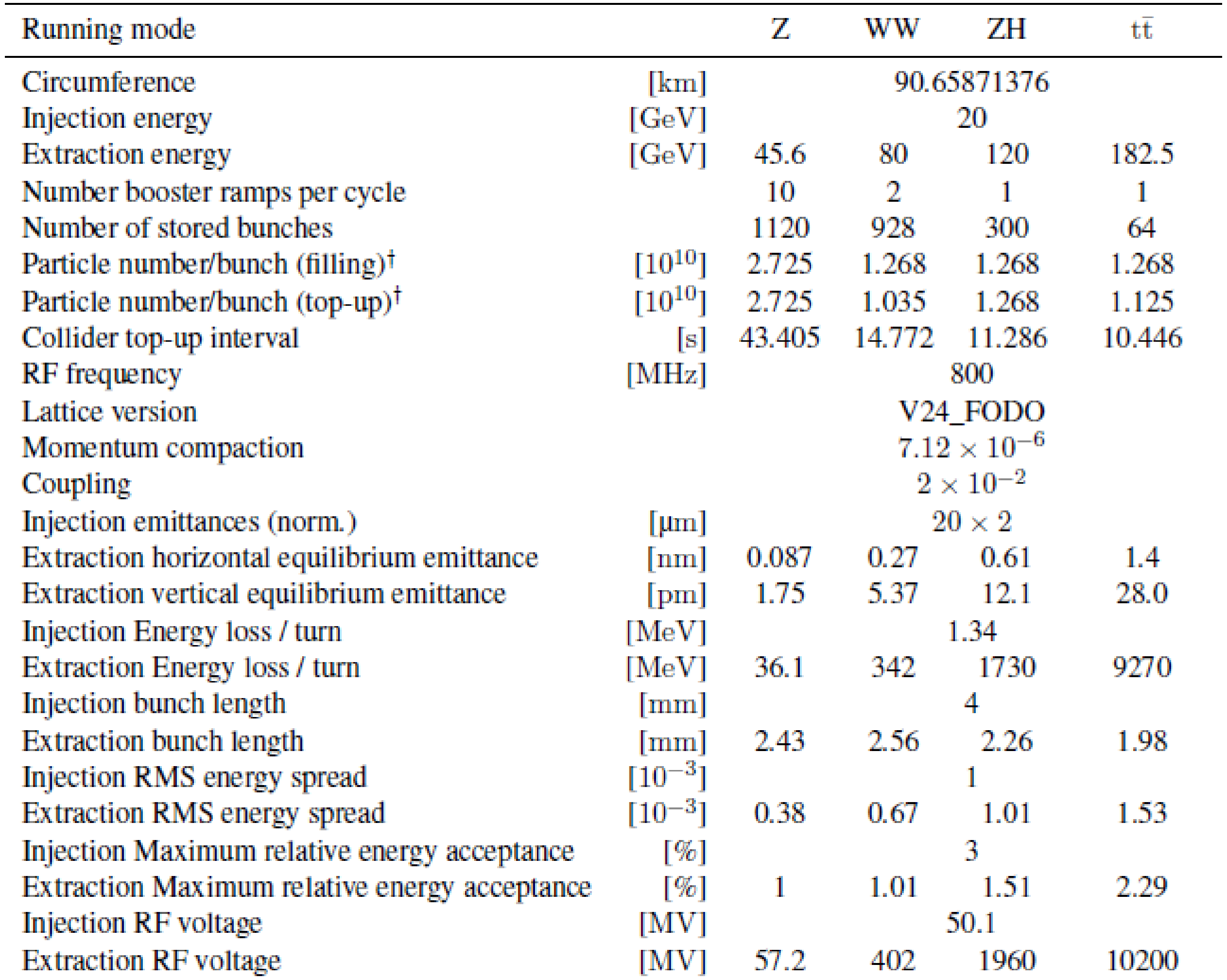
FCC

HIGH-ENERGY BOOSTER OVERVIEW

A. Chance (CEA)
On behalf of booster team

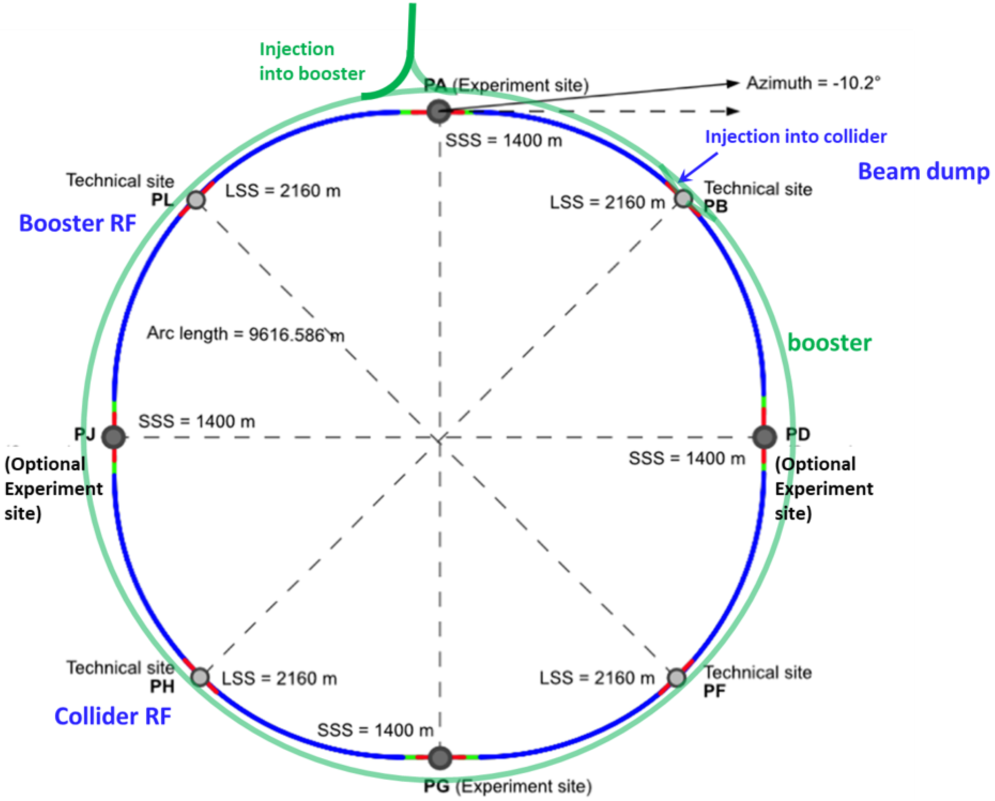
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Booster parameter table



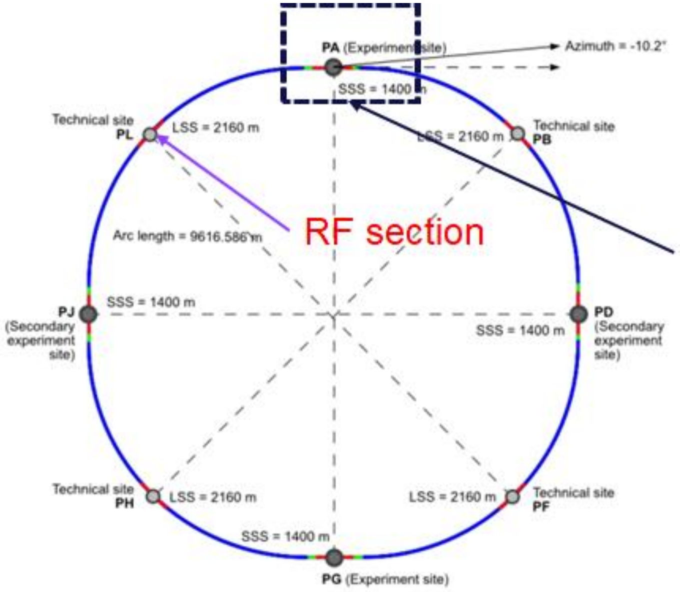
Running mode		Z	WW	ZH	$t\bar{t}$
Circumference	[km]	90.65871376			
Injection energy	[GeV]	20			
Extraction energy	[GeV]	45.6	80	120	182.5
Number booster ramps per cycle		10	2	1	1
Number of stored bunches		1120	928	300	64
Particle number/bunch (filling)†	[10^{10}]	2.725	1.268	1.268	1.268
Particle number/bunch (top-up)†	[10^{10}]	2.725	1.035	1.268	1.125
Collider top-up interval	[s]	43.405	14.772	11.286	10.446
RF frequency	[MHz]	800			
Lattice version		V24_FODO			
Momentum compaction		7.12×10^{-6}			
Coupling		2×10^{-2}			
Injection emittances (norm.)	[μm]	20×2			
Extraction horizontal equilibrium emittance	[nm]	0.087	0.27	0.61	1.4
Extraction vertical equilibrium emittance	[pm]	1.75	5.37	12.1	28.0
Injection Energy loss / turn	[MeV]	1.34			
Extraction Energy loss / turn	[MeV]	36.1	342	1730	9270
Injection bunch length	[mm]	4			
Extraction bunch length	[mm]	2.43	2.56	2.26	1.98
Injection RMS energy spread	[10^{-3}]	1			
Extraction RMS energy spread	[10^{-3}]	0.38	0.67	1.01	1.53
Injection Maximum relative energy acceptance	[%]	3			
Extraction Maximum relative energy acceptance	[%]	1	1.01	1.51	2.29
Injection RF voltage	[MV]	50.1			
Extraction RF voltage	[MV]	57.2	402	1960	10200

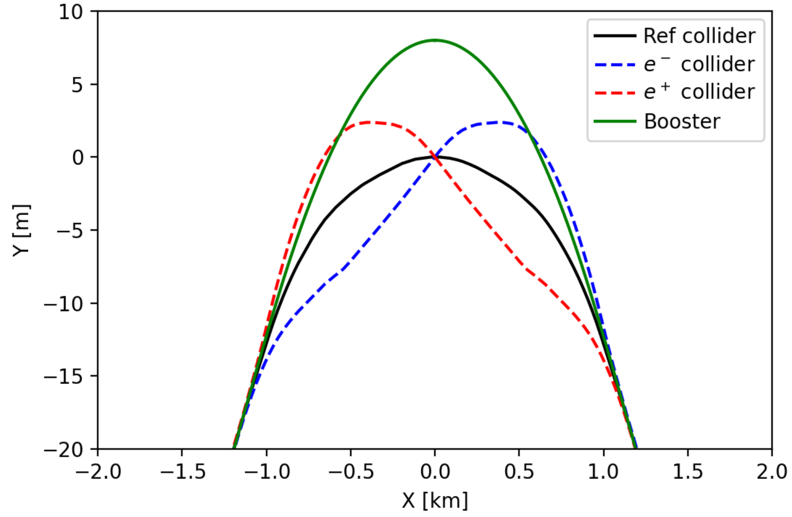
We assume an injection efficiency of 80% between the booster and the collider.



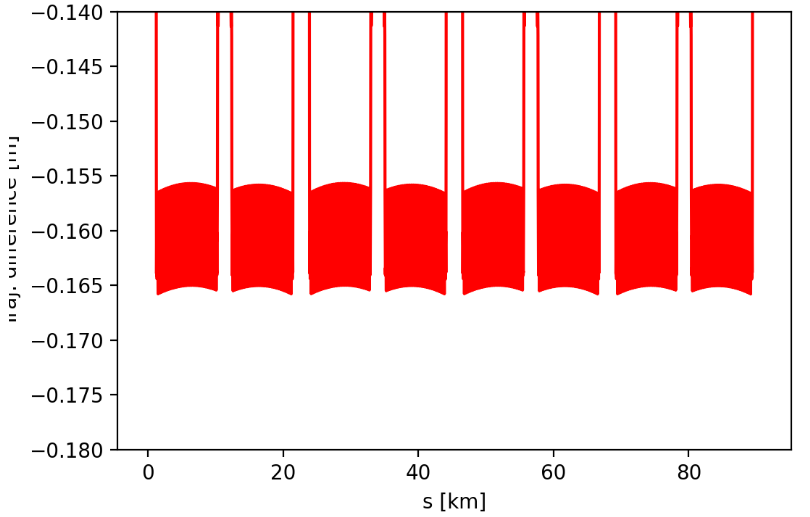
Layout status

May 2025





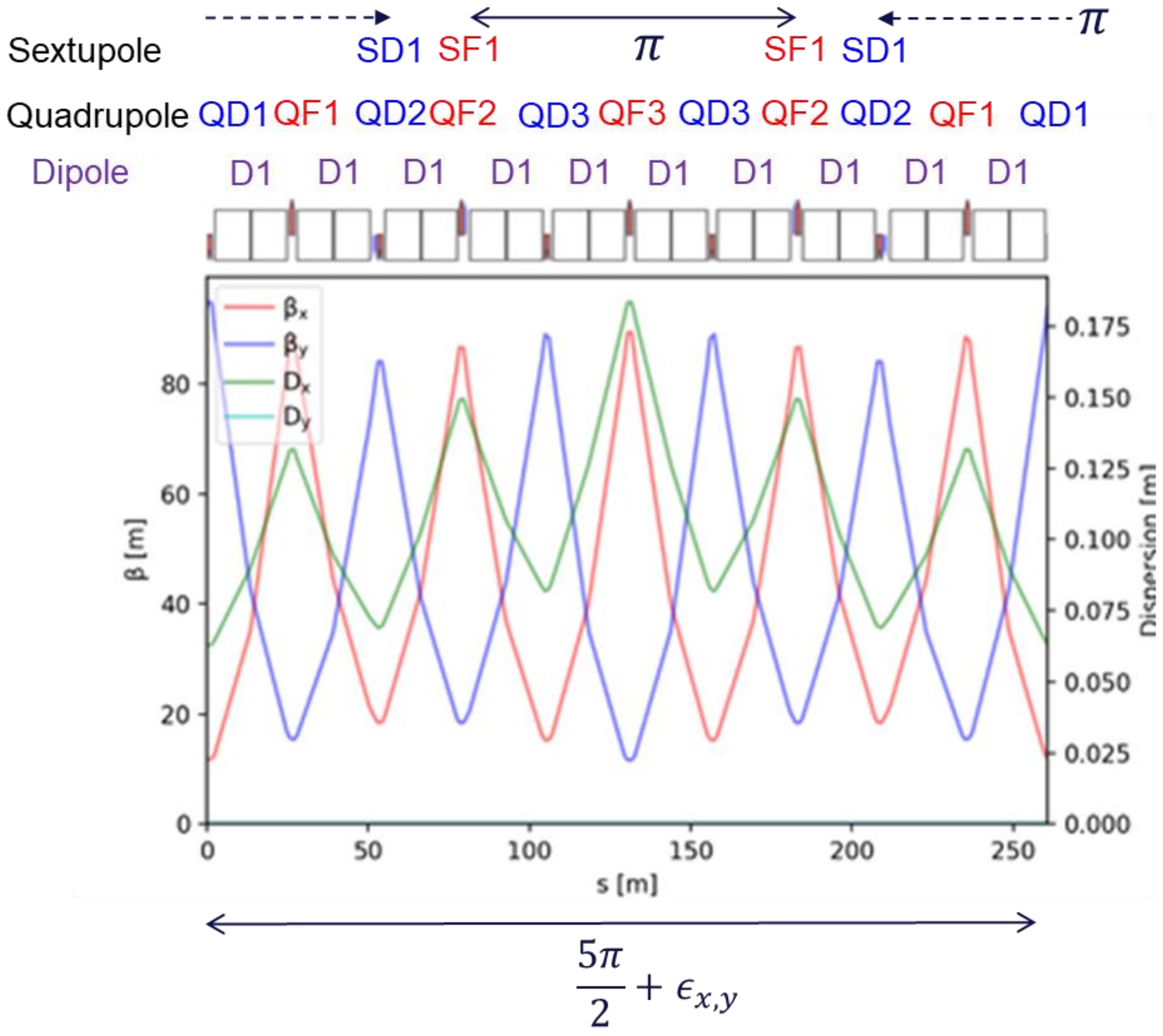
- No major change since FCC week 2024.
- The booster is in the outer side of the collider with an offset at the IP of 8 m.
- The offset in the arcs has been adjusted according to get the same circumference as the collider.
- The booster has an offset of -0.160 m in the arcs.
- In the coming year, **the booster layout is likely to change to have a negative offset at the IP** and **a ballistic transport line near the detector** to avoid any perturbation. Going to a positive offset in the arcs goes to the right direction for the mechanical vibration.



Major changes since FCC week 2024

- Same number of installed cryomodules for the Z, WW, ZH modes: reverse phase operation (RPO).
- Updated injection/extraction optics and integration in the lattice.
- Revised filling schemes.
- Updated lattice to use a bit longer quadrupoles and reduce the power consumption.
- Tuning scheme has made deep progress: beta-beating, dispersion beating, and coupling are now corrected.
- First tapering schemes have been considered.
- Intra-beam scattering and space charge effects are considered.
- Study of using the booster as a light source.

Baseline optics: FODO

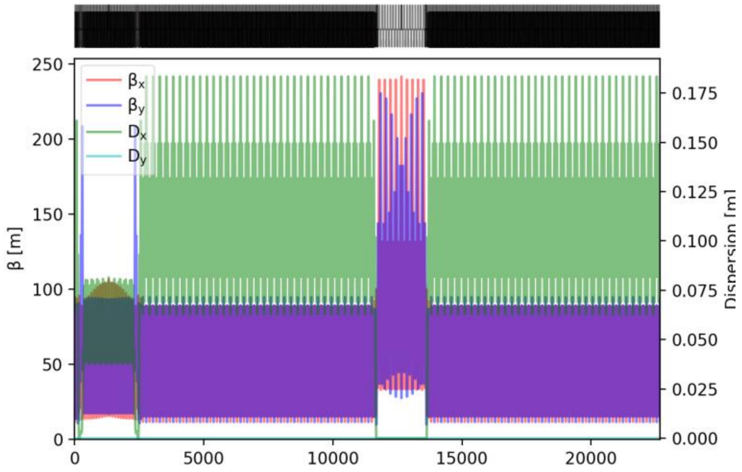


$$\frac{5\pi}{2} + \epsilon_{x,y}$$

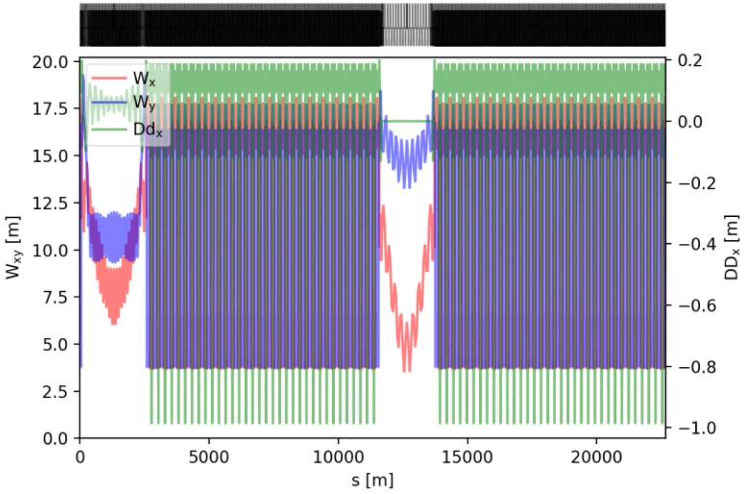
- Made of about 5 FODO cells of 52 m.
- 6 quadrupole families with about the same strength
  - to have a phase advance of π between the pair of sextupoles
  - To adjust the tune of the arc cell to get the target global tune.
- 1 dipole corrector + 1 BPM per quadrupole:
  - Horizontal when QF
  - Vertical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

Baseline optics: FODO

Optical functions (1/4 of ring)



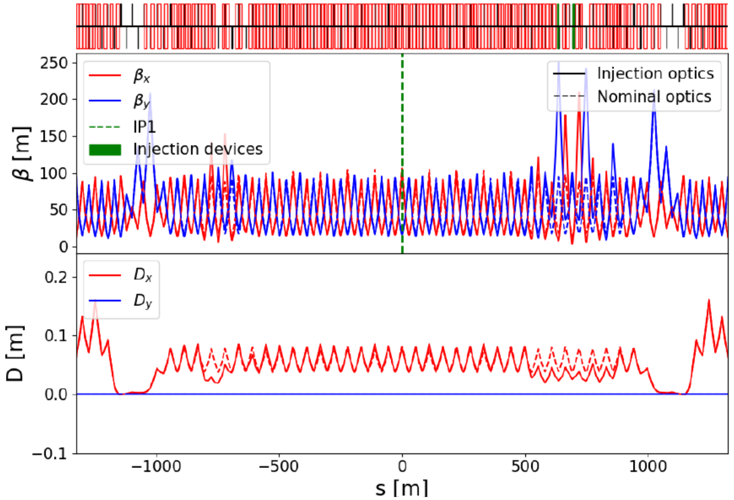
Montague functions (1/4 of ring)

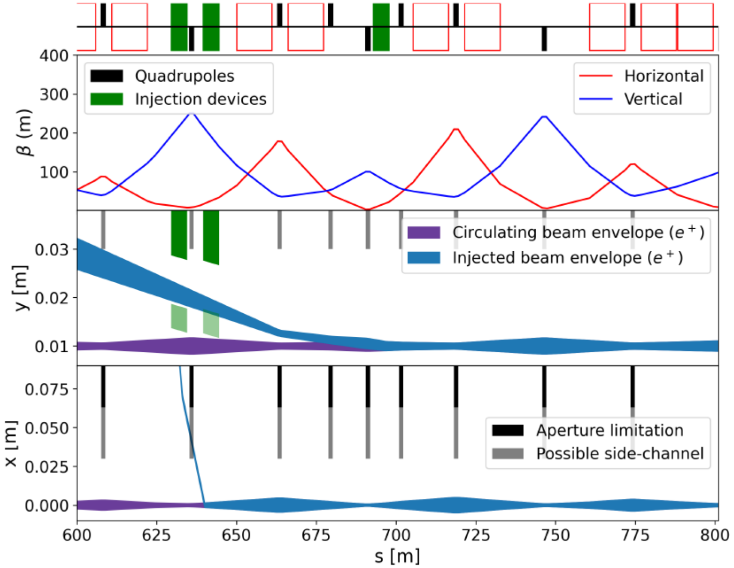


- Arc cell of 260 m with 5 quasi-FODO cells of 90° of 52 m each.
- Transparency conditions for the insertions:
  - Phase advance of π in both planes of between the focusing sextupoles in the dispersion suppressor to maximize the geometric aberration cancellation.
  - The angles of some dipoles in the dispersion suppressors are 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: 7.12e-06; I5: 1.70e-11
- Needs to refine the magnet length to balance the fields

→ see H. Deveci and L. van Freeden presentation: “Booster magnets”

Injection into the booster

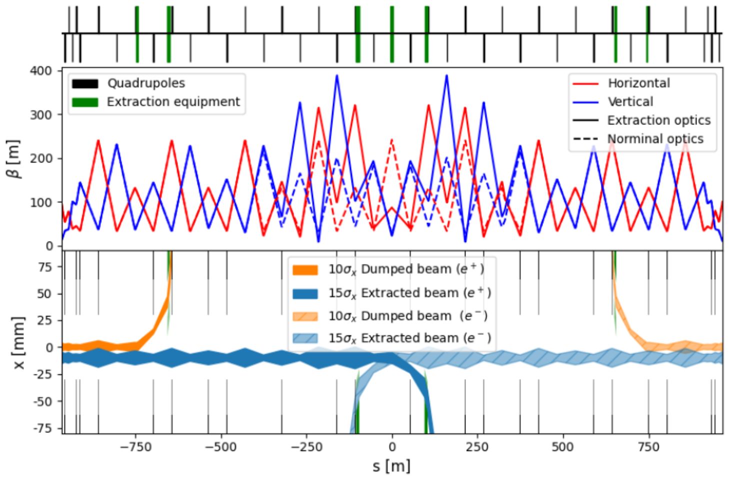


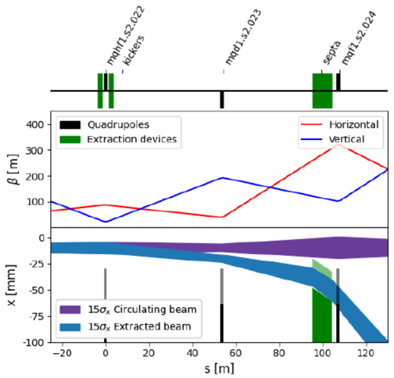


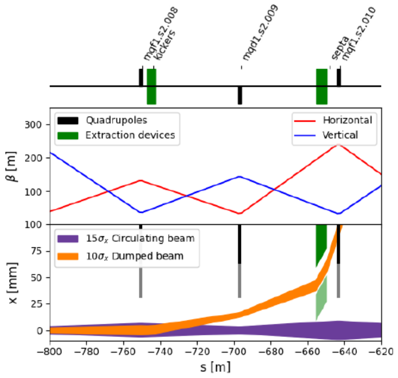
→ see Sen Yue presentation: “beam transfer concepts across the complex”

- **Updated injection optics**
- Angle of ~150 mrad between injection and booster beamlines.
- Modification of the insertion near PA:
  - 6 dipoles are removed on each side (double the field of the 6 neighboring dipoles).
  - Phase advance close to 90° between the kicker and the septum.
  - Independent powering of 2 x 11 quadrupoles + 2 additional quadrupoles to match the optics.
- In case of layout change in the experimental insertion, the scheme may change.

Extraction from the booster



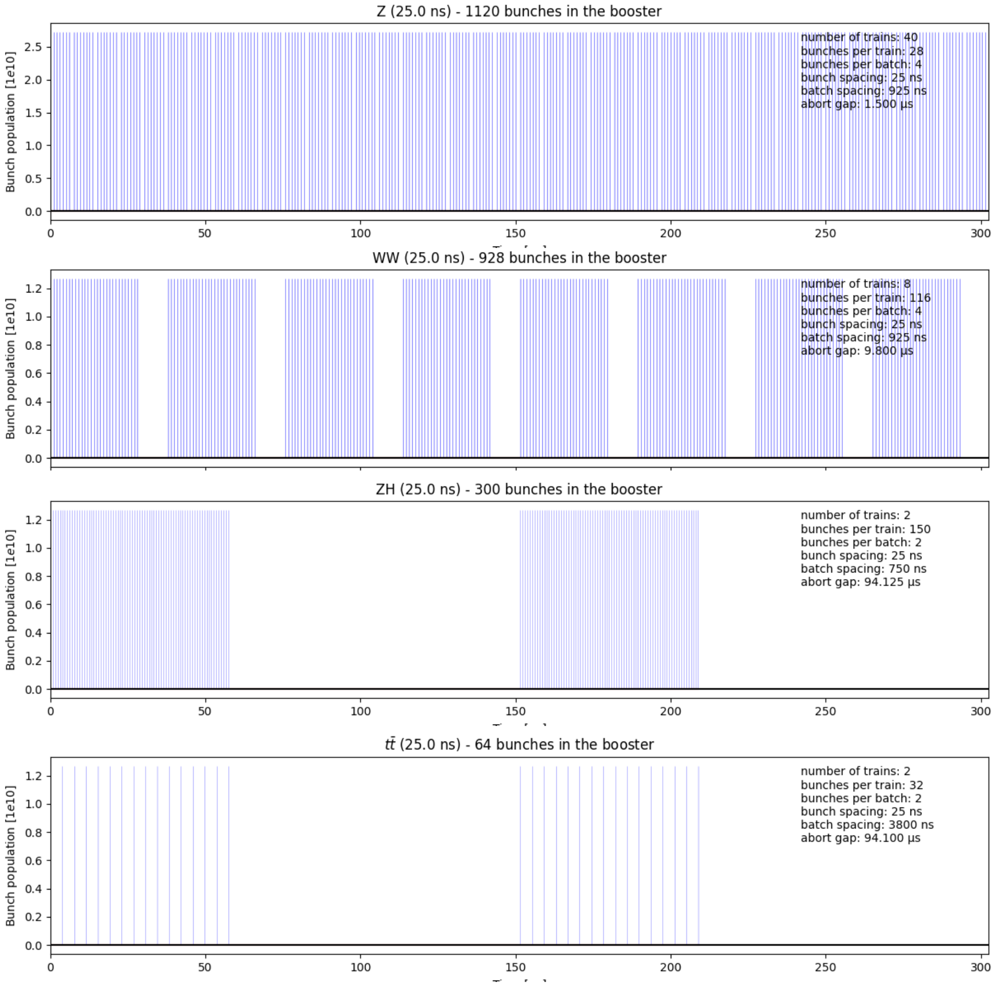




→ see Sen Yue presentation: “beam transfer concepts across the complex”

- Symmetric extraction optics.
- Extraction in the technical straight section in PB.
- **No modifications to the layout** are required to accommodate the extraction elements.
- The nominal optics follows a FODO structure with a phase advance close to 90°without dispersion and features a strong beating over a period of two cells.
- Independent powering of 9 quadrupoles + no additional quadrupoles to match the optics.

Filling schemes



→ **see Hannes Bartosik presentation: "Update on the filling scheme"**

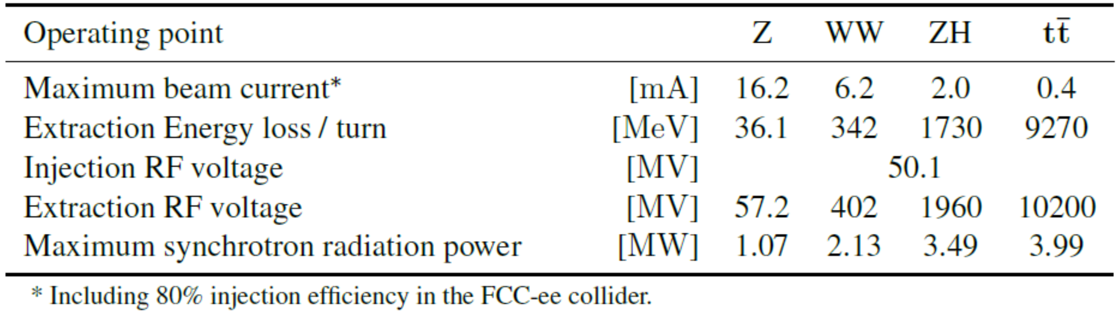
- The **collider filling scheme** has been **revised**.
- Each booster cycle provides 1/10 of the collider bunch positions at Z operation.
  - **Less constraints** on **machine protection**.
  - **Shorter injection plateau**: **reduces the emittance growth** due to IBS and rest gas collisions.
  - **Relaxed beam loading compensation**.
  - **More flexibility** to fill the booster.
  - **Increase the number of ramps** and thus the required time to top-up all the bunches.

Studies on injector synchronization are ongoing.

Reverse phase operation (RPO)

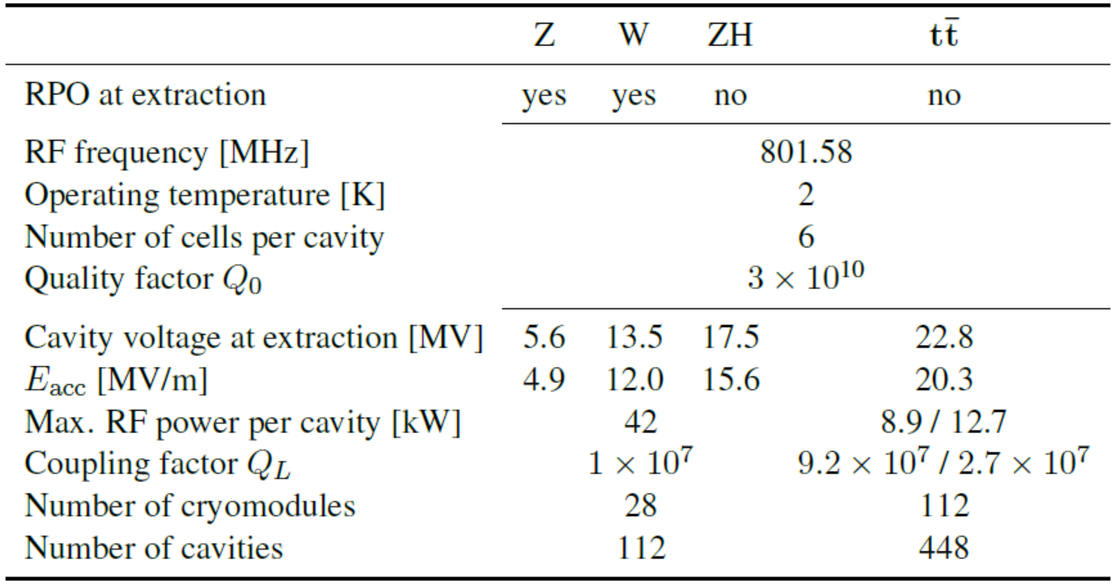
New baseline RF system requires flexibility for switching between Z, WW, and ZH operating points.

- Same 6-cell 800 MHz elliptical cavities as in the collider.
- To avoid hardware modification, common quality factor that minimizes RF power requirements in the first stage.
- RPO must be deployed at injection energy.



Operating point		Z	WW	ZH	$t\bar{t}$
Maximum beam current*	[mA]	16.2	6.2	2.0	0.4
Extraction Energy loss / turn	[MeV]	36.1	342	1730	9270
Injection RF voltage	[MV]	50.1			
Extraction RF voltage	[MV]	57.2	402	1960	10200
Maximum synchrotron radiation power	[MW]	1.07	2.13	3.49	3.99

* Including 80% injection efficiency in the FCC-ee collider.



	Z	W	ZH	$t\bar{t}$
RPO at extraction	yes	yes	no	no
RF frequency [MHz]	801.58			
Operating temperature [K]	2			
Number of cells per cavity	6			
Quality factor Q_0	3×10^{10}			
Cavity voltage at extraction [MV]	5.6	13.5	17.5	22.8
E_{acc} [MV/m]	4.9	12.0	15.6	20.3
Max. RF power per cavity [kW]	42			8.9 / 12.7
Coupling factor Q_L	1×10^7			9.2×10^7 / 2.7×10^7
Number of cryomodules	28			112
Number of cavities	112			448

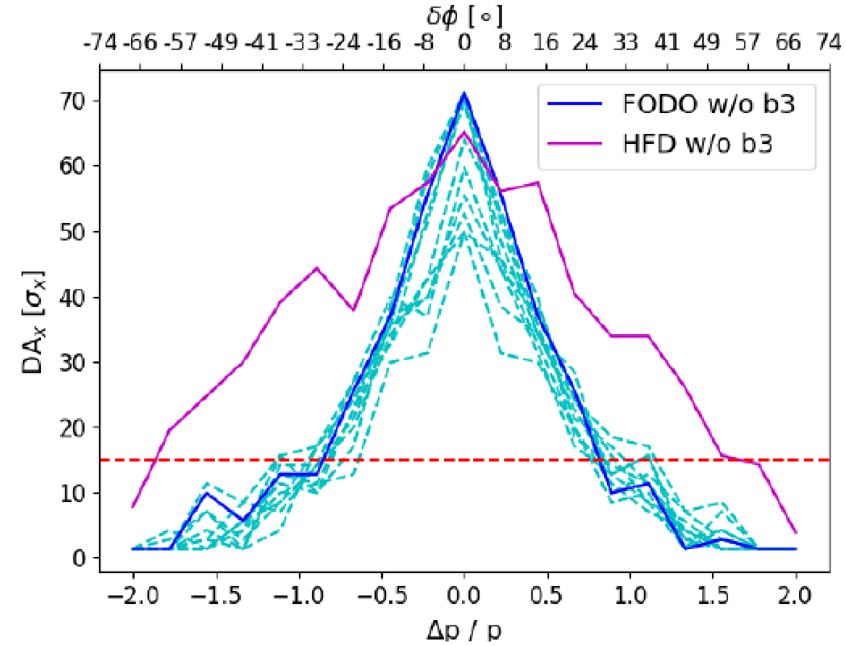
→ see Ivan Karpov presentation: "FCC operation scenarios - new baseline"

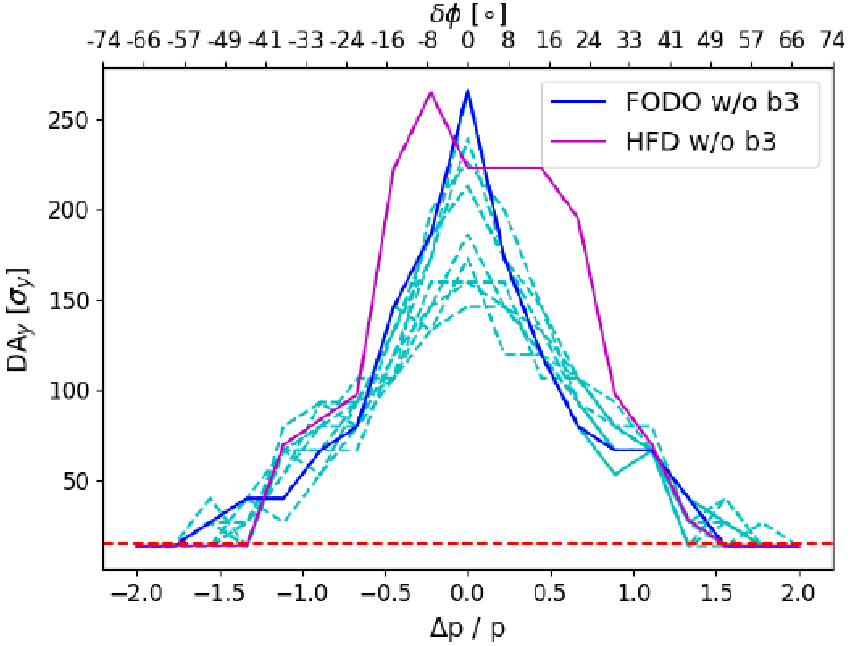
→ see Lina Valle presentation: "Beam dynamics and RF requirements in HEB"

Dynamic aperture and momentum acceptance

Courtesy: B. Dalena, A. Mashal

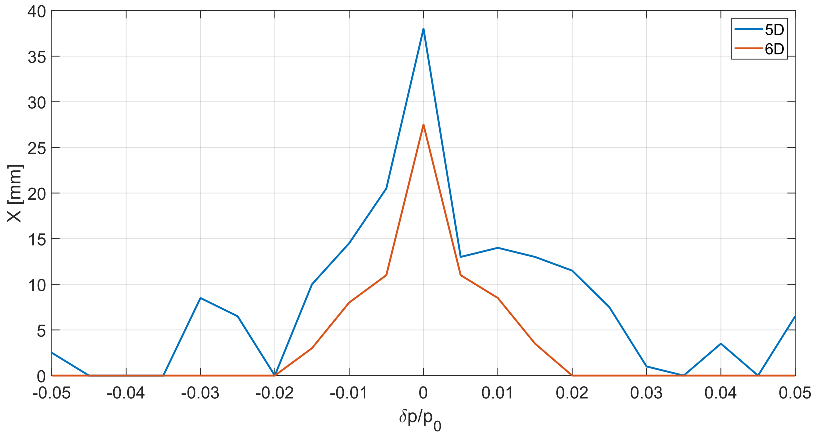
- Dynamic aperture at injection.
- Normalized emittances: $20\ \mu\text{m} \times 2\ \mu\text{m}$
- Dashed red line: target value of 15 σ
- Dashed cyan lines: effect of the systematic b_3 in the main dipoles due to eddy-current for different integrated values (from -0.01 to 0.01 m^{-2}; the estimated value in nominal operation is 0.0025 m^{-2}).
- **The momentum acceptance exceeds $\pm 0.75\%$/1% in each plane**, equivalent to 5 σ_δ.

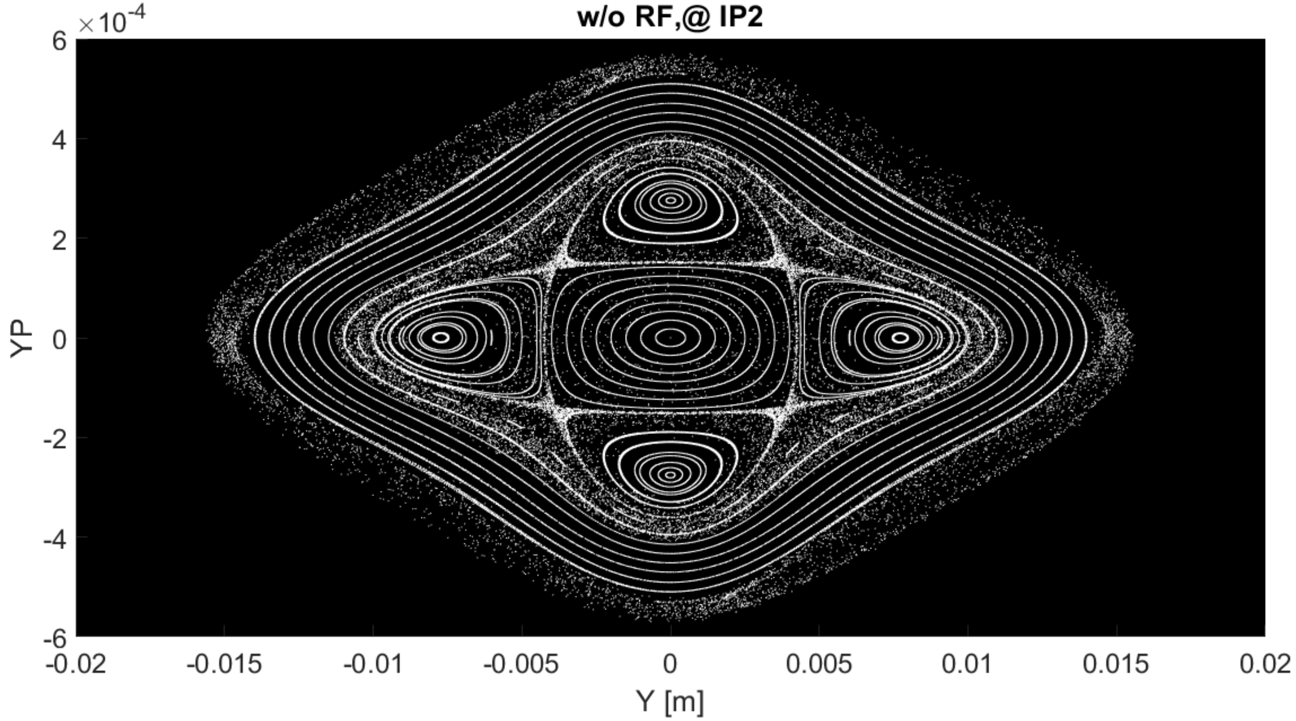


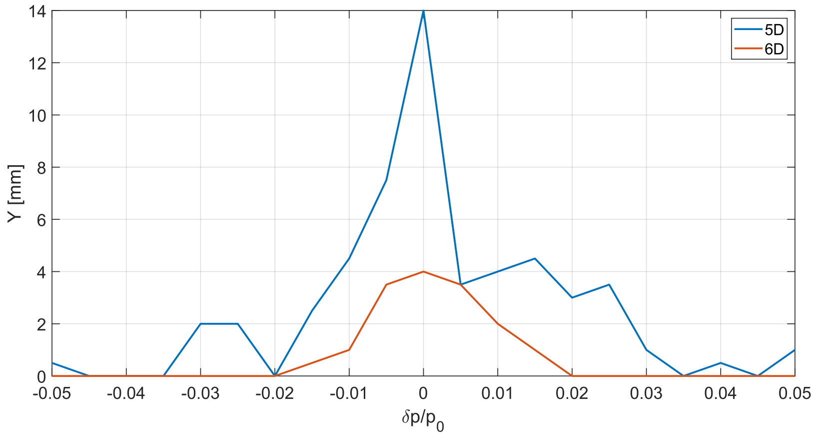


- **Including RF cavities** in tracking (6D) **significantly reduces the dynamic aperture** (DA) of on-momentum particles in the vertical plane.
- Analysis of the vertical phase space indicates the presence of 4th resonances.
- Work is ongoing to compensate for this resonance without adding extra multipole elements (e.g., octupoles) and while keeping the arc optics untouched.

Courtesy: A. Mashal

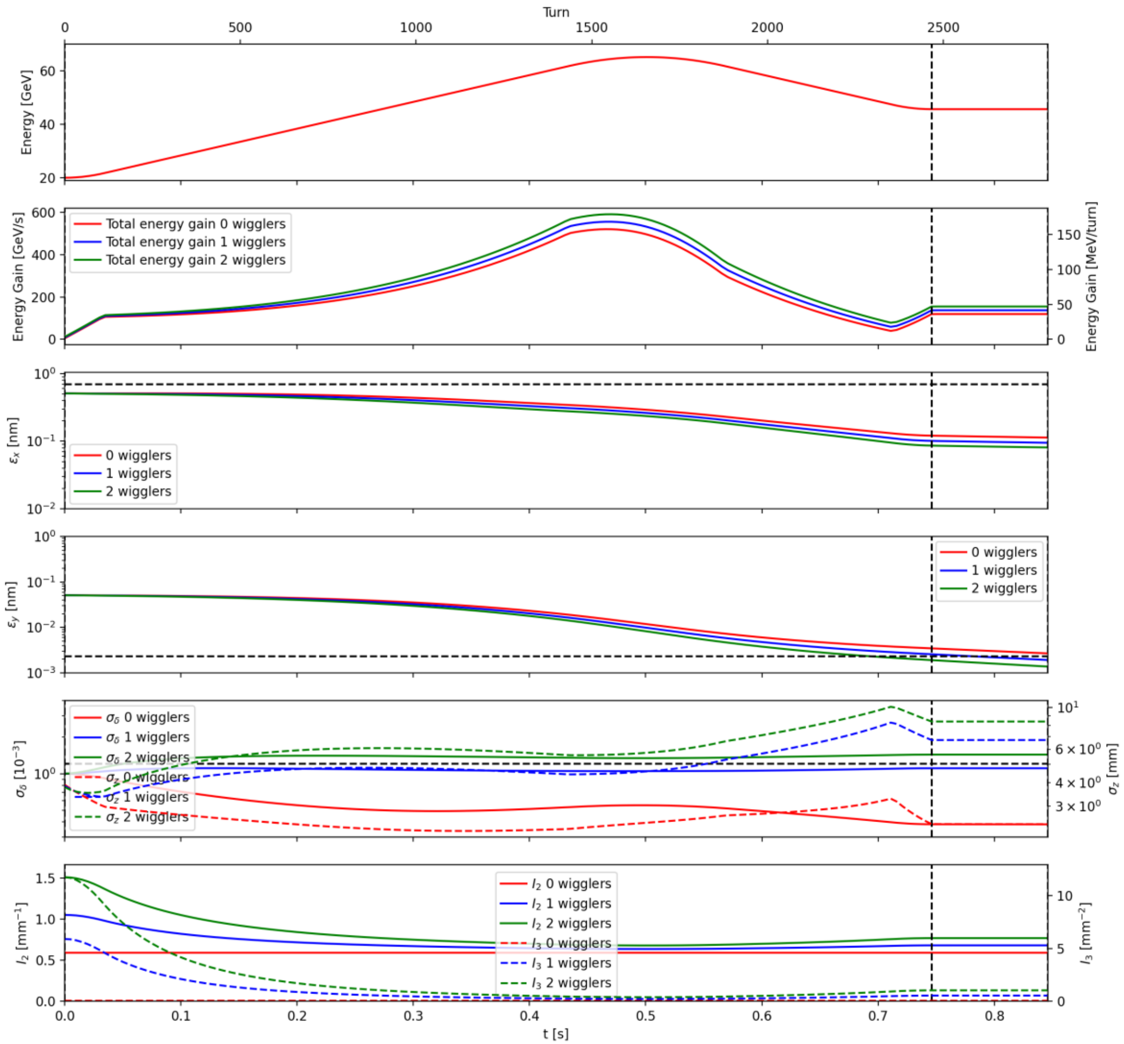






Emittance evolution for Z operation

Total cycling: 0.746 (ramp-up) +0.1 (flat-top) + 0.294 (ramp-down) = 1.14 s



We use the double parabolic ramp + energy overshoot. Wigglers can help mitigating coupled bunch instabilities at injection.

- Consideration for 0/1/2 permanent wigglers.

Wiggler 4.925 m, B_{axis}=1.0 T, L_{pole}=9.5 cm, L_{gap}=2cm, 43 poles

- 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.
- Initial beam parameters: 20 µm x 2 µm x 1e-3
- Final beam parameters:
  - Hor. Emittance: **113 pm / 95 pm / 81 pm**
  - Vert. Emittance: **2.69 pm / 1.93 pm /1.38 pm** 2
  - Energy spread: **0.383e-3, 1.109e-3, 1.437e-3**
- Because of the I_3 increase, the energy spread is too large at extraction.
- How to get a smaller energy spread at extraction is under investigation.

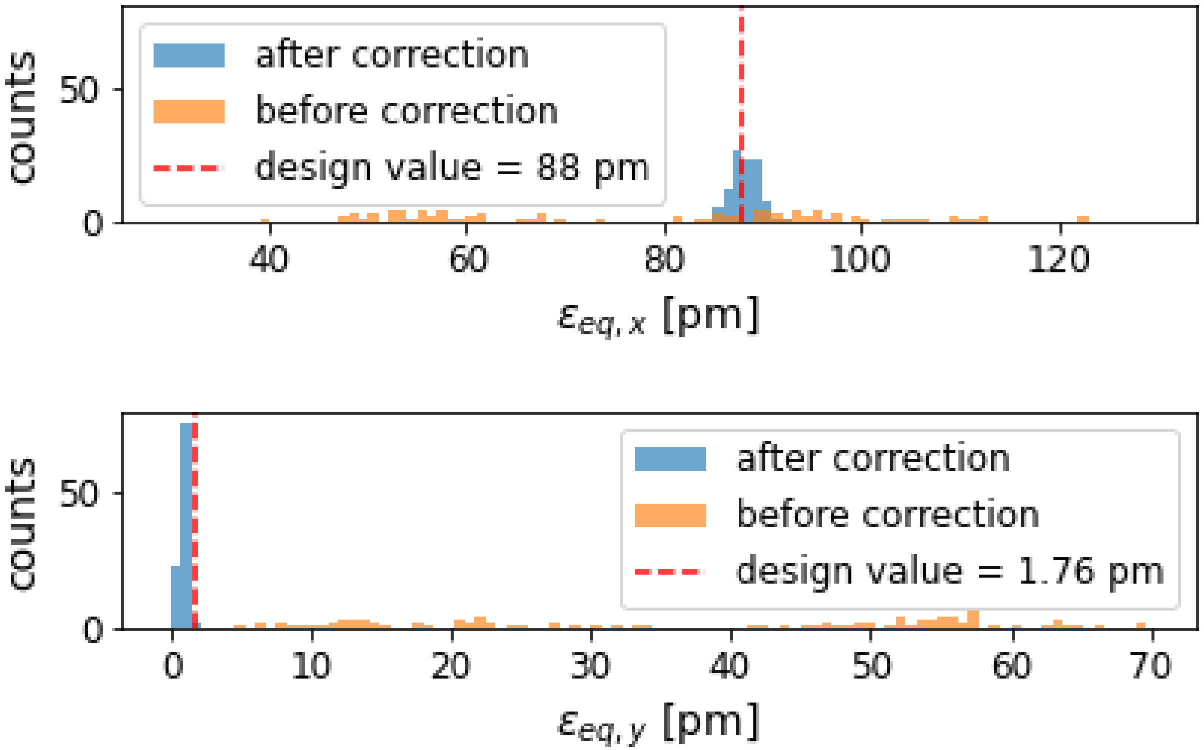
Booster tuning

Great improvement in emittance tuning

Error type	σ value
Dipole relative field error	10^{-3}
Quadrupole relative field error	2×10^{-4}
Sextupole relative field error	2×10^{-4}
Main dipole roll error	300 µrad
Offset quadrupoles	200 µm (girder) + 50 µm
Main Quadrupoles roll	300 µrad
Offset BPMs	200 µm (girder) + 50 µm
Offset sextupoles	200 µm (girder) + 50 µm

→ see « Status and perspectives of the emittance tuning of the FCC-ee High Energy Booster ring » by Q. Bruant

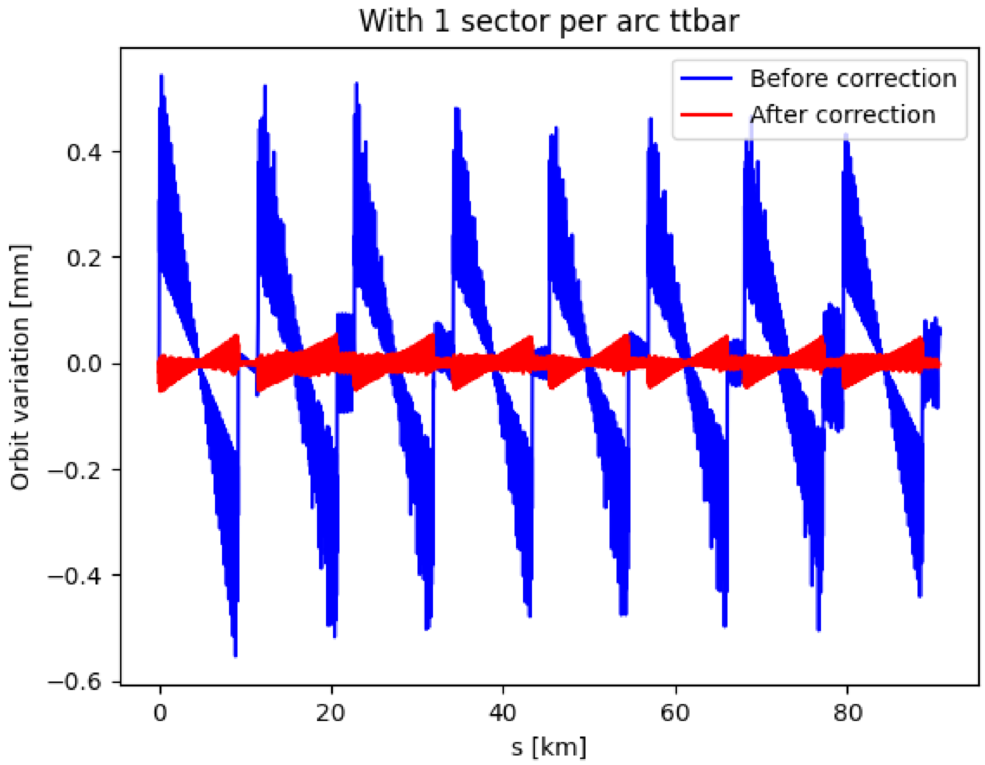
Sextupoles ramp (Quad and sextupole field errors, roll quad 300 μrad)



100 successful seeds

Tapering

With 1 sector per arc ttbar



- Relative energy lost per turn at $t\bar{t}$ (182.5 GeV): 5×10^{-2}

⇒ The beam energy continuously decreases from the RF section exit to the RF section entrance.

⇒ The magnetic fields should scale accordingly.

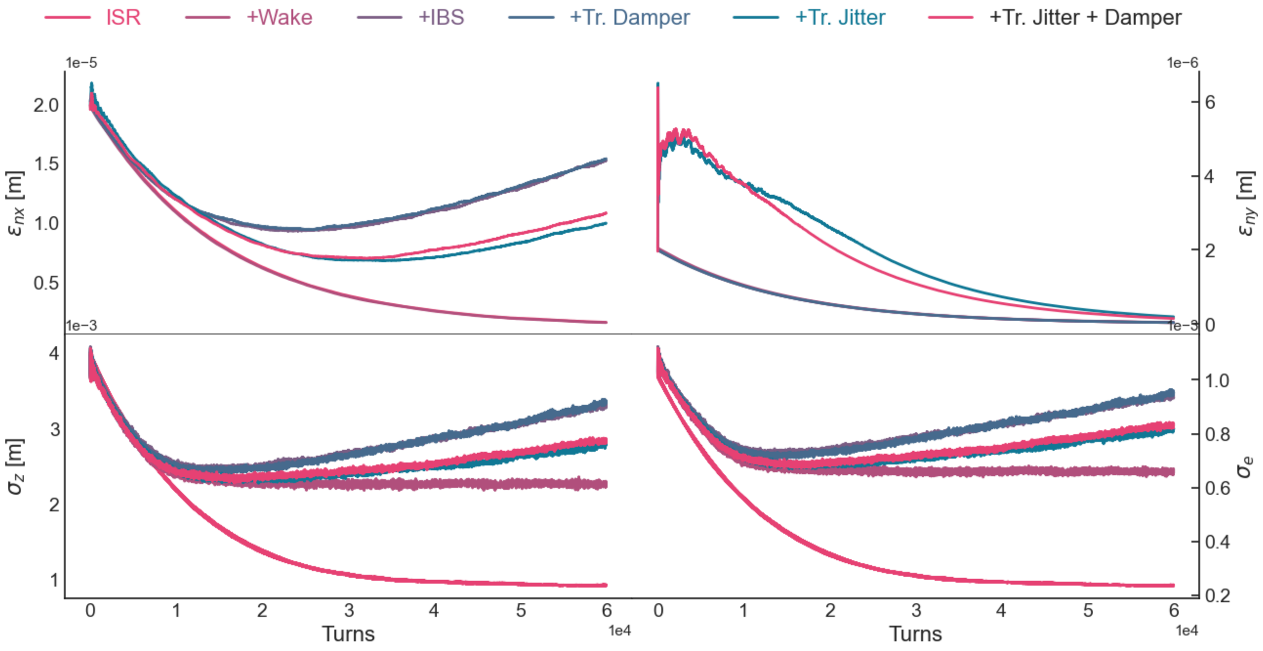
- **Individual powering excluded** because very costly.
- **Individual arc powering**. The maximum beam deflection in the booster can be **reduced to 553 μm**.
- **Individual arc powering + horizontal dipole correctors**. The maximum orbit variation is **reduced to 55 μm**, while the maximum corrector integrated strength **remains at 6.3 mTm**, which is below the specified dipole strength.

Next steps:

- Increase the number of dipole sectoring.
- Application of the booster tuning to correct beta-beating and check that the emittance is preserved.

Courtesy: A. Ghribi

Collective effects Interplay



Interplay between different collective effects at 20 GeV and for the z operation mode, 2.7e10 bunch population, 1e6 macroparticles, 300 longitudinal slices.

A robust design for collective effects instabilities

- **No instabilities so far for the baseline design ;**
- **Unchanged transverse damper ;**

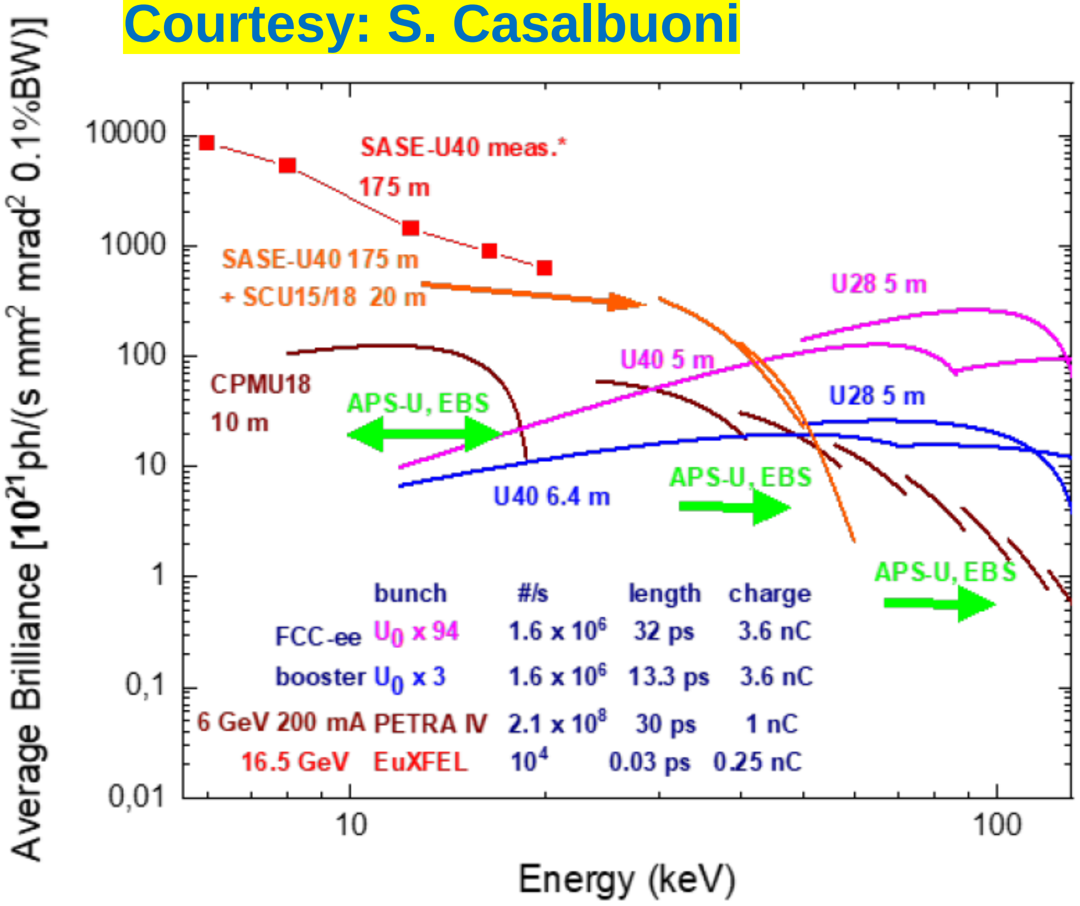
Coming next :

- **A Realistic impedance budget**
- **Ramp**

→ See Collective effects in the high energy booster by A. Ghribi.

Booster as a light source

Courtesy: S. Casalbuoni



	bunch	#/s	length	charge
FCC-ee	U_0 x 94	1.6 x 10^6	32 ps	3.6 nC
booster	U_0 x 3	1.6 x 10^6	13.3 ps	3.6 nC
6 GeV 200 mA	PETRA IV	2.1 x 10^8	30 ps	1 nC
16.5 GeV	EuXFEL	10^4	0.03 ps	0.25 nC

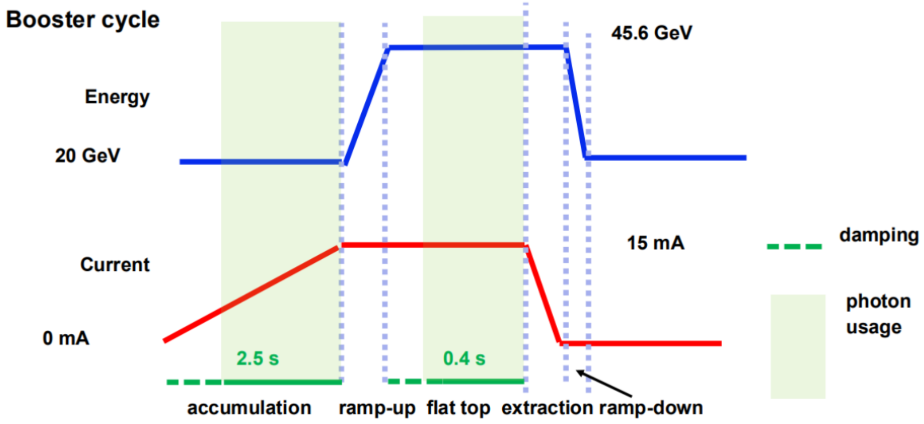
Proposal to add wigglers in the booster to generate high-energy and high brightness photon beams.

Parasitic use of the booster: the photon beam should be generated during the operation with a marginal impact on the collider operation.

The use of the wiggler (3 x U_0) is already planned to mitigate CBI.

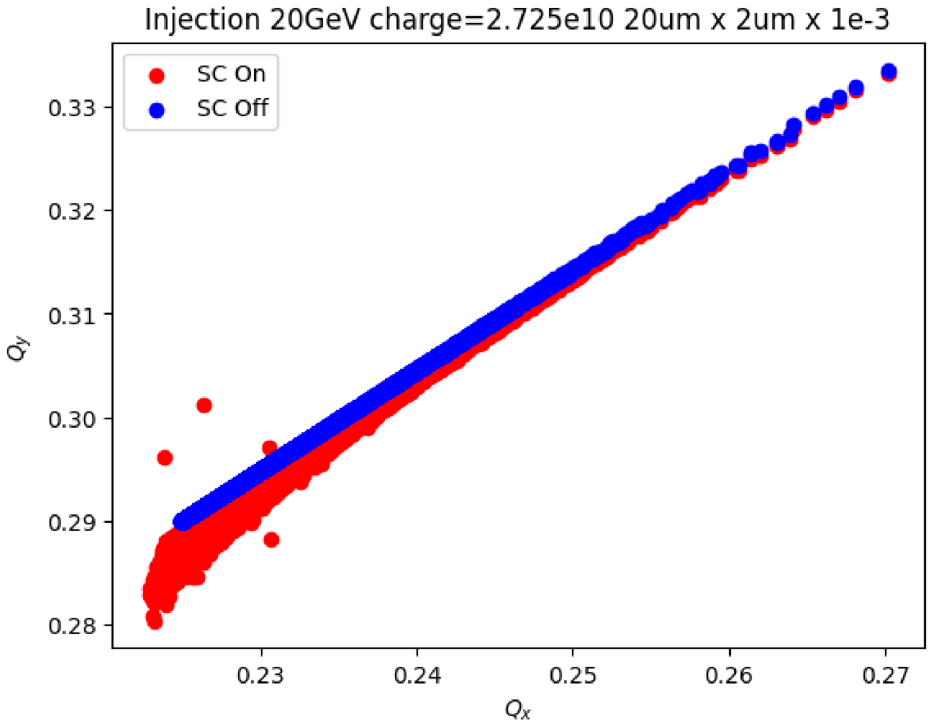
The implications of **intrabeam scattering** and Touschek effect for the ultralow-emittance beams at 20 GeV **will need to be examined**.

Proposal to use Compton scattering (I. Drebot).



Space charge limits

$$\Delta\nu_{x,y}^{\mathrm{SC}} = -\frac{N r_e C}{(2\pi)^{3/2}\gamma^3\sigma_z}\left\langle \frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x+\sigma_y)}\right\rangle$$



	Injection **No wiggler**	**Injection** **U_0 x 3**
Beam energy [GeV]	20	20
Bunch intensity [10^{10}]	2.725	2.725
Rms bunch length [mm]	4	4
Rms energy spread	0.001	0.001
Rms hor. Emittance [pm]	511	15
Rms vert. Emittance [pm]	51.1	1.5
$\Delta Q_{SC,x}$ Analytic	-0.0020	-0.0155
$\Delta Q_{SC,x}$ Xsuite	-0.0020	-0.0185
$\Delta Q_{SC,y}$ Analytic	-0.0082	**-0.124**
$\Delta Q_{SC,y}$ Xsuite	-0.0095	**-0.108**

Good agreement between Xsuite and analytical formula.
Space charge may be an issue to go to very small emittances. More investigation is required to evaluate the minimum reachable emittance in the booster (including IBS and other effects) and includes dispersion effects.

Conclusions and perspectives (1)

Optics

- Integration of the injection/extraction optics.
- The dynamic aperture and momentum acceptance stay large (thanks to second-order matching in the insertions).
- More work is under progress to understand the driver of the dynamic aperture and momentum acceptance and how to correct in in presence of errors.

Operation

- **New baseline RF system** : reverse phase operation in Z, WW, and ZH operation modes.
- The filling scheme has been revised.
- The ramping is under progress (study of the use of wigglers to damp coupled bunch instabilities).

Collective effects

- Single bunch and transverse multi-bunch instabilities are mitigated.

Conclusions and perspectives (2)

Optics tuning

- **Great progress**: beta-beating, dispersion beating, and coupling are now corrected. The equilibrium emittance in presence of errors is near the target.
- Study on the tapering has begun: first results show that we could have a residual orbit manageable by using the dipole correctors + dipole sectoring in the dipoles.

Other opportunities

- The use of the booster as a light source is under study. Space charge effects may be a limitation.

Perspectives

- Update the lattice to follow the changes in tunnel geometry or in collider lattice.
- Continue the good work on optics tuning (including tapering), collective effects (to study space charge effects and IBS together with a refined impedance budget), operation with an optimized ramp, integration of the insertions (injection, extraction, …), spin transport, and feed the database and the global parameter tables.
- Impact of the leaking field of the detector sloenoid on booster optics.

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.

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 2 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: $\boldsymbol{\epsilon_{xRMS} < 1.42\text{nm} \times \epsilon_{yRMS} < 9.4\ \text{pm} \times \sigma_{\Delta p/p} = 1.09\ 10^{-3}}$

Emittance evolution summary

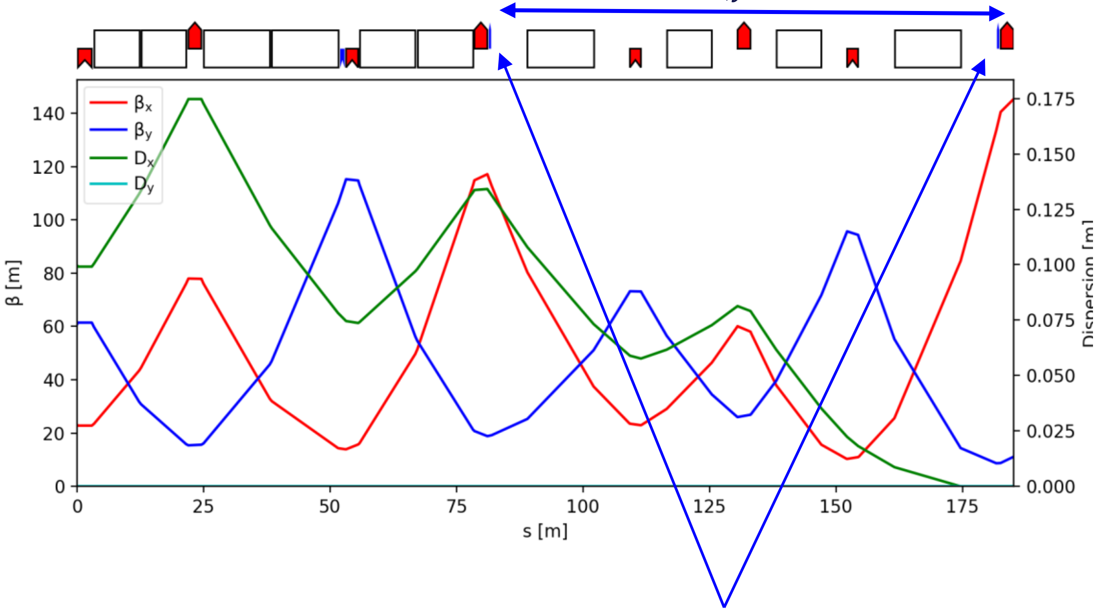
- **Going through higher energy** than the target during the ramp **speeds up the emittance damping** and gives a **smaller final vertical emittance**.
    - That requires a **higher voltage** (possible for Z operation since the required voltage is smaller than for the other modes) and **higher consumption**.
- **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.
    - → **See RF-based optimisation of the booster cycle by Alice Vanel for the RF 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**

Transparency + dispersion suppressor

Dispersion suppressor

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

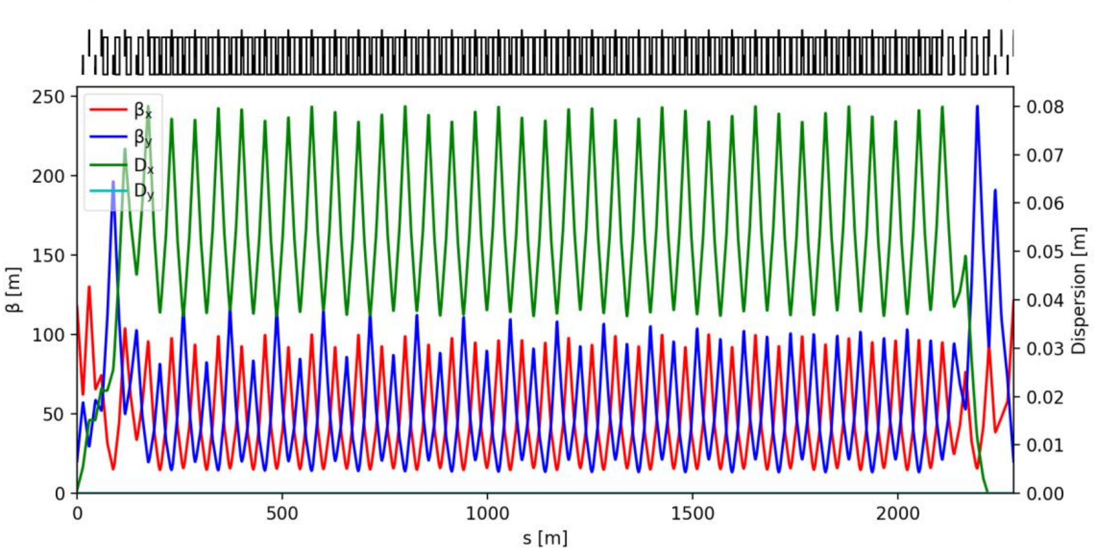


Sextupole pair used to correct

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

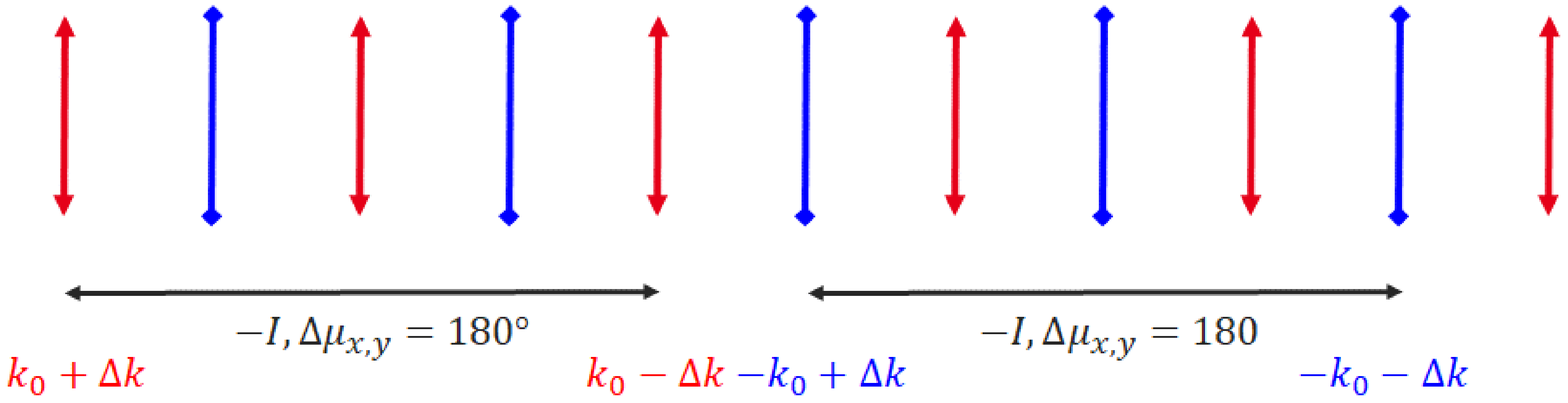
Momentum compaction tuning

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.



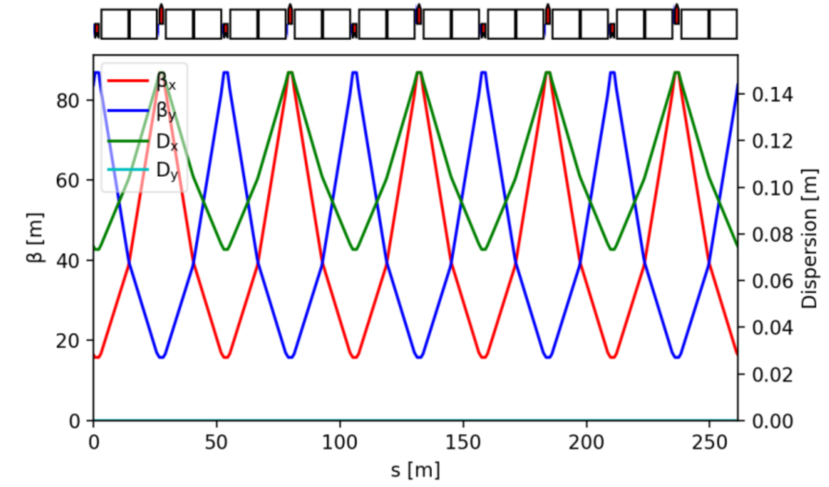
$-I, \Delta\mu_{x,y} = 180°$ $-I, \Delta\mu_{x,y} = 180$

$k_0 + \Delta k$ $k_0 - \Delta k$ $-k_0 + \Delta k$ $-k_0 - \Delta k$

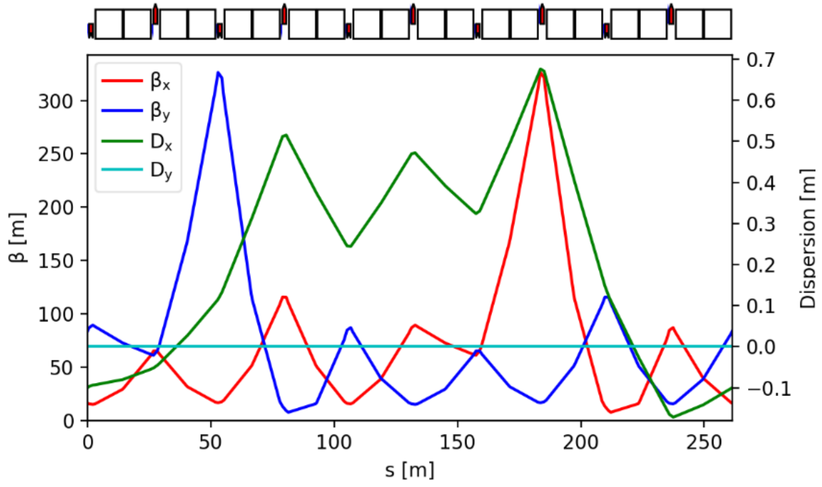
$$\Delta k \approx \frac{\sqrt{x}}{2\sqrt{3}} \text{ with } x = \frac{\alpha}{\alpha_0} - 1 \text{ where } \alpha \text{ is the momentum compaction and 0 when } \Delta k\text{=0}$$

Alternative optics: comparison with the cell

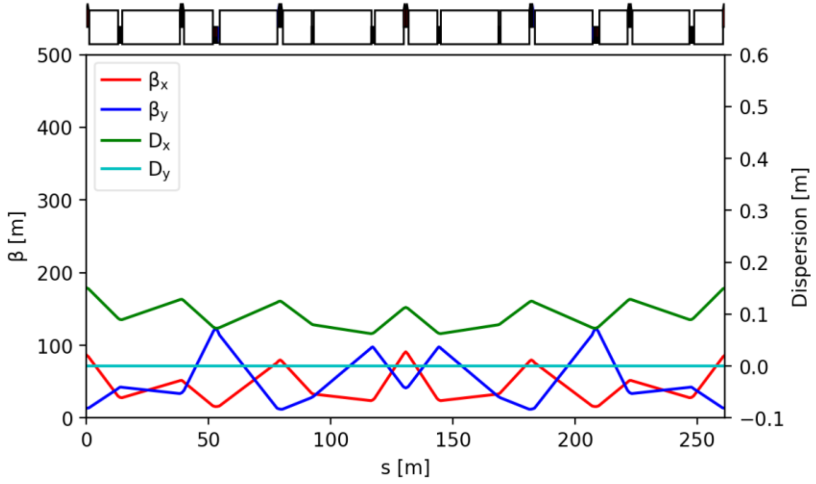
Arc FODO cell



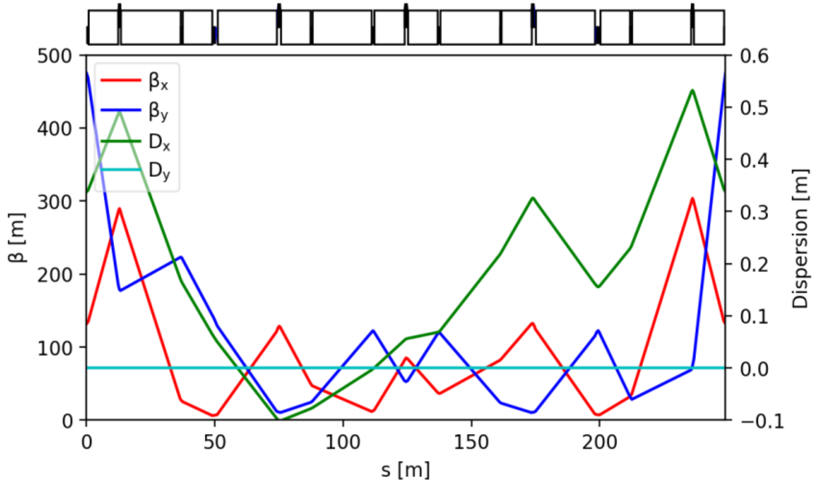
Arc FODO cell $\alpha \times 2$



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.