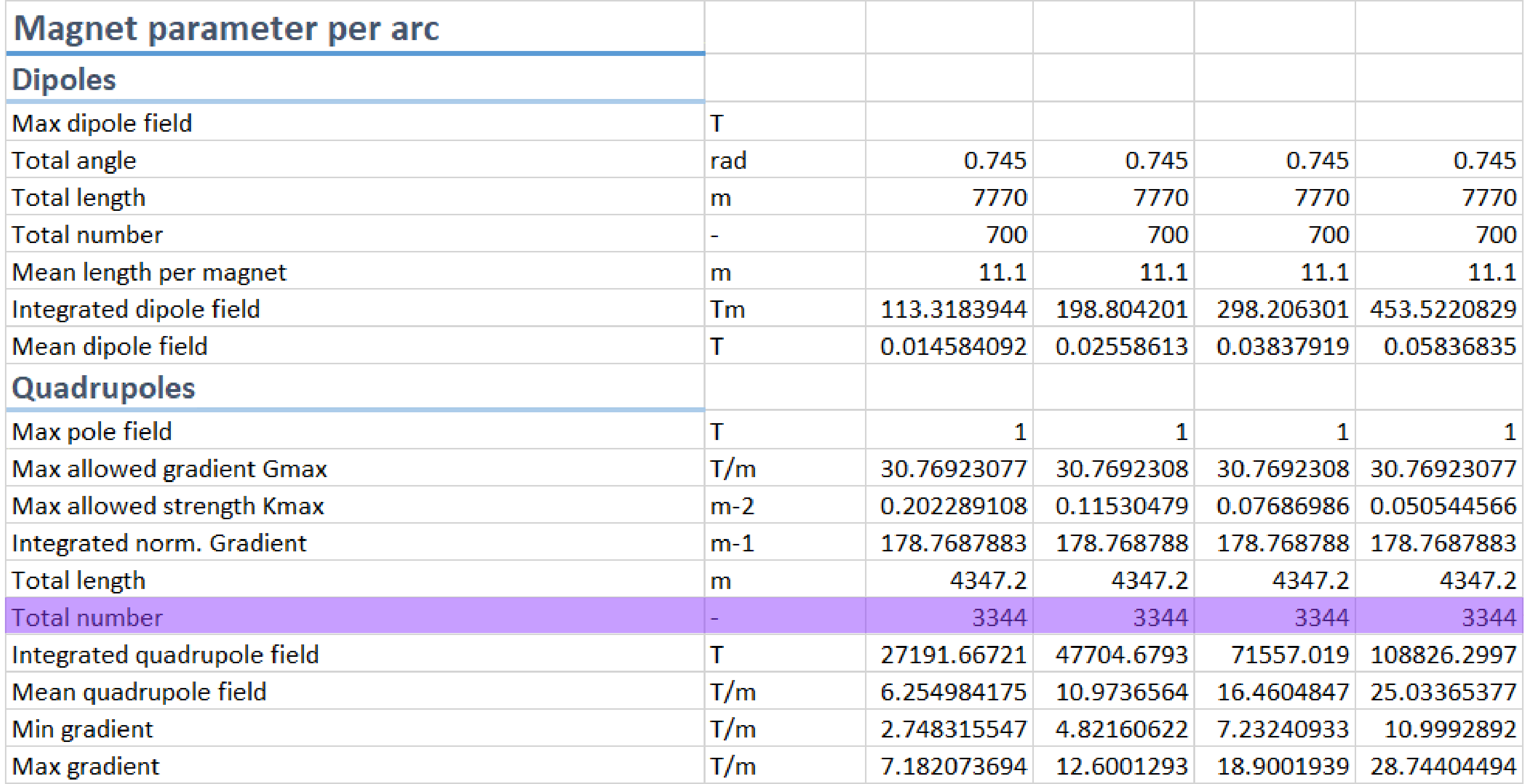
We use the double parabolic ramp + energy overshoot.

- Adiabatic start of the ramp (5% of initial energy gain)
- Steep linear energy ramp in the middle (80 GeV/s)
- Adiabatic approach of the flat top energy (80% of total gain)

IBS seems not to be an issue (shorter accumulation time)

- Linac alone: Initial beam parameters: 10 μm x 10 μm x 1e-3
  - Hor. Emittance: **0.106 nm**
  - Vert. Emittance: **20.0 pm**
  - Energy spread: **0.383e-3**
- High-energy DR: Initial beam parameters: 20 μm x 2 μm x 1e-3
  - Hor. Emittance: **0.126 nm**
  - Vert. Emittance: **4.13 pm**
  - Energy spread: **0.383e-3**

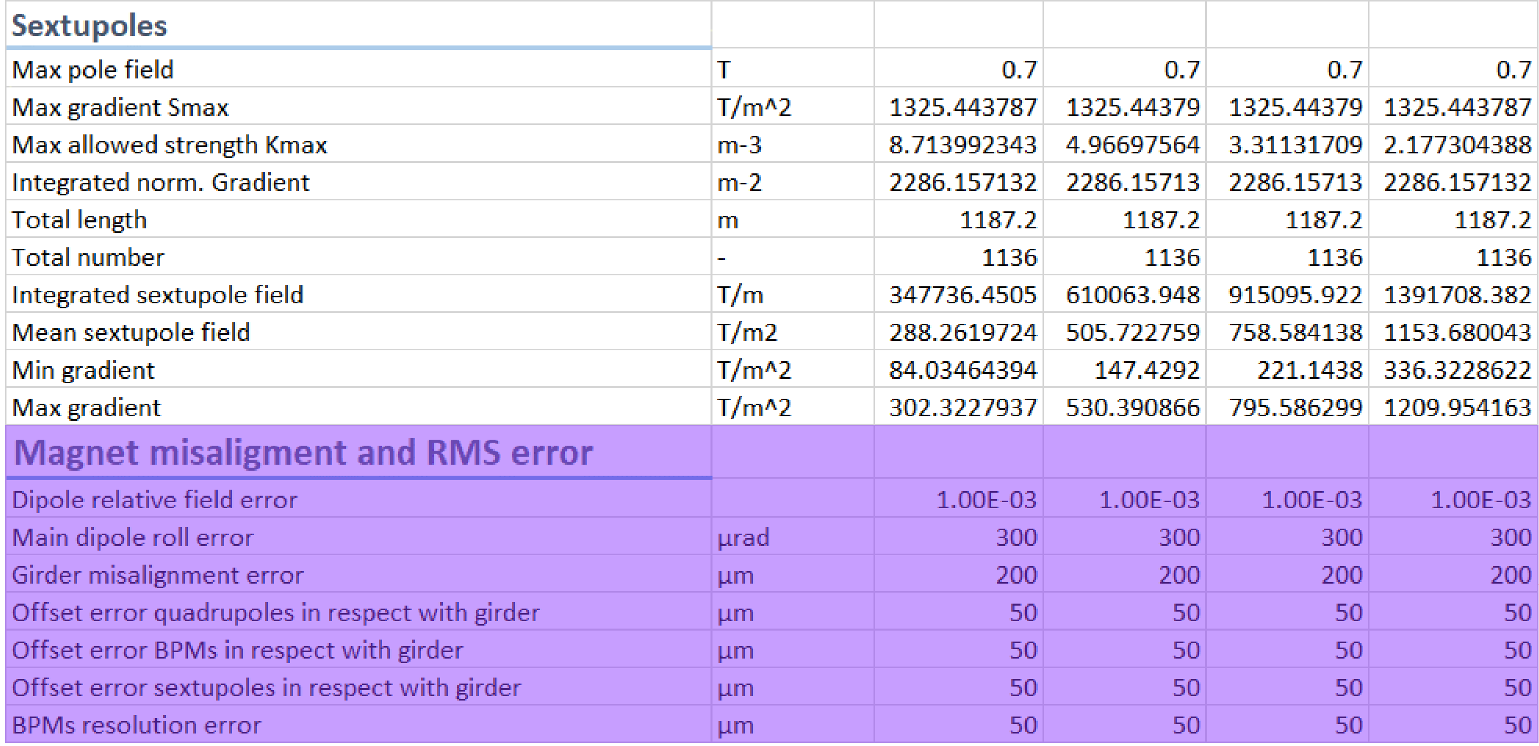
Booster parameter table (V24_FODO)



Magnet parameter per arc					
Dipoles					
Max dipole field	T				
Total angle	rad	0.745	0.745	0.745	0.745
Total length	m	7770	7770	7770	7770
Total number	-	700	700	700	700
Mean length per magnet	m	11.1	11.1	11.1	11.1
Integrated dipole field	Tm	113.3183944	198.804201	298.206301	453.5220829
Mean dipole field	T	0.014584092	0.02558613	0.03837919	0.05836835
Quadrupoles					
Max pole field	T	1	1	1	1
Max allowed gradient Gmax	T/m	30.76923077	30.7692308	30.7692308	30.76923077
Max allowed strength Kmax	m-2	0.202289108	0.11530479	0.07686986	0.050544566
Integrated norm. Gradient	m-1	178.7687883	178.768788	178.768788	178.7687883
Total length	m	4347.2	4347.2	4347.2	4347.2
Total number	-	3344	3344	3344	3344
Integrated quadrupole field	T	27191.66721	47704.6793	71557.019	108826.2997
Mean quadrupole field	T/m	6.254984175	10.9736564	16.4604847	25.03365377
Min gradient	T/m	2.748315547	4.82160622	7.23240933	10.9992892
Max gradient	T/m	7.182073694	12.6001293	18.9001939	28.74404494

In the current tuning scheme, we have one BPM and one dipole corrector per quadrupole.
We will need also to correct the coupling.

Booster parameter table (V24_FODO)

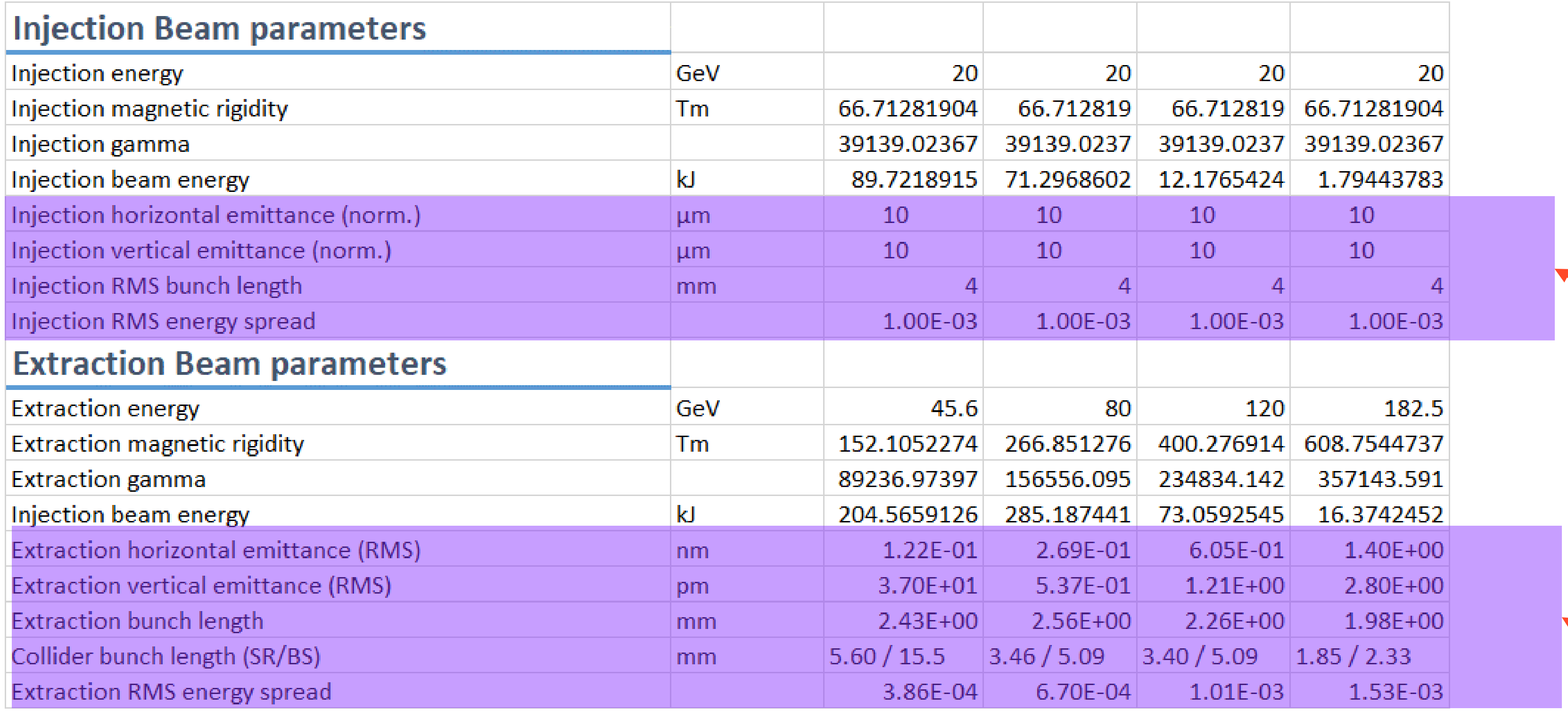


Sextupoles					
Max pole field	T	0.7	0.7	0.7	0.7
Max gradient Smax	T/m^2	1325.443787	1325.44379	1325.44379	1325.443787
Max allowed strength Kmax	m-3	8.713992343	4.96697564	3.31131709	2.177304388
Integrated norm. Gradient	m-2	2286.157132	2286.15713	2286.15713	2286.157132
Total length	m	1187.2	1187.2	1187.2	1187.2
Total number	-	1136	1136	1136	1136
Integrated sextupole field	T/m	347736.4505	610063.948	915095.922	1391708.382
Mean sextupole field	T/m2	288.2619724	505.722759	758.584138	1153.680043
Min gradient	T/m^2	84.03464394	147.4292	221.1438	336.3228622
Max gradient	T/m^2	302.3227937	530.390866	795.586299	1209.954163
Magnet misaligment and RMS error					
Dipole relative field error		1.00E-03	1.00E-03	1.00E-03	1.00E-03
Main dipole roll error	µrad	300	300	300	300
Girder misalignment error	µm	200	200	200	200
Offset error quadrupoles in respect with girder	µm	50	50	50	50
Offset error BPMs in respect with girder	µm	50	50	50	50
Offset error sextupoles in respect with girder	µm	50	50	50	50
BPMs resolution error	µm	50	50	50	50

Assumptions on the dipole and quadrupole misaligment for error correction.
Assumptions of a 3-sigma truncated Gaussian distribution.

We assume also a transverse jitter of one sigma at injection.

Booster parameter table (V24_FODO)



Injection Beam parameters					
Injection energy	GeV	20	20	20	20
Injection magnetic rigidity	Tm	66.71281904	66.712819	66.712819	66.71281904
Injection gamma		39139.02367	39139.0237	39139.0237	39139.02367
Injection beam energy	kJ	89.7218915	71.2968602	12.1765424	1.79443783
Injection horizontal emittance (norm.)	µm	10	10	10	10
Injection vertical emittance (norm.)	µm	10	10	10	10
Injection RMS bunch length	mm	4	4	4	4
Injection RMS energy spread		1.00E-03	1.00E-03	1.00E-03	1.00E-03
Extraction Beam parameters					
Extraction energy	GeV	45.6	80	120	182.5
Extraction magnetic rigidity	Tm	152.1052274	266.851276	400.276914	608.7544737
Extraction gamma		89236.97397	156556.095	234834.142	357143.591
Injection beam energy	kJ	204.5659126	285.187441	73.0592545	16.3742452
Extraction horizontal emittance (RMS)	nm	1.22E-01	2.69E-01	6.05E-01	1.40E+00
Extraction vertical emittance (RMS)	pm	3.70E+01	5.37E-01	1.21E+00	2.80E+00
Extraction bunch length	mm	2.43E+00	2.56E+00	2.26E+00	1.98E+00
Collider bunch length (SR/BS)	mm	5.60 / 15.5	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
Extraction RMS energy spread		3.86E-04	6.70E-04	1.01E-03	1.53E-03

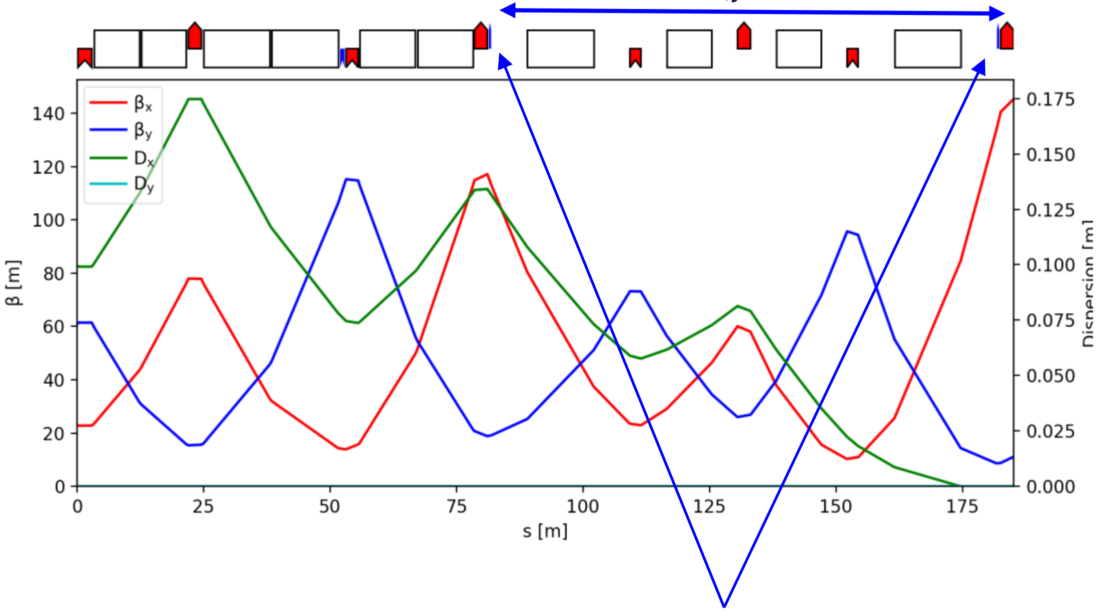
Baseline injection beam parameters. Nota: an alernative with a high-energy damping ring is under study.

Extraction beam parameters (emittances and energy spread) are different from the collider and equilibrium (especially for Z-mode).

Transparency + dispersion suppressor

Dispersion suppressor

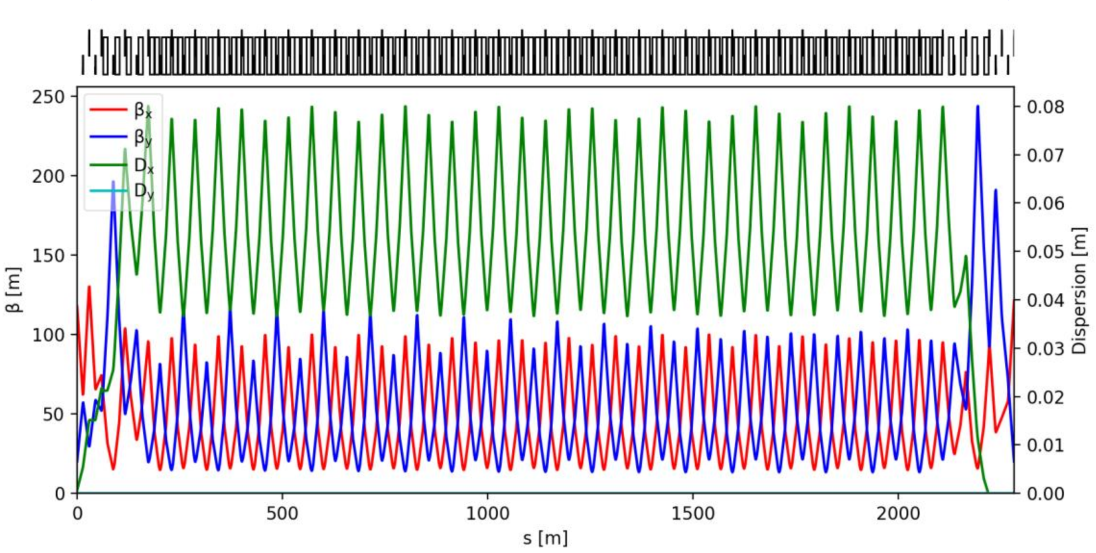
$\Delta\mu_{x,y} \approx \pi$



Sextupole pair used to correct 2nd order chromaticity

Insertion 1

$\Delta\mu_{x,y} = 2\,n\,\pi + \mu_{x,y\ cell}$



Matching quadrupoles are used to match the Montague functions between the arcs

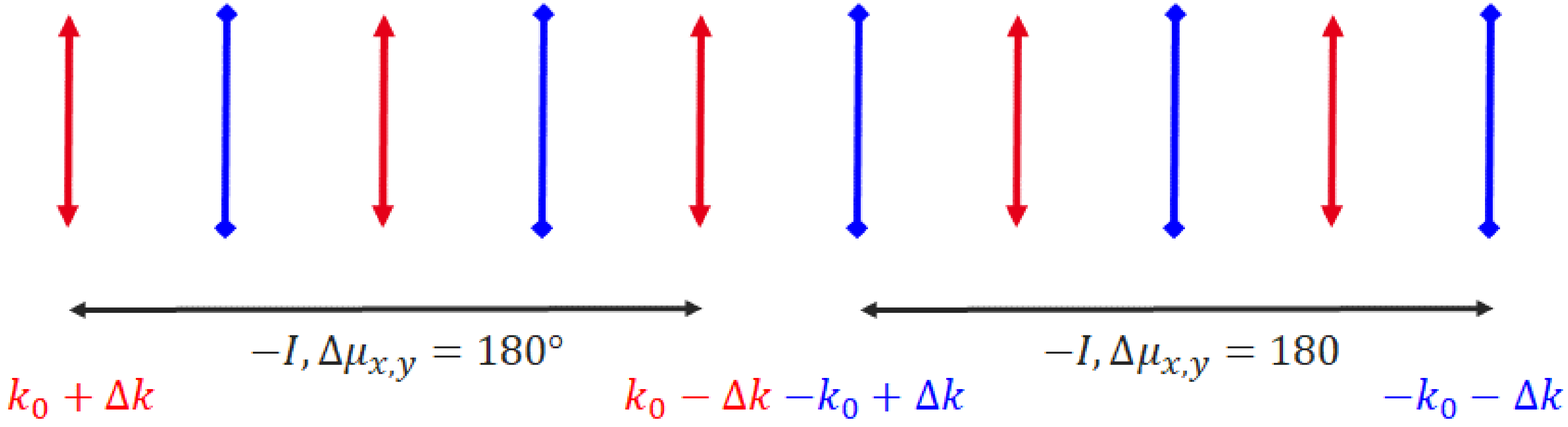
Momentum compaction tuning

Due to collective effects, we have to maintain 2 arc optics

- Z/W operations (with a momentum compaction of $\mathbf{1.49 \times 10^{-5}}$ corresponding to a FODO cell of 60 degrees and an I5 of $\mathbf{5.21 \times 10^{-11}}$).
- H/ttbar operations (with a momentum compaction of $\mathbf{0.73 \times 10^{-5}}$ corresponding to a FODO cell of 90 degrees and an I5 of $\mathbf{1.79 \times 10^{-11}}$).

The motivation is to have an additional knob to tune the momentum compaction during the ramp:

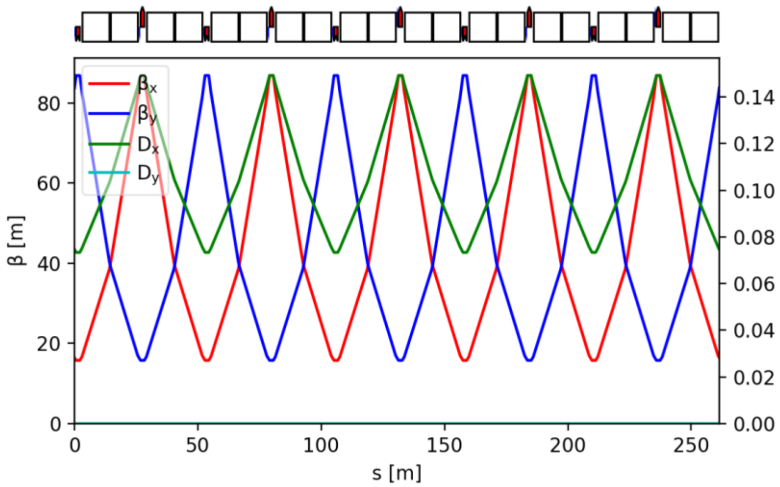
- We can have a larger momentum comapction at injection energy: better for collective effects.
- At higher energies, we can reduce the momentum compaction because collective effects are less critical at higher energy and we can get a smaller equilibrium emittance.



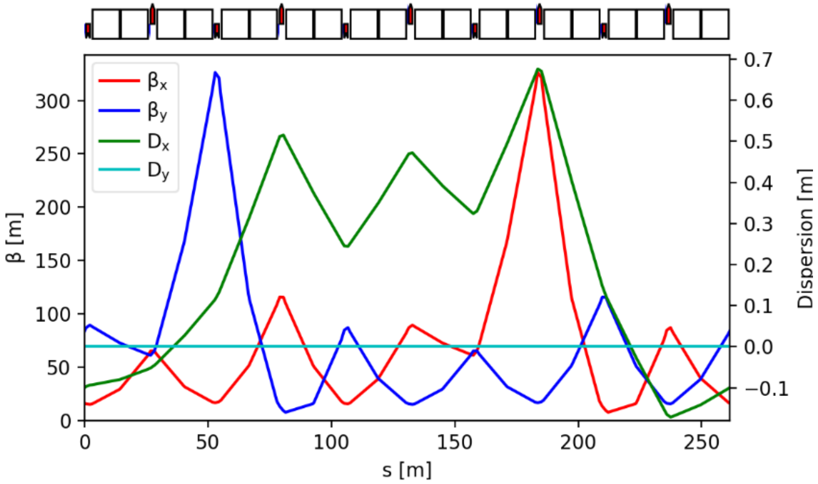
$\Delta k \approx \frac{\sqrt{x}}{2\sqrt{3}}$ with $x = \frac{\alpha}{\alpha_0} - 1$ where α is the momentum compaction and 0 when Δk=0

Alternative optics: comparison with the cell

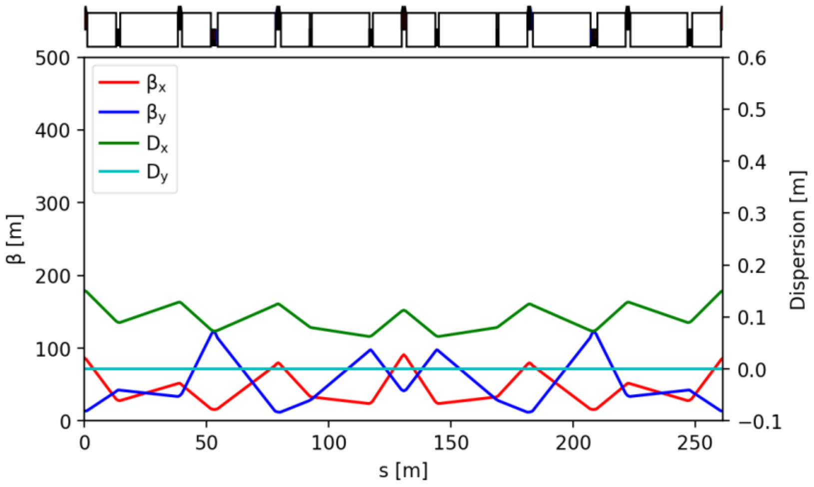
Arc FODO cell



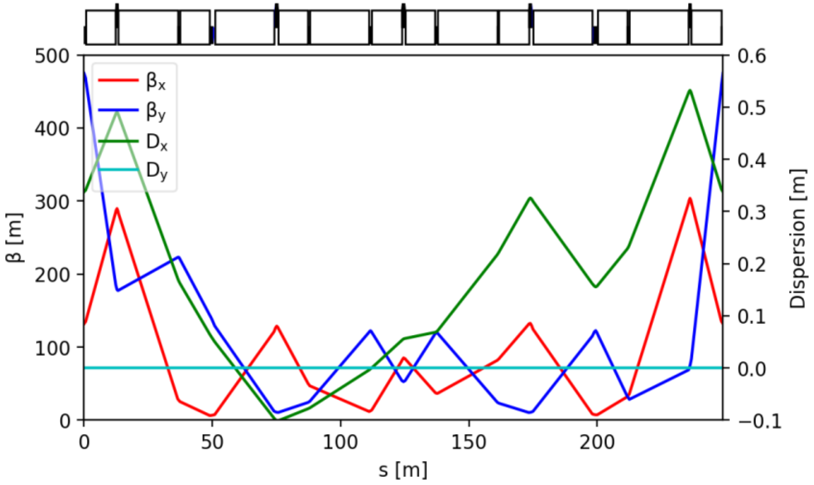
Arc FODO cell $\alpha \times 2$



HBD cell



HBD cell $\alpha \times 2$



Ratio FODO cells:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} = 2; \frac{I_{5,2}}{I_{5,1}} = 6.25$$

Ratio HBD cells:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} = 1.8; \frac{I_{5,2}}{I_{5,1}} = 5.6$$

60 degrees cells:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} \approx 2; \frac{I_{5,2}}{I_{5,1}} \approx 3$$

90 degrees twice longer cells:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} \approx 4; \frac{I_{5,2}}{I_{5,1}} \approx 8$$

Alternative optics: discussion

The advantages of this alternative optics are:

- **Possibility to tune the momentum compaction** during the ramp.
  - Different I5 at injection and extraction.
  - Needs to know the limitation of collective effects at injection but also at extraction to evaluate the optimum momentum comapction during the ramp.
- **We keep the same sextupole correction scheme for all modes.**
  - We could add an additional sextupole at the dispersion peak to correct the extra chromaticity due to the betatron wave (the chromaticity increase is about 50% more in comparison with the reference case). The extra sextupoles are 10 times weaker to double the momentum compaction.

The drawbacks are:

- A larger equilibrium emittance in comparison with FODO cells.
  - We are still below the equilibrium emittance of the long 90 degrees cells.
  - We can reduce the imapct by decreasing the momentum compaction during the ramp.
- We need to increase the number of quadrupole families and thus power supplies.
  - 6 families against 2 families.
- Larger maximum peak betatron functions in the arcs.
  - Need for more work to improve the matching sections.

We have to evaluate the impact on the dynamic aperture and momentum acceptance.