DE LA RECHERCHE À L'INDUSTRIE

www.cea.fr

Status of the high-energy booster

Antoine CHANCE [1] Hervé de GRANDSAIGNES de HAUTERIVES [1]
Barbara DALENA [1] Bastian HAERER [2]

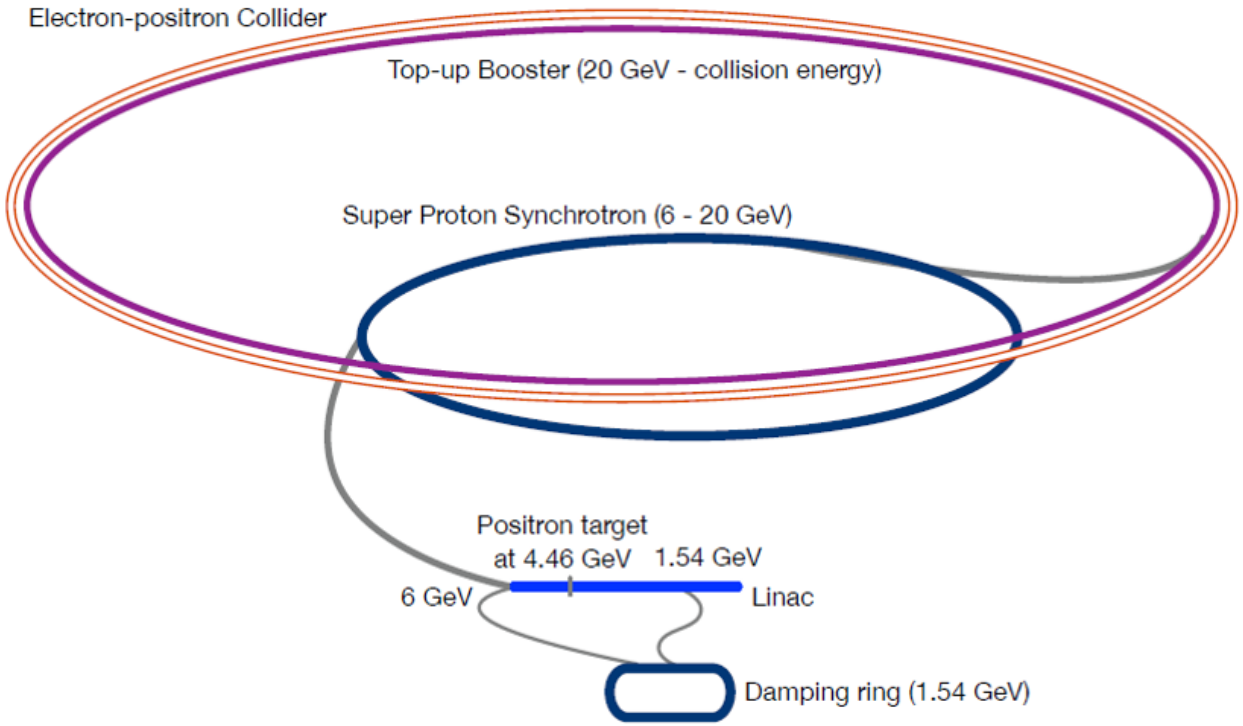
[1]CEA IRFU DACM

[2]KIT

FCC week 2021
30 June 2021

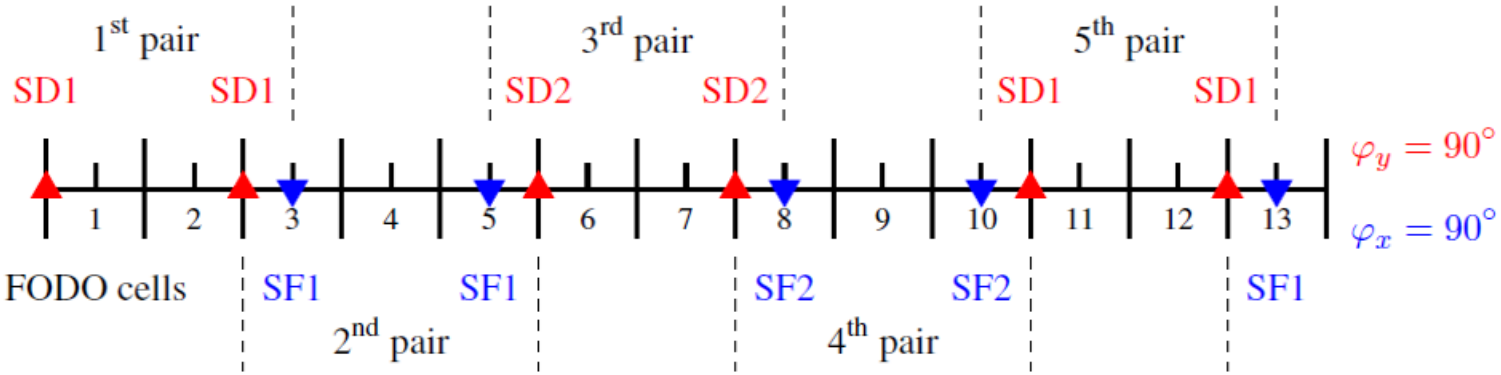
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Irfu



- Injection energy into the booster: 20 GeV.
- Alternative: injection from the linac without intermediate booster.
- Top-up injection mode into the collider.
- Ramping similar to SPS: 80 GeV s^{-1}.
- Total filling time $<$ 20 min.

- Arc optics. Two different optics are mandatory to get:
  - A larger momentum compaction at Z (45.6 GeV) and W (80 GeV) operation mode to handle microwave instability and IBS ! **phase advance of** $60°/60°$.
  - A smaller equilibrium emittance (smaller I_5) at H (120 GeV) and $t\bar{t}$ (182.5 GeV) operation mode ! **phase advance of** $90°/90°$.
- Chromaticity correction.
  - **Non-interleaved sextupole scheme** gives the largest dynamic aperture.

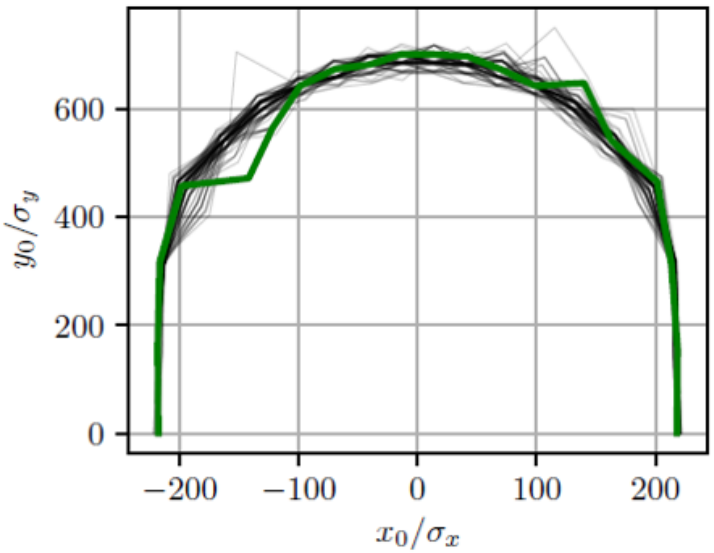


- **Same correction procedure as in main collider** of the linear errors (orbit correction, beta and dispersion beating, coupling, ...).
- Dynamic and momentum aperture calculations performed with MADX-PTC for 2000 turns and 100 seeds (radiation on/ no wigglers).
- Non-interleaved sextupole scheme.
- Quadrupole misalignment: 100 µm.

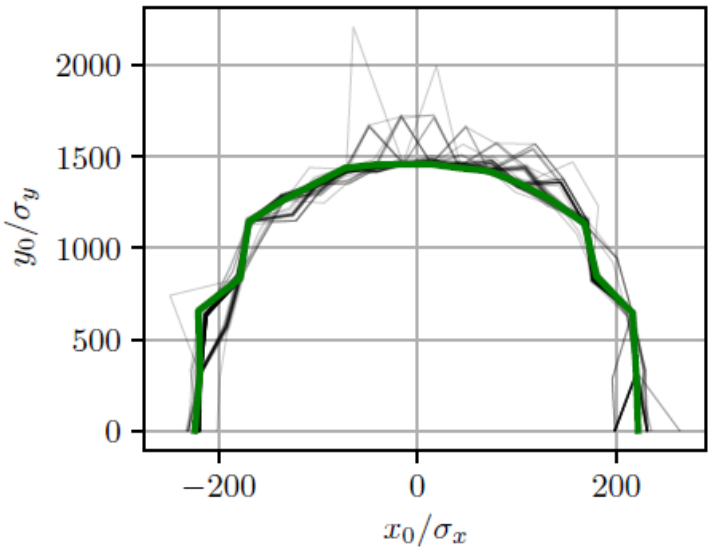
Dynamic aperture at 20 GeV

Courtesy: T. Tydecks

90°/90°



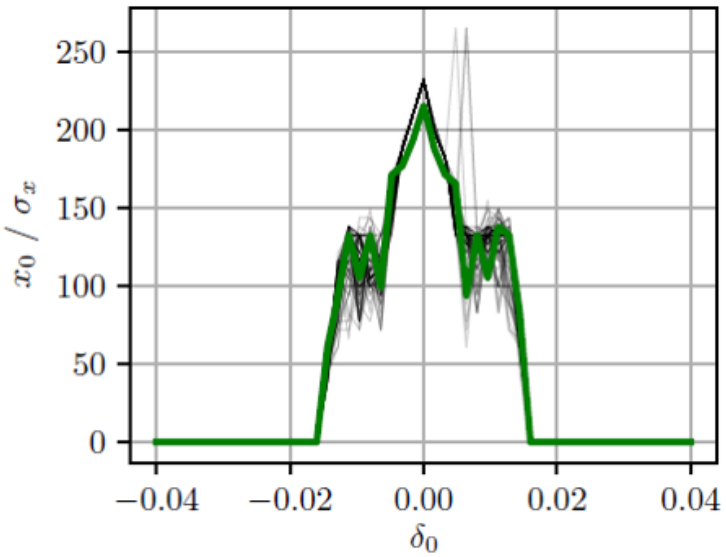
60°/60°



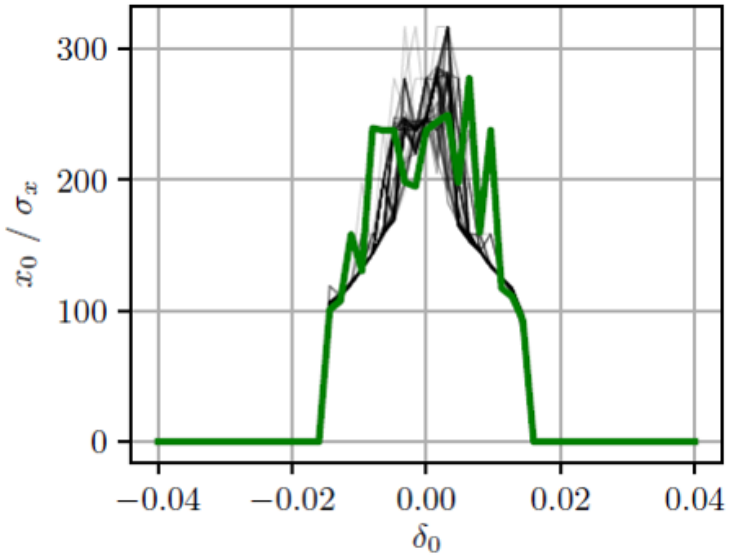
- **Same correction procedure as in main collider** of the linear errors (orbit correction, beta and dispersion beating, coupling, ...).
- Dynamic and momentum aperture calculations performed with MADX-PTC for 2000 turns and 100 seeds (radiation on/ no wigglers).
- Non-interleaved sextupole scheme.
- Quadrupole misalignment: 100 µm.

Momentum aperture
Courtesy: T. Tydecks

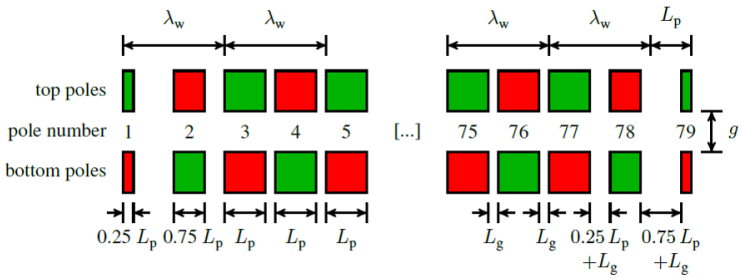
90°/90°



60°/60°



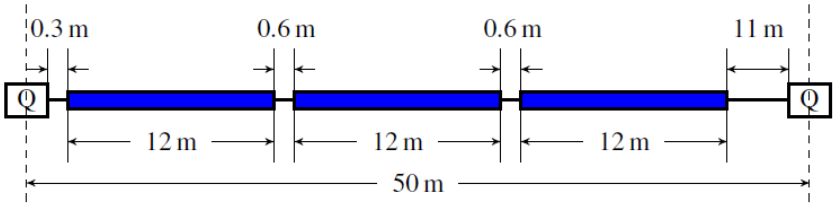
- No wiggler: **damping time of** 10 s at injection (20 GeV).
- Advantages to add wigglers:
  - To increase the integrate I_2: **to reduce the damping time**.
  - Larger equilibrium momentum spread and thus **larger bunch length**.
  - **Good** to mitigate **IBS**.
  - **Good** to mitigate **microwave instability** (Boussard's criteria).
- Target damping time: 0.1 s at 20 GeV.



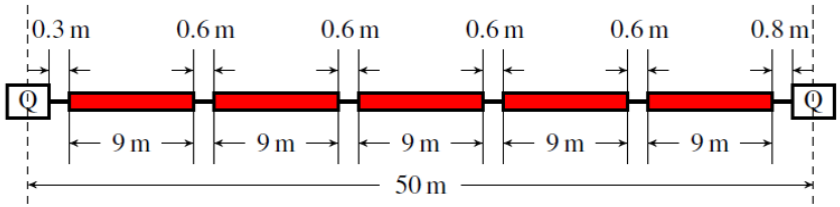
Pole length	0.095 m
Pole separation	0.020 m
Gap	0.050 m
Number of poles	79
Wiggler length	9.065 m
Magnetic field	1.45 T
Energy loss per turn	126 MeV
Hor. damping time	104 ms
Hor. emittance (60°optics)	300 pm rad

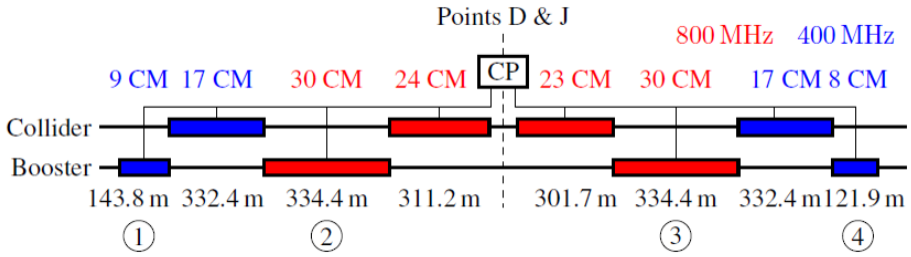
- Equilibrium emittance at 45.6 GeV: 300 pm **>** 235 pm (emittance in the collider).
- **Still room for optimisation** with shorter pole length and larger number of poles for instance.

RF cavities of 400 MHz



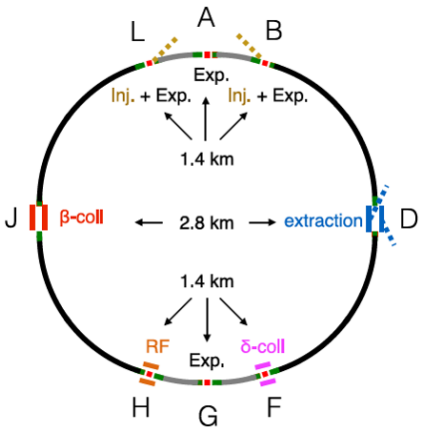
RF cavities of 800 MHz

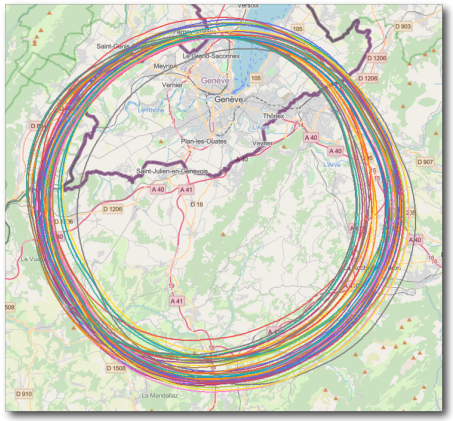




frequency (MHz)	400	800
length of cryo module (m)	12	9
no. of cavities per module	4	4
no. of cells per cavity	4	5
cell length (m)	0.375	0.1875

- Two long RF sections in D and J instead of distributed RF stations to reduce costs.
- At Z operation: total voltage of 140 MV against 100 MV because of wigglers.
- The number of RF cavities per FODO cell is 6 at 400 MHz and 10 at 800 MHz.
- Diameter of the cryomodules (CMs): $\grave{E}$ 1 m.
  - The CMs cannot be installed in parallel with the CMs of the collider
  -) **The CMs are staggered**.



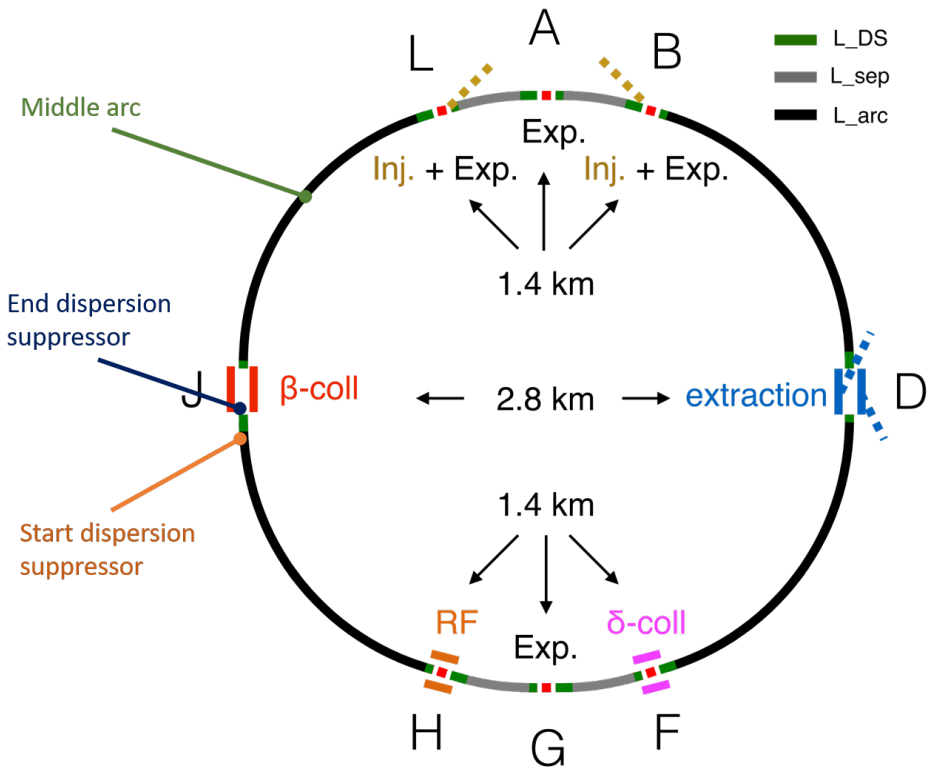


Layout	Tot. length	Arc radius of curvature	Short arc A-B, F-G, G-H, L-A	Long arc B-D, D-F, H-J, J-L	Straight sections A, G	B, F, H, L	D, J
CDR	97750	13329	4448	16489	1400	1400	2800
17.08	96109	12922	5782	14517	1400	1400	3250
19.03	91350	12380	3864	15582	1360	1360	2690
20.03	95713	13058	10256	10256	1450	2000	1450

- The booster geometry is driven by civil engineering:
  - A few years ago, the FCC-ee tunnel should fit the FCC-hh tunnel.
  - To reduce cost, the tunnel geometry is under deep optimization.
  - New layout with 4 IPs in the collider is under discussion: deep impact on booster geometry.
- **Needs for a booster generator** to handle layout modifications.

The input data are:

- The positions (in laboratory frame and Cartesian coordinates) of:
  - the **entrance of the dispersion suppressors**,
  - the **exit of the dispersion suppressors**,
  - the position of the **middle of the arc**.



The input data are:

- The positions (in laboratory frame and Cartesian coordinates) of:
  - the **entrance of the dispersion suppressors**,
  - the **exit of the dispersion suppressors**,
  - the position of the **middle of the arc**.
- The total length of the booster.
- The number of cells per dispersion suppressor.
- The number of cells in each arc.
- The number of dipoles per cell.
- The length and separation between dipoles.

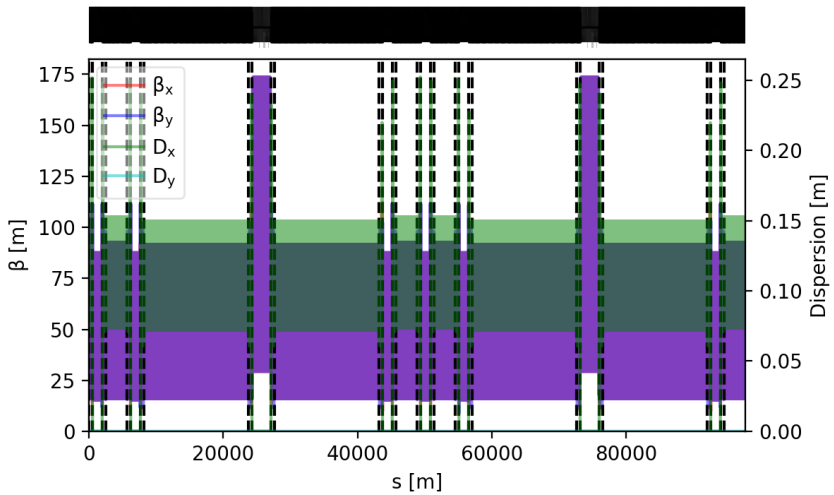
The input data are:

- The positions (in laboratory frame and Cartesian coordinates) of:
  - the **entrance of the dispersion suppressors**,
  - the **exit of the dispersion suppressors**,
  - the position of the **middle of the arc**.
- The total length of the booster.
- The number of cells per dispersion suppressor.
- The number of cells in each arc.
- The number of dipoles per cell.
- The length and separation between dipoles.

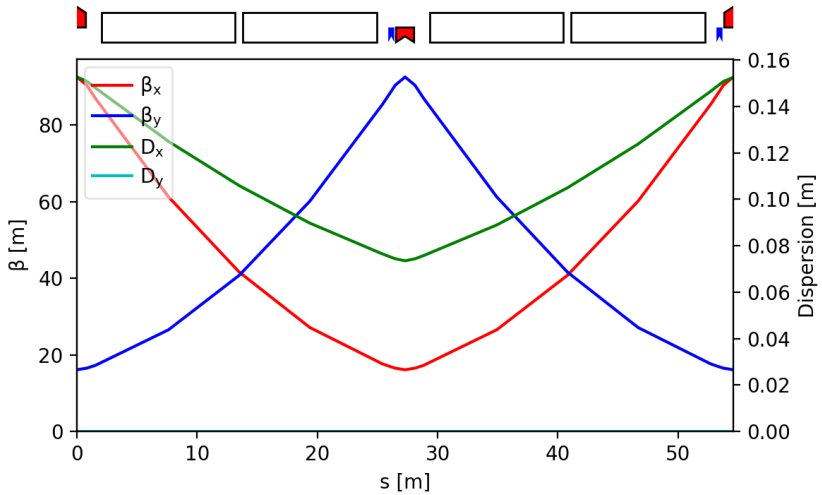
The generator calculates then the length of the cells in the dispersion suppressor and arcs to fit this geometry.

- The software generates then the **input files with the naming convention** for MAD-X calculations: sequence, element definitions, element strengths, matching macros, ...
- The insertions are FODO cells (with a parameter of length).
  - It is possible to choose its own sequence file for the insertions.
- The **tune** of the booster is matched by tuning the **phase advances in the RF sections** (sections D and J).
  - In the next future, possibility to use other schemes (for instance with a phase advance of $90°/60°$ Åϵ in the arcs and other sextupole pattern).
- The **sextupoles and the correctors are inserted in the lattice**.
  - The macros for chromaticity correction and correctors are to be updated.

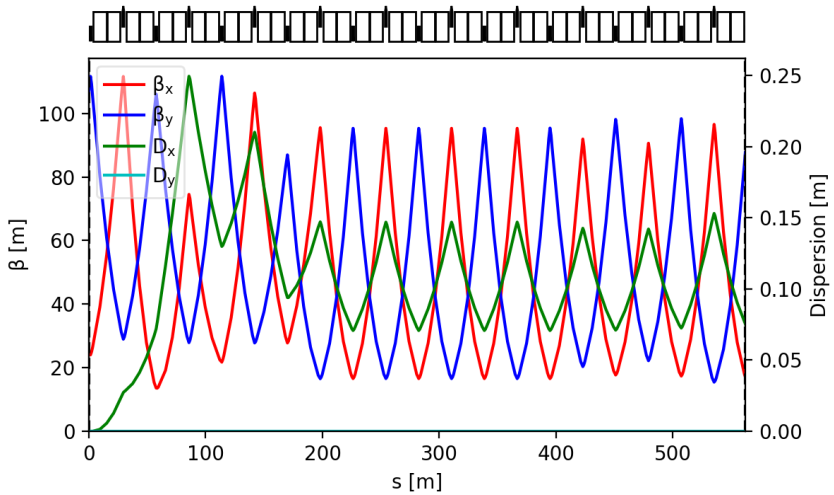
Ring



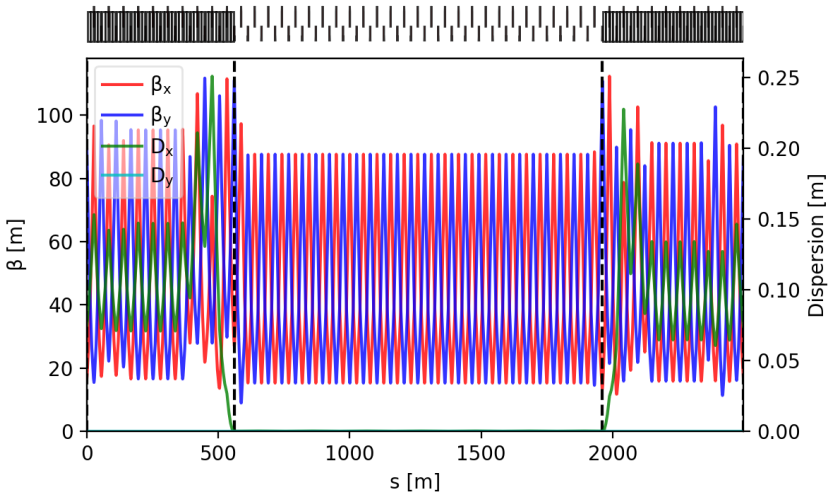
Arc FODO cell



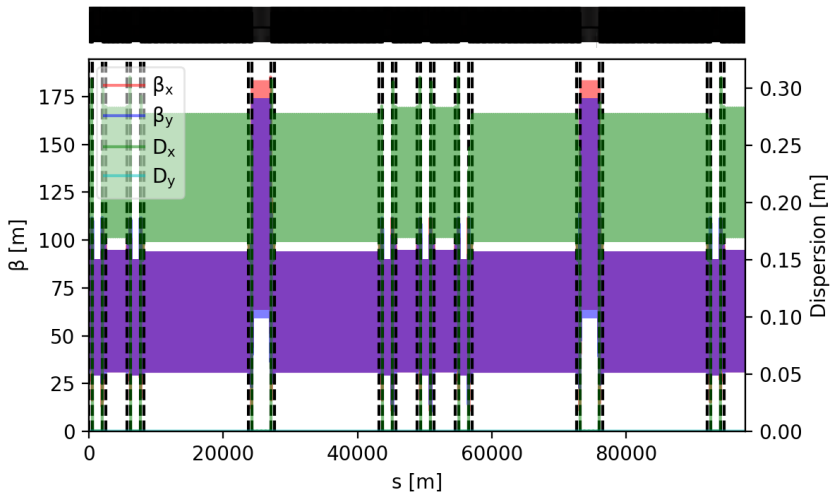
Dispersion suppressor



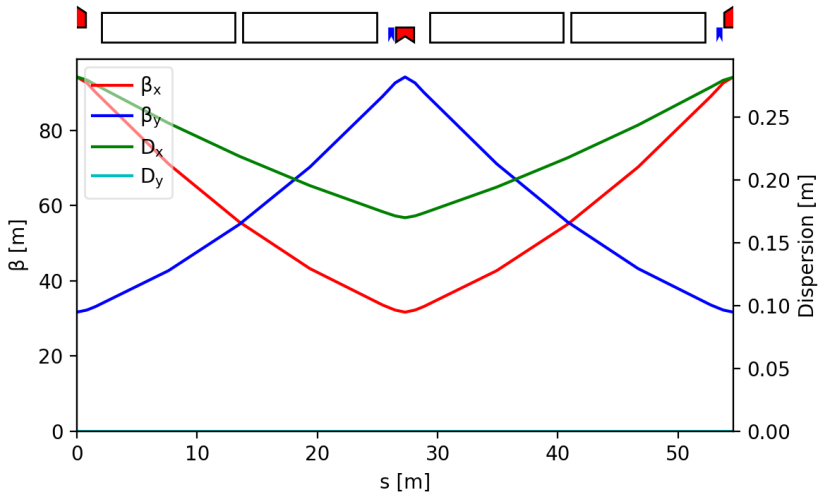
Insertion



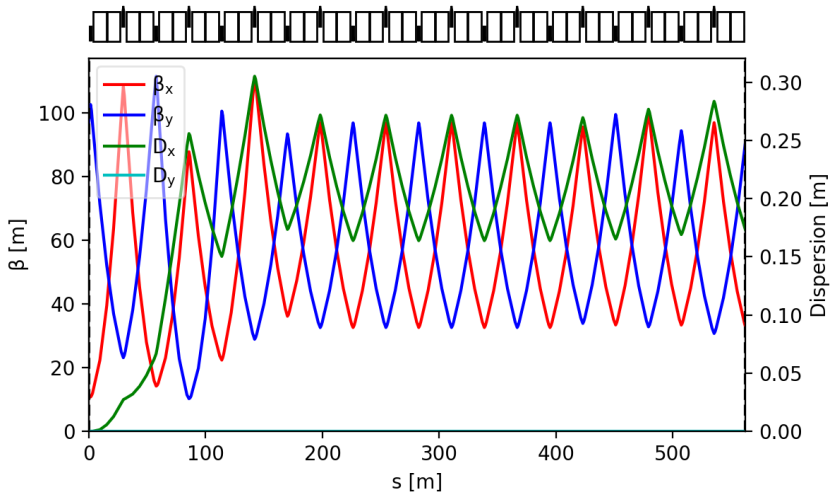
Ring



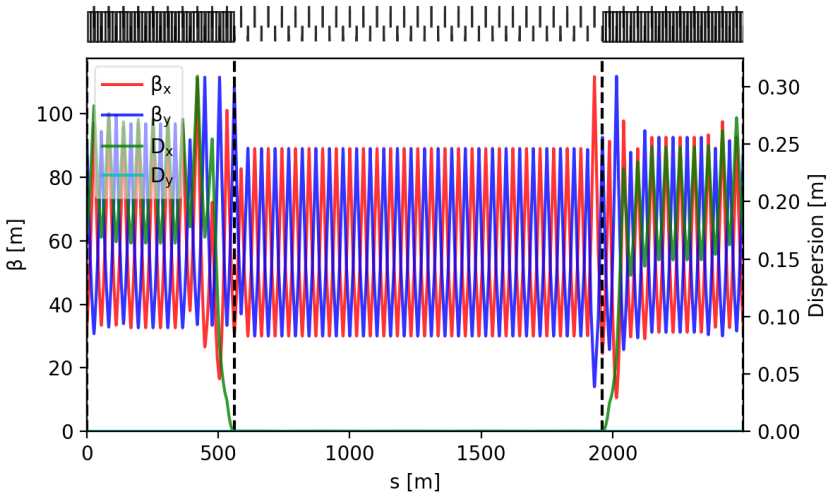
Arc FODO cell



Dispersion suppressor



Insertion

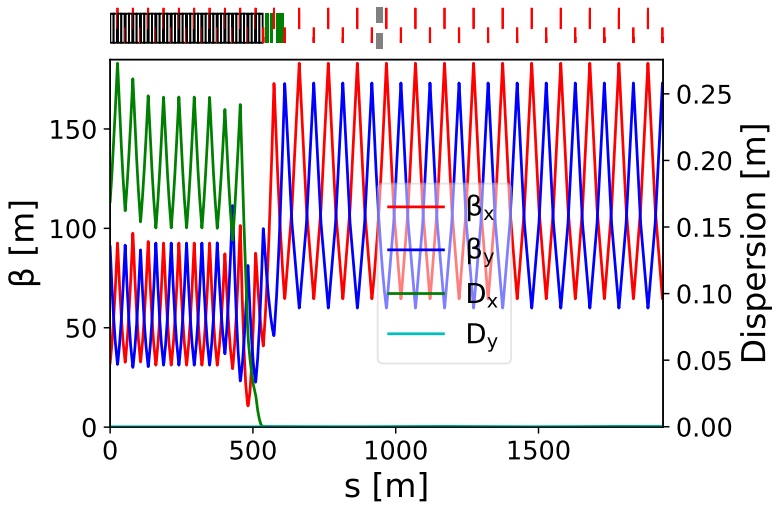


- Equilibrium emittances and damping times are evaluated from synchrotron integrals.
- **With no correction of the damping in the arcs, TWISS module fails** in MAD-X at $t\bar{t}$ operation) (cannot use tapering: needs for a correction scheme).
- **Very good agreement** between CDR valeus and the ones obtained

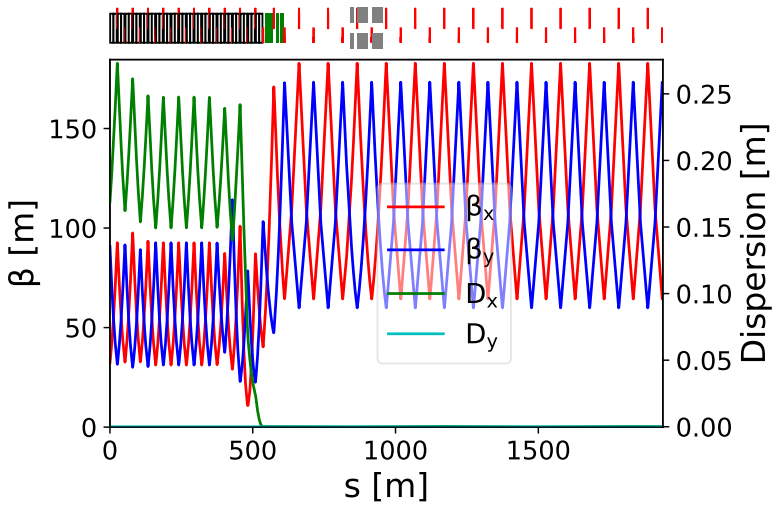
Beam energy [GeV]	Eq. emittance Optics 60°/60° [nm]		Eq. emittance Optics 90°/90° [nm]		Transverse damping time [s]	
	CDR	new	CDR	new	CDR	new
20	0.045	0.045	0.015	0.015	10.054	10.047
45.6	0.235	0.236	0.078	0.080	0.854	0.848
80.0	0.729	0.726	0.242	0.247	0.157	0.157
120.0	1.641	1.633	0.545	0.556	0.047	0.047
175.0	3.540	3.472	1.172	1.183	0.015	0.015

The wigglers and RF sections are inserted.

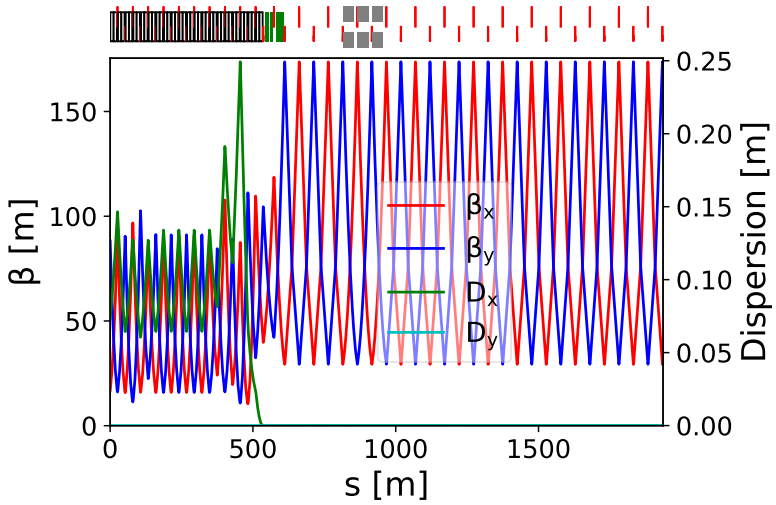
ESS 7, Z operation



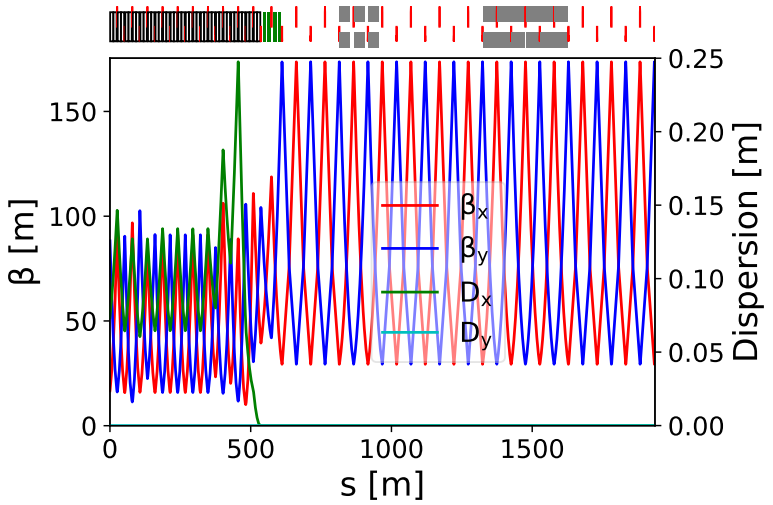
ESS 7, W operation



ESS 7, H operation



ESS 7, $t\bar{t}$ operation



- A python code has been written to generate the MAD-X files of the booster in agreement with the layout.
- The code makes a first guess of the initial quadrupole strengths and generates macros to tune the machine.
- The tune is obtained by matching the phase advances in the RF sections.
- We have got an optics for the 4 beam operation modes.
- We have got a **good agreement with the CDR** values for the equilibrium emittance and damping times for the 60°/60° and 90°/90° optics.

- Non-interleaved sextupole scheme will be implemented again soon.
- Correction scheme (similar to the collider) is to be tested again.
- Evaluation of the impact of the energy loss in the arcs and of mitigation schemes.
- Calculation of the final equilibrium emittance with updated misalignment errors.
- Integration of random dipole errors (including field error at injection with a **dipole field of only** 6 mT**!** at 20 GeV).
- Evaluation of the dynamic aperture and momentum acceptance with no error (only sextupoles on), with field and/or misalignment errors.
- **Determination of the minimum injection energy**.
- **New booster optics for the case of a 4 IPs layout**.

- Currently, the poles of the undulator are made of TKICKER or RBEND in MAD-X.
- Energy loss along the arcs needs to be better taken into account: That is a different feature from the collider. **We cannot apply the tapering**.
  - We could benefit from CHART-II developments for a better simulation of the radiation (including wigglers and amplification).
- **Alternative lattice** for the arcs: different constraint from the collider (no beamstrahlung/no beam-beam effects in the boster).

FCC WEEK 2021

28 June – 2 July

Thank you for your attention !

ONLINE EVENT

Register Here:
https://indico.cern.ch/e/fccw2021

FUTURE CIRCULAR COLLIDER

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