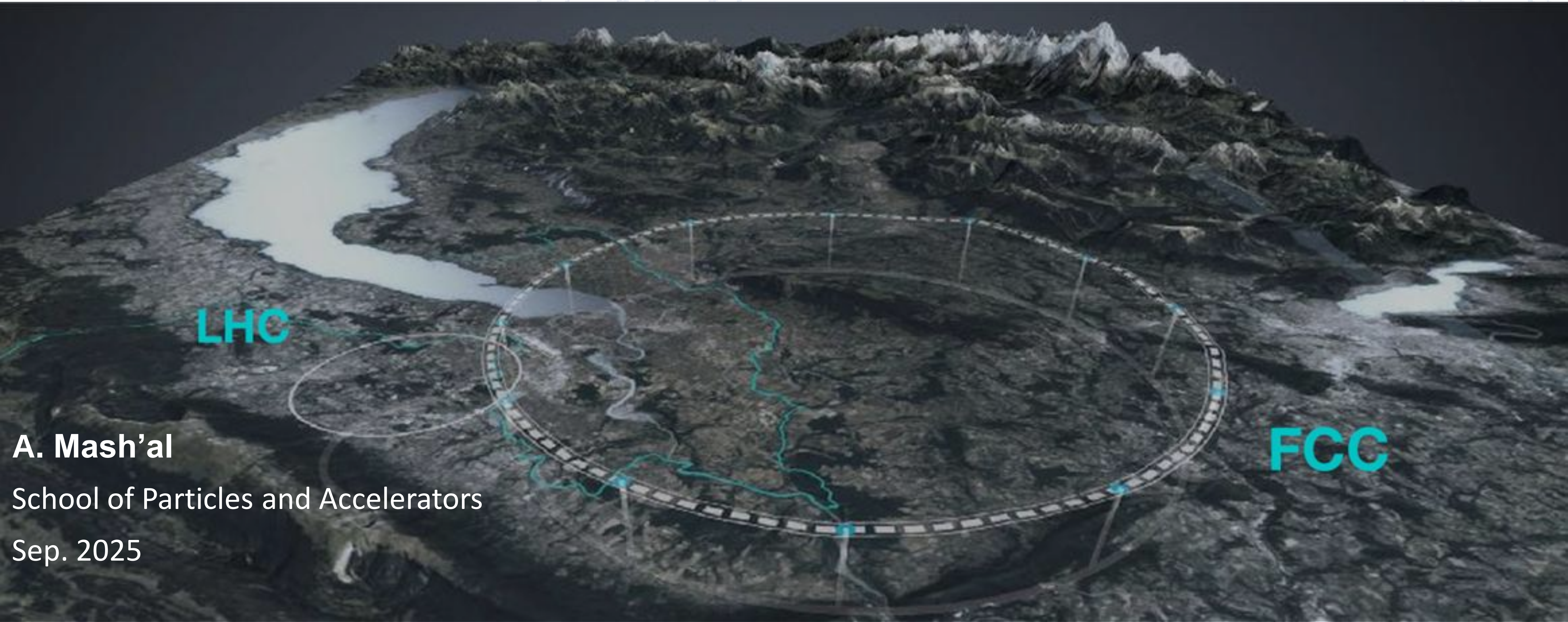
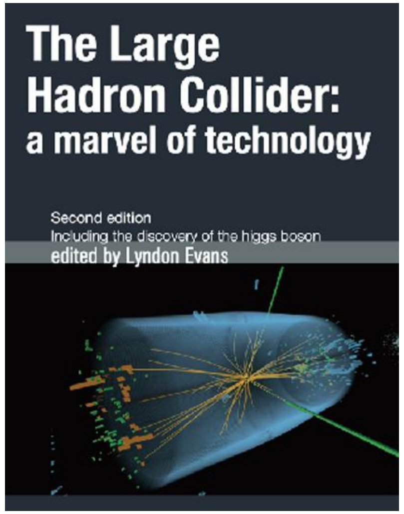
Future Circular Collider
Feasibility Study Report
Accelerator Part



A. Mash'al

School of Particles and Accelerators

Sep. 2025



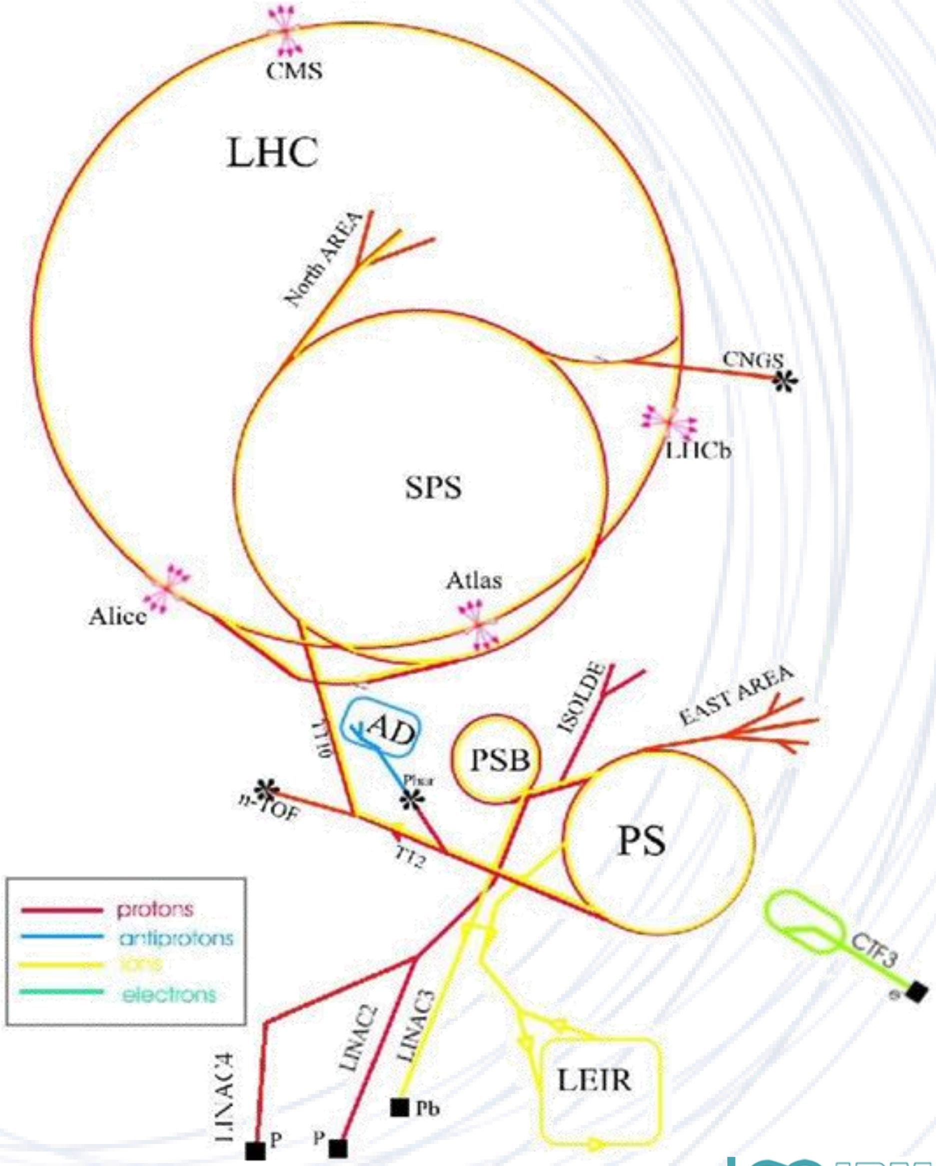
Unrivalled at Energy Frontier

13.6 TeV (COM energy)

Outstanding at Intensity Frontier

Record Luminosity* $2.26 \times 10^{34}\ cm^{-2}s^{-1}$

*Close to SuperKEKB at $5.1 \times 10^{34}\ cm^{-2}s^{-1}$



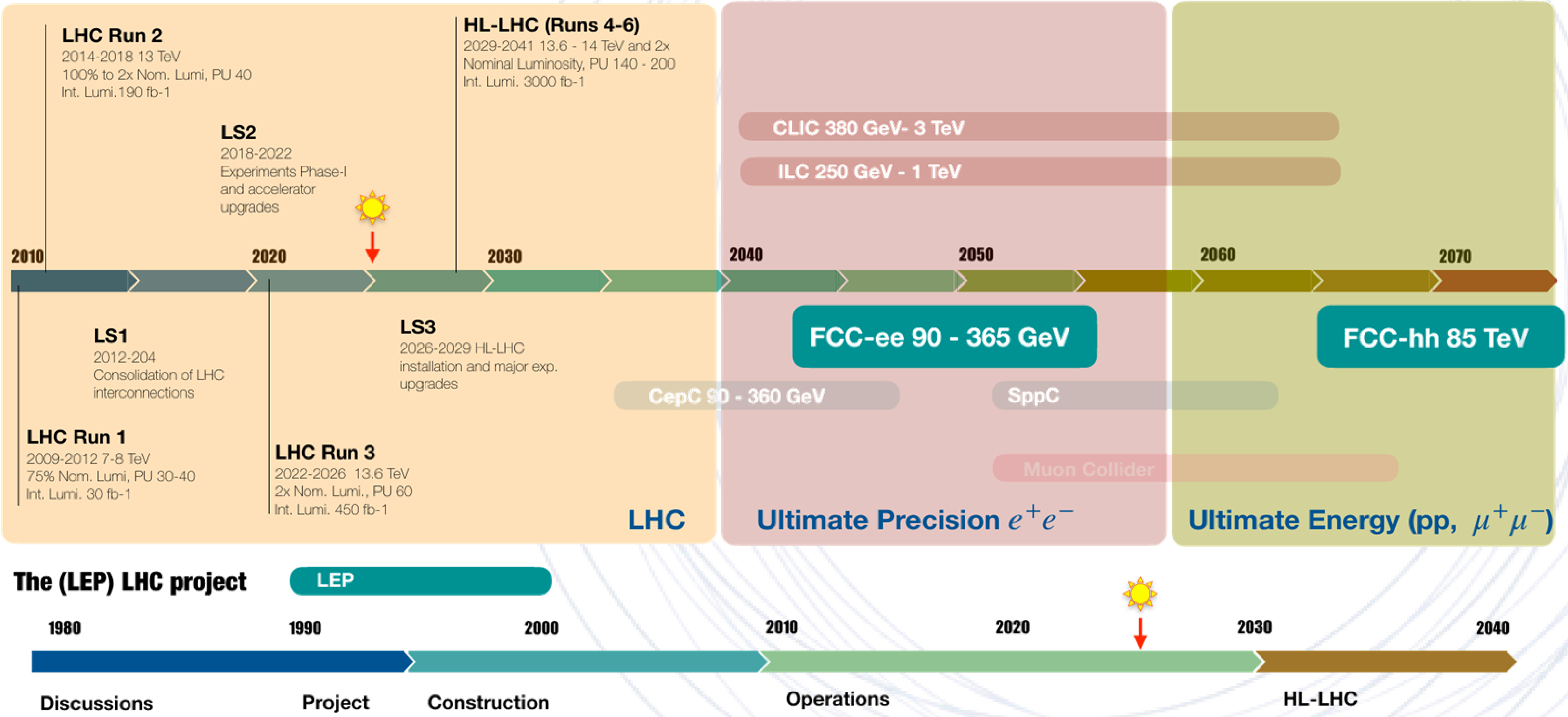
So far the LHC has delivered:

- 15 Million Higgs bosons produced
- 600 Million top quarks produced
- 15 Billion Z bosons
- 60 Billion W bosons

Still 10 times more statistics expected at HL-LHC!

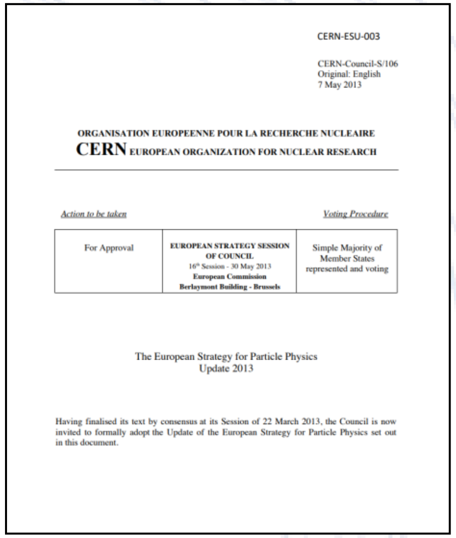
Two main outcomes of the LHC: **The discovery of the Higgs boson and nothing else (so far)!**

A Scientific Mission for the 21st Century



2013 Update of European Strategy for Particle Physics:

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines."


CERN-ESU-003

CERN-Council-S/106
Original: English
7 May 2013

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken		*Voting Procedure*
For Approval	EUROPEAN STRATEGY SESSION OF COUNCIL 16th Session - 30 May 2013 European Commission Berlaymont Building - Brussels	Simple Majority of Member States represented and voting

The European Strategy for Particle Physics
Update 2013

Having finalised its text by consensus at its Session of 22 March 2013, the Council is now invited to formally adopt the Update of the European Strategy for Particle Physics set out in this document.

After the **LHC**, the **FCC** is the most ambitious and the prefect flagship project for CERN!

FCC-ee at intensity frontier

Ultimate Precision and discovery potential

Goal Luminosity $144 \times 10^{34}\ cm^{-2}s^{-1}$

One LEP1 every few minutes !! At the Z peak (per IP) – 4 Ips

Z, WW, ZH and $t\bar{t}$ COM energies

Targets to deliver

- -3 Million Higgs bosons
- -2 Million top quarks
- -240 Million WW events
- - 6 x 10^{12} Z bosons

All these in a much cleaner environment!

FCC Collaboration delivered 4 volumes Conceptual Design Reports as input to ESPPU 2019/20

Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

2020 Update of European Strategy for Particle Physics:

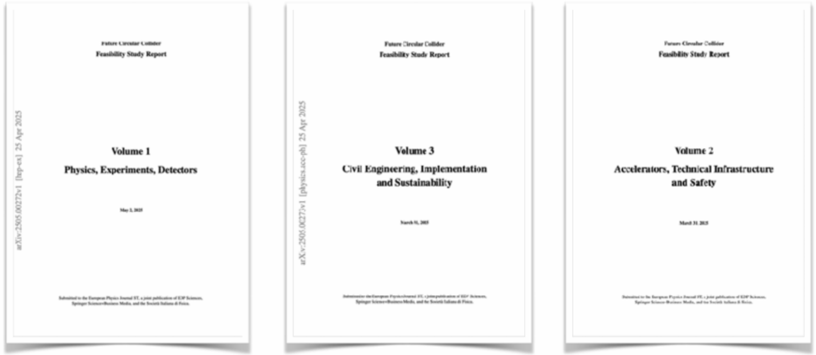
“*Europe, together with its international partners, should investigate technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of* ***at least 100 TeV*** *and with an electron-positron Higgs and electroweak factory as a possible first stage.*”

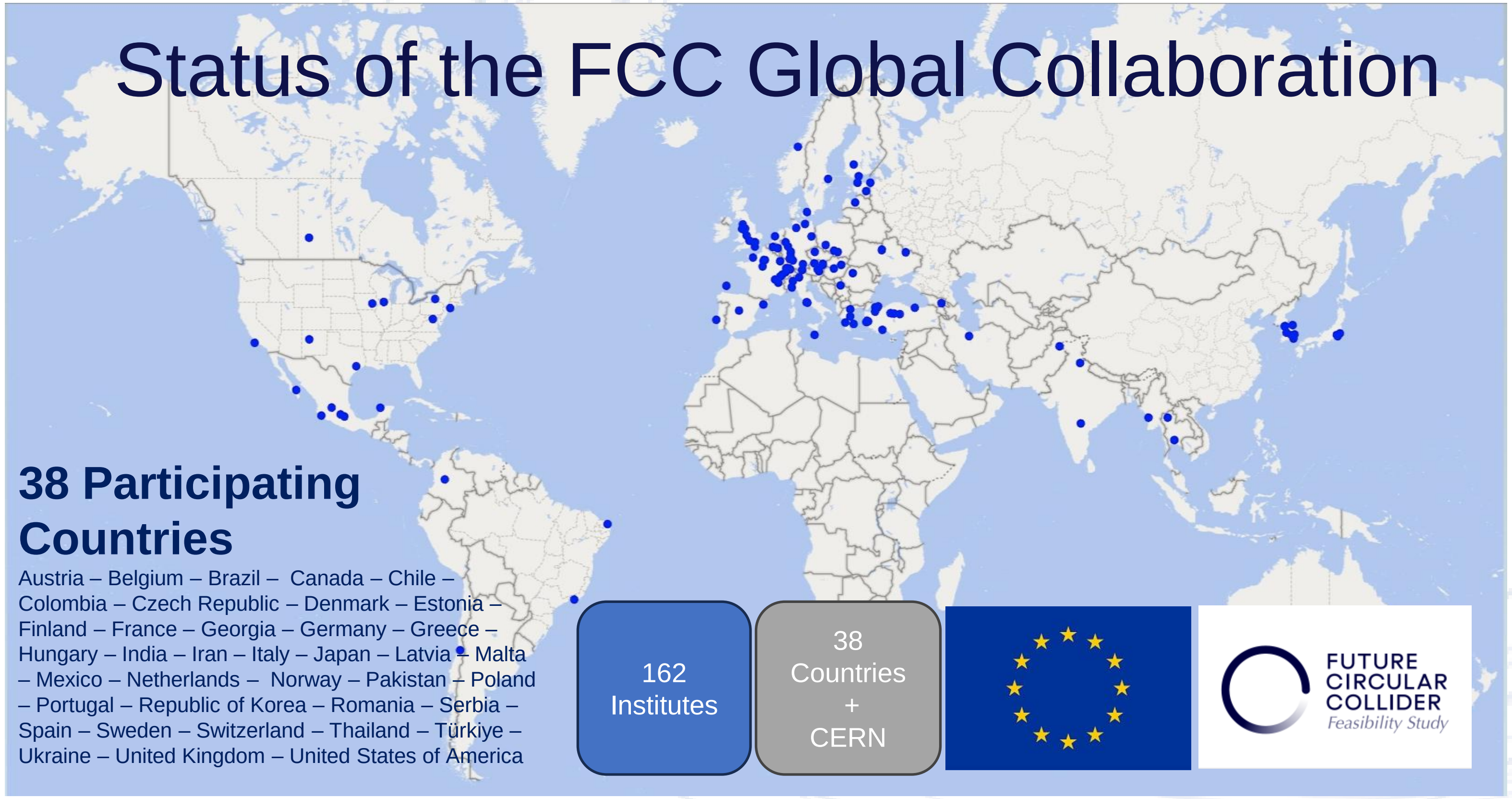
➔ Launch of the FCC Feasibility Study mid 2021

Feasibility Study Report published on 31 March 2025

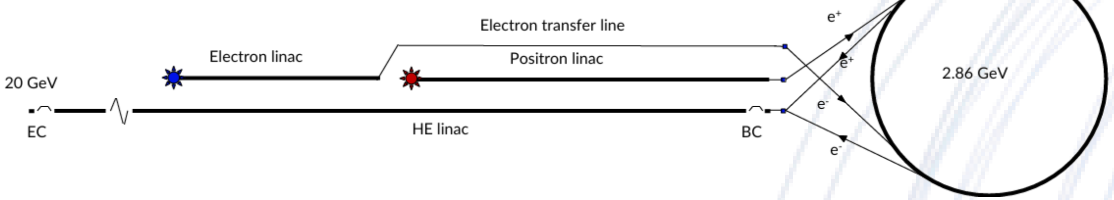
Structure: Three Volumes

- ***Vol. 1*: Physics, Experiments and Detectors**
- ***Vol. 2*: *Accelerators*, Technical Infrastructures, Safety Concepts**
- ***Vol. 3*: Civil Engineering, Implementation & Sustainability**

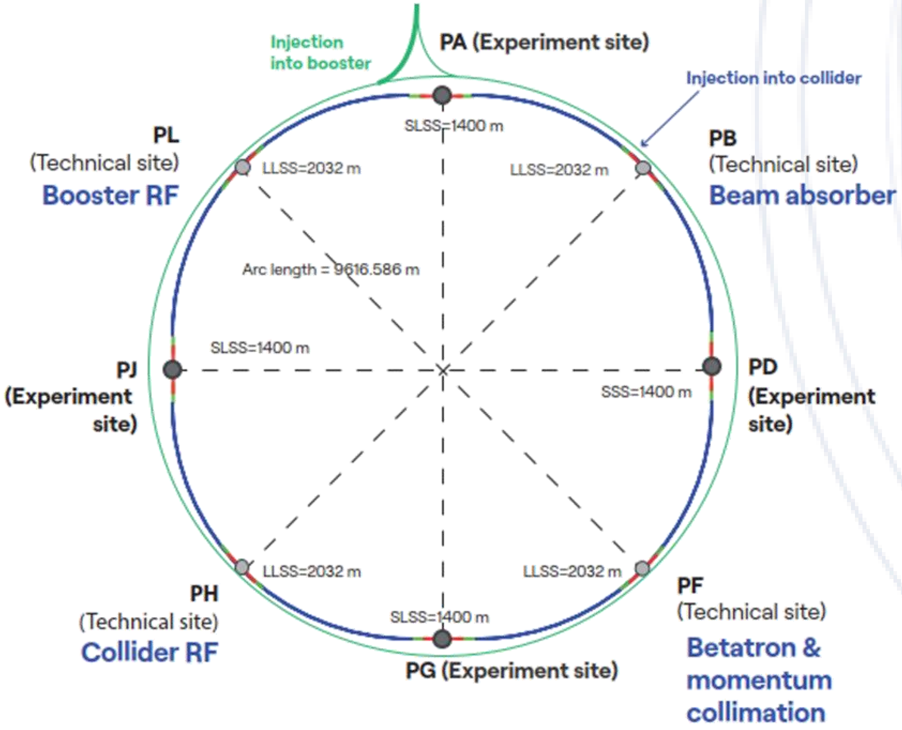


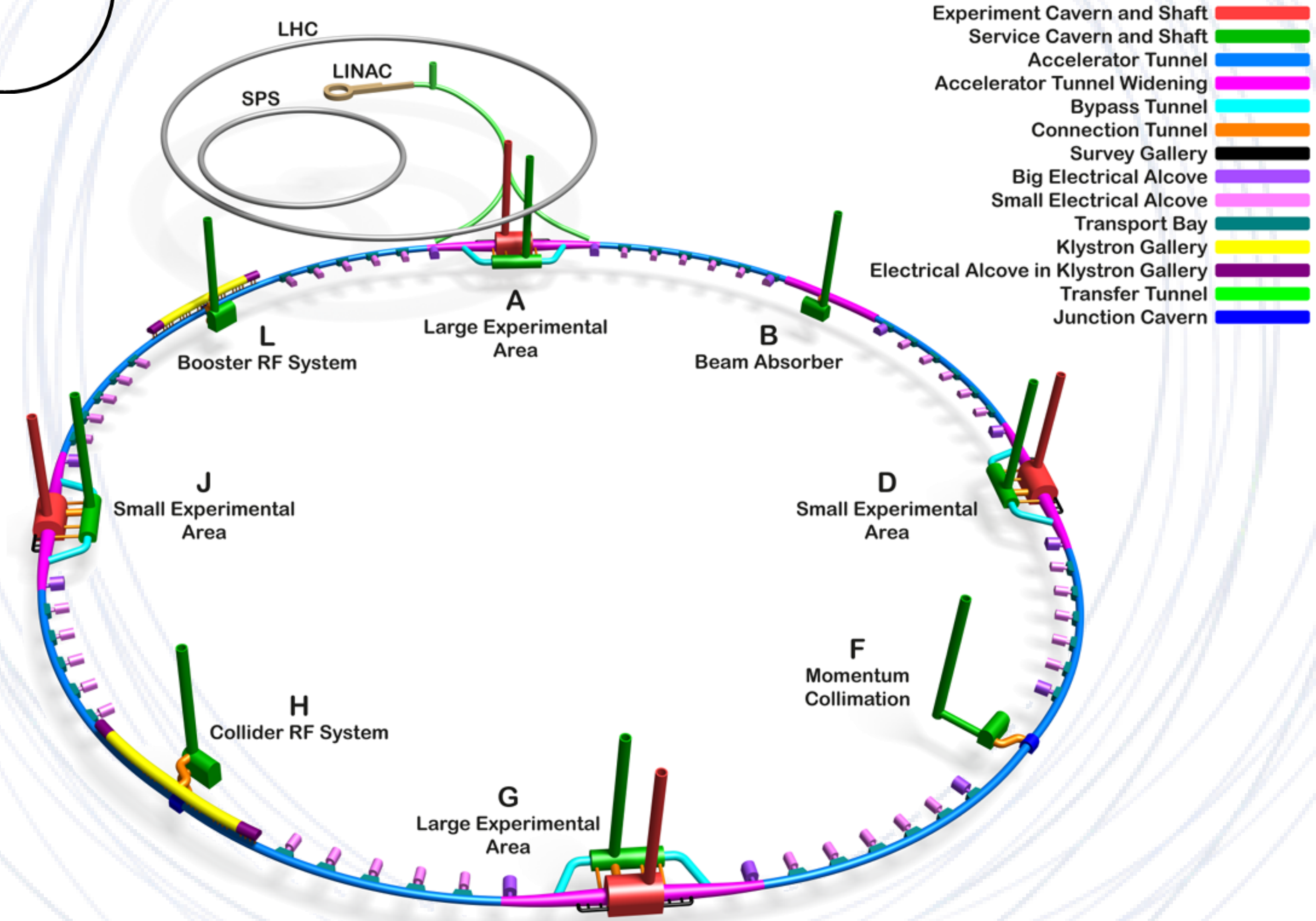


Linear Accelerator (LINAC)



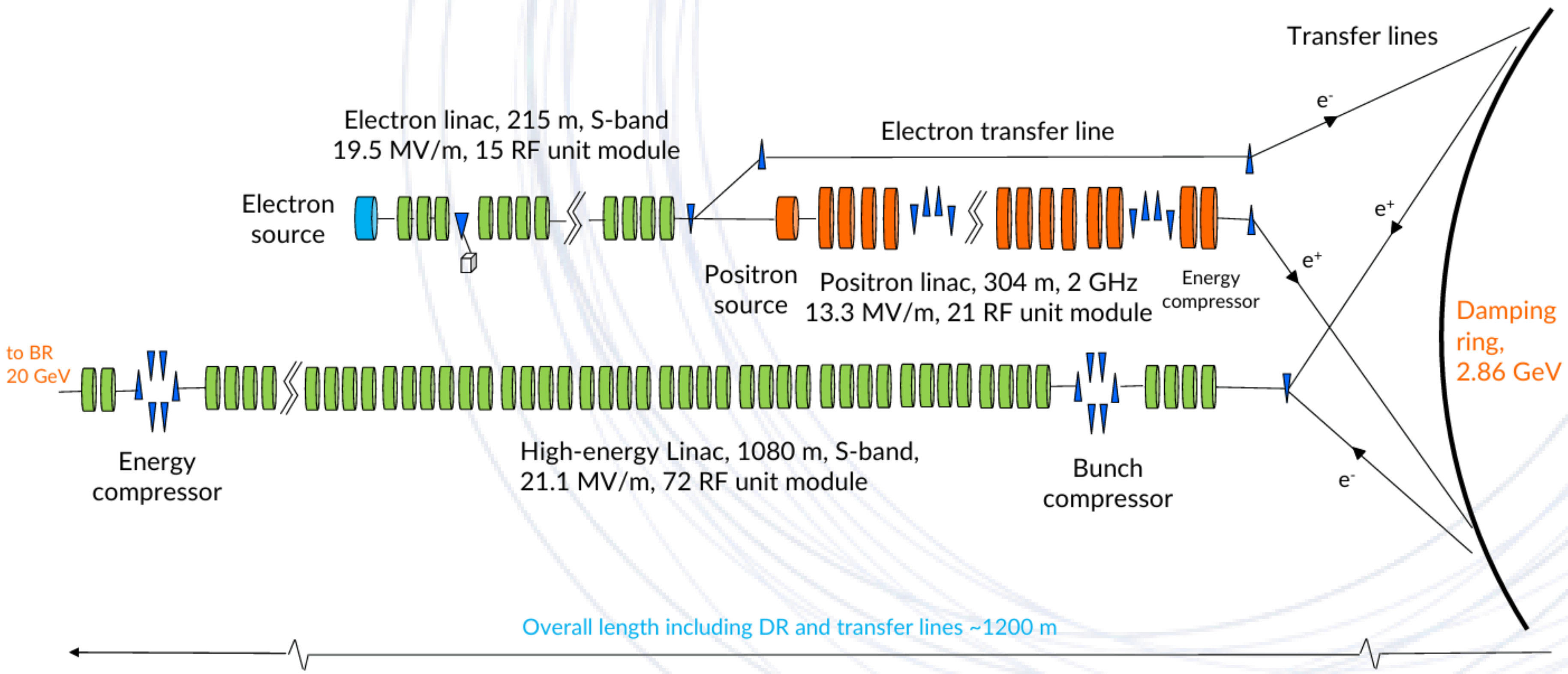
Shared Tunnel Booster and Collider Rings





[Not to scale]

- The FCC-ee injector complex must provide the electron and positron bunch trains for injection during, both, top-up and filling-from-scratch operations.
- It includes **separate linacs** for electrons and positrons up to a beam energy of **2.86 GeV**.
- Following the positron and electron linacs, both species are injected into the **damping ring (DR)** for emittance reduction.
- The layout also includes the **high-energy (HE)** linac, which boosts the beam energy from **2.86 GeV** up to **20GeV** in order to inject beams directly into the booster ring (BR).



- The electron source is composed of a photo-cathode 2.6 cell RF photo gun followed by three RF accelerating structures reaching the beam energy of approximately **200MeV**.
- The main requirement for the electron source is to generate four bunches with a charge of **5 nC** each, keeping the normalised emittance below **4 mm·mrad**.
- using up to 4 lasers would allow more flexibility to change the charge independently of a few hundred pC up to 5nC.

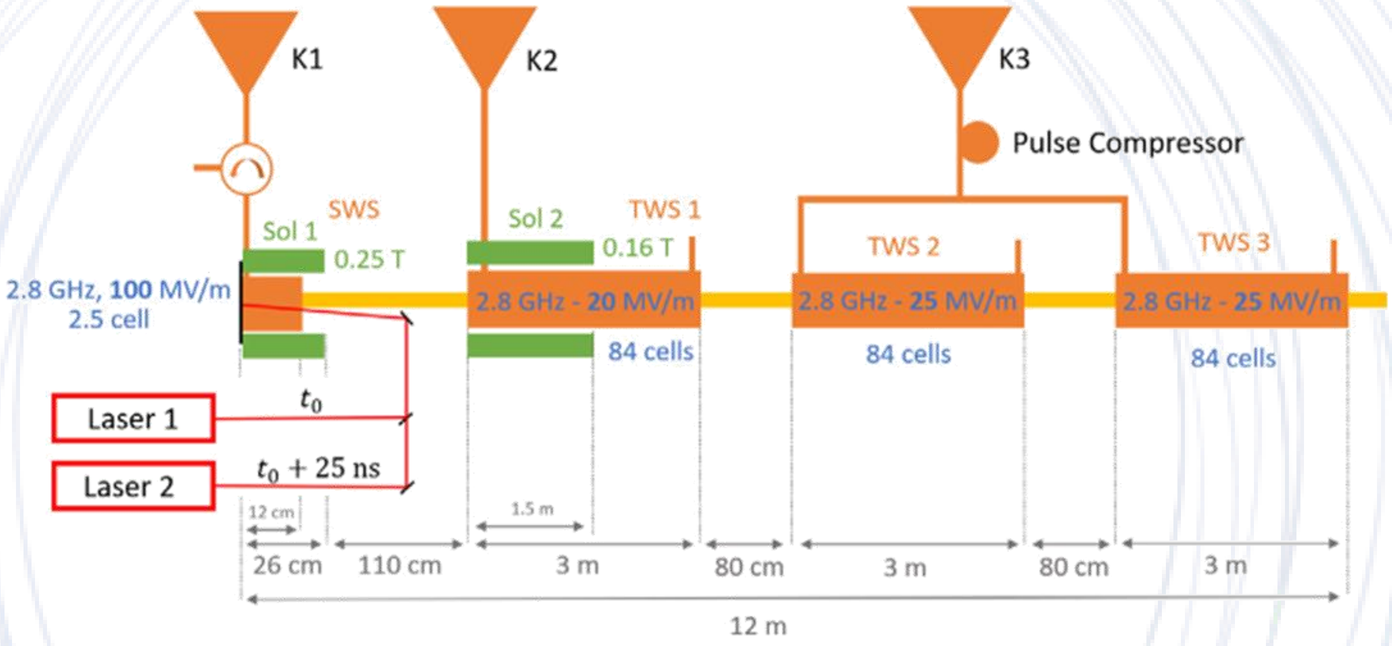
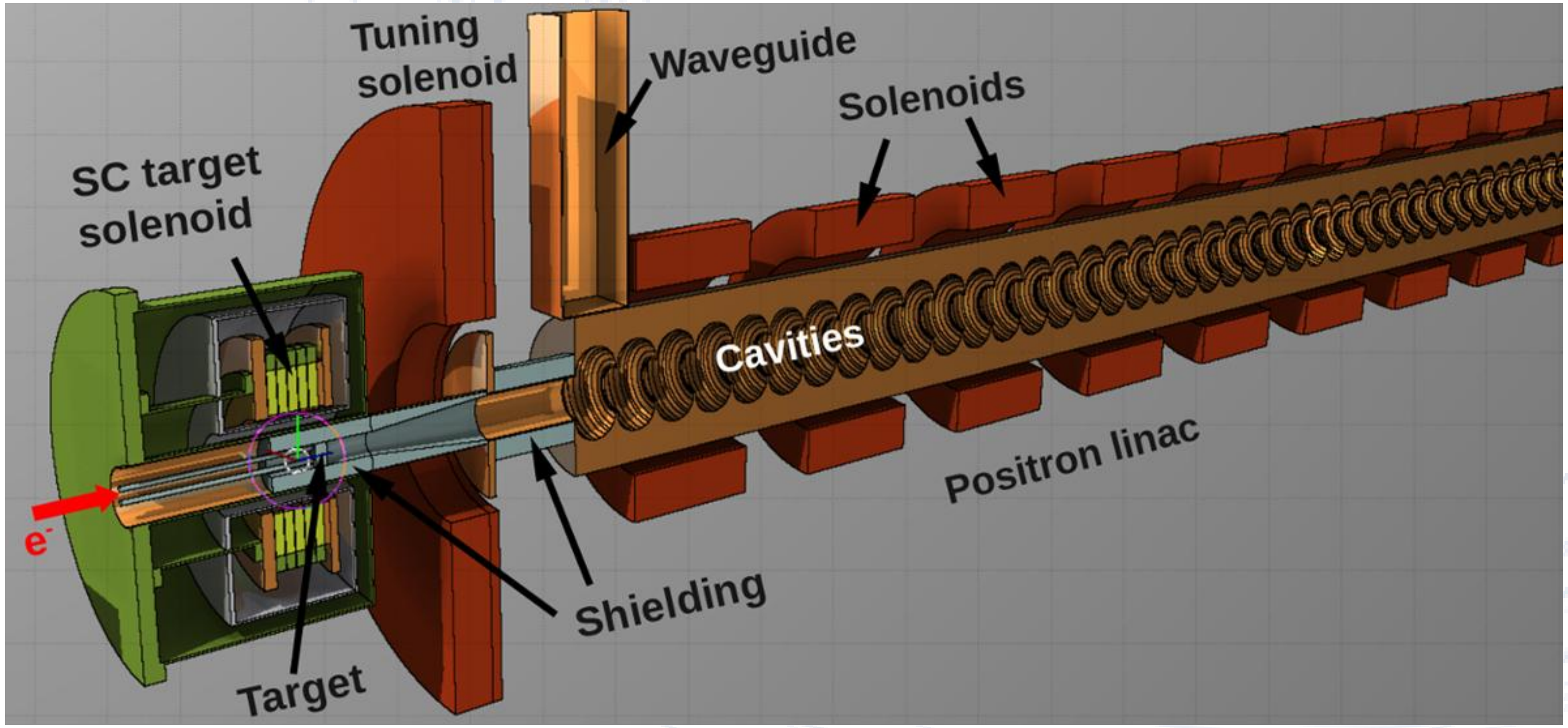


Table 7.3: Electron source beam parameters at 200 MeV with a bunch charge of 5 nC.

Parameter	Uniform Distribution	Gaussian Distribution
Transverse Emittance [mm·mrad]	2	3
Energy Spread rms [%]	0.4	0.25
Bunch Length rms (mm)	0.98	1.3

- At the injector level, the primary requirement for the positron source is to deliver a positron bunch charge of 5nC, which must be accepted into the damping ring (DR).
- Based on the available experience of designing and operating previous or current positron sources, a **safety margin of 2.56** has been applied to the FCC-ee positron source design, requiring the delivery of a total positron bunch intensity of 12.8 nC at the injection into the DR.
- A conventional positron source using **2.86 GeV electrons** impinging on a **15mm thick tungsten target** is the basis for FCC-ee positron production. The **bremsstrahlung radiation** of the electrons in the field of the target nuclei is converted in e^+e^- pairs.



- The DR lattice features a **six-fold symmetry**.
- Each straight session is used to host three **wiggler magnet insertions**, one **RF cavity** module, and two independent **injection/extraction** sections.
- The injection will be performed using an **on-axis scheme**.
- Arc cells are based on an **achromatic multi-bend** optics, symmetric with respect to the cell center. Each half cell provides 30° deflection angle, using **15 bends** of five different types.
- A further reduction of the damping time is obtained using three **3.5m long wiggler** magnets, each with a moderate magnetic field intensity of **1.8T**.
- Straight sections are based on the FODO structure and modified according to their function.

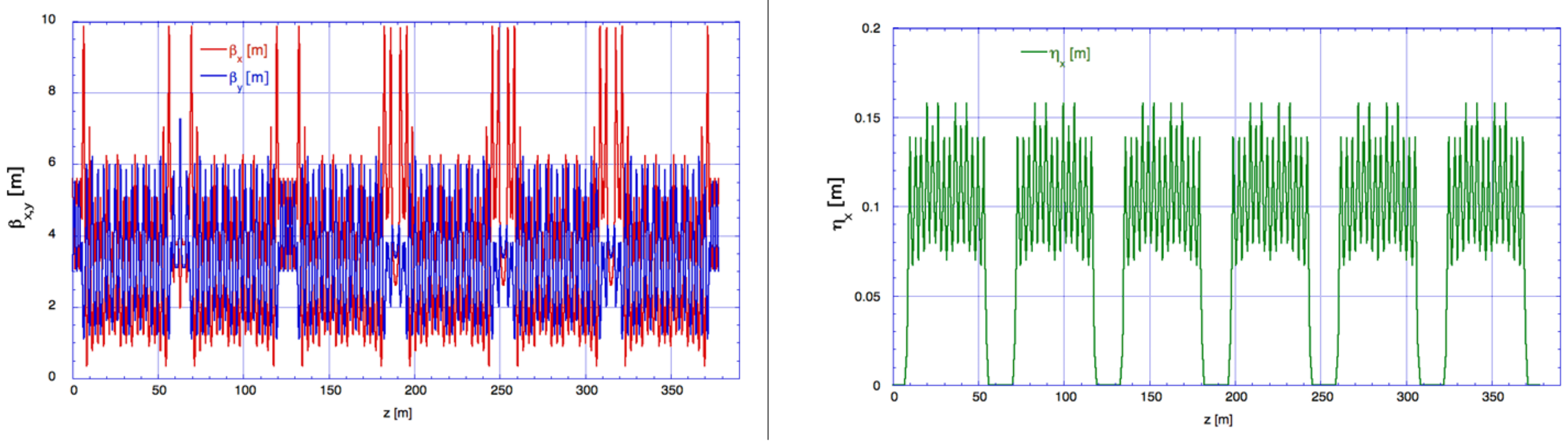
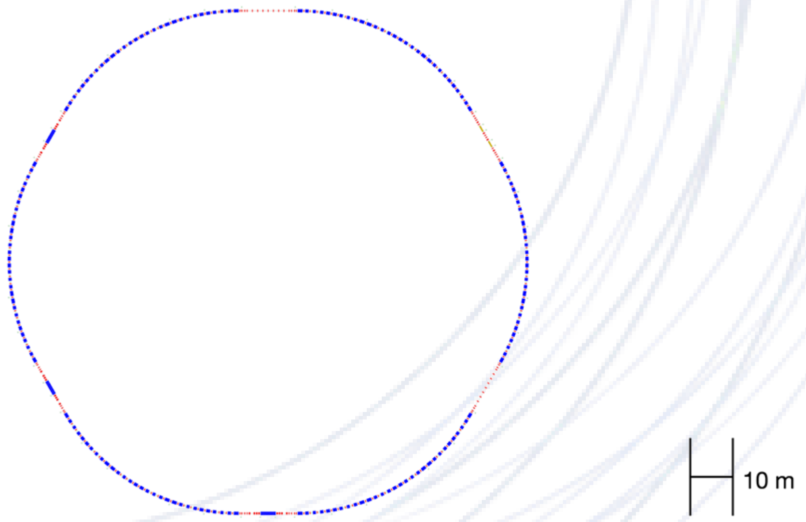


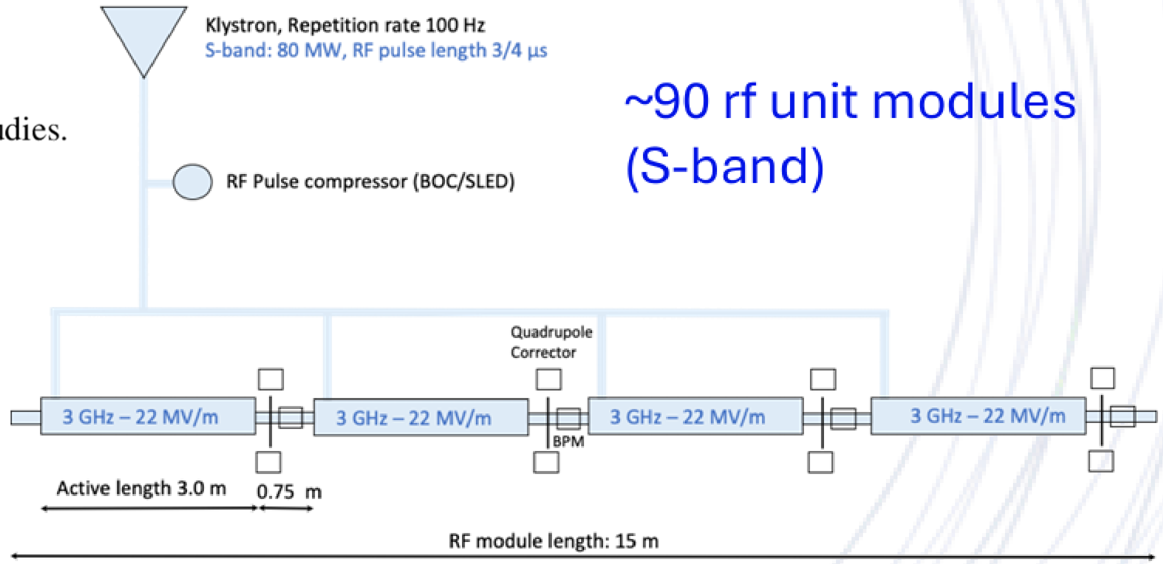
Fig. 7.20: Damping Ring optics: betatron amplitude (left) and dispersion (right).



The high energy (HE) linac accelerates electron and positron beams from the exit of the chicane down stream of the DR at **2.86 GeV** energy up to the transfer line towards the **booster ring injection at 20 GeV energy**.

Table 7.9: Summary of the optimised RF and lattice parameters based on the beam dynamics studies.

Parameter	Value
Mean RF structure aperture (mm)	13.9 ($a/\lambda = 0.12$)
RF structure length (m)	3
RF structure operating phase	on-crest
Phase advance/cell (degrees)	90
Number of BPM/RF structure	1
Number of quadrupoles/RF structure	1
Distance between the quadrupoles (m)	3.75



~90 rf unit modules (S-band)

Transfer Lines from HE-Linac to Booster

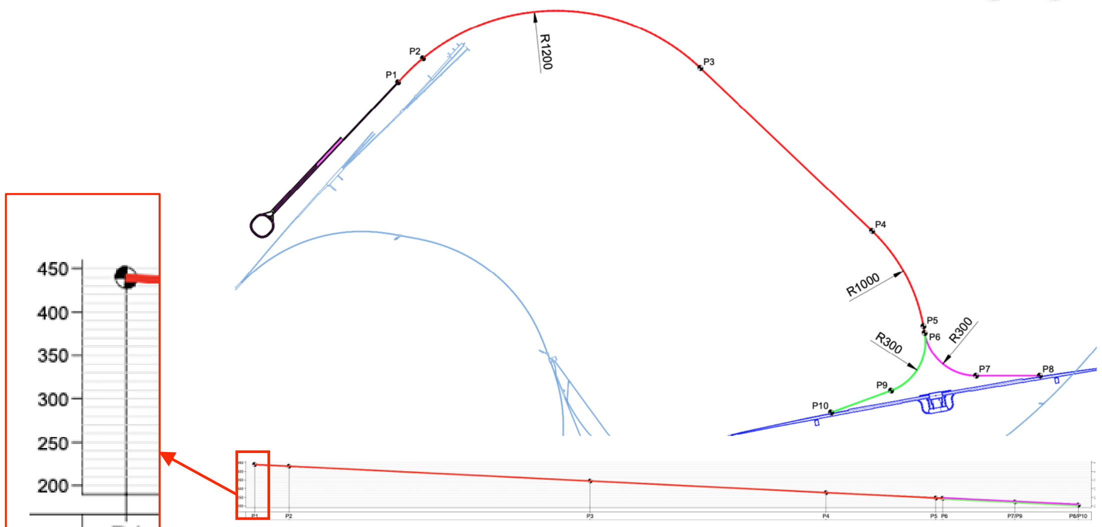


Fig. 7.24: Lepton transfer lines from the injector complex on the surface to the collider tunnel.

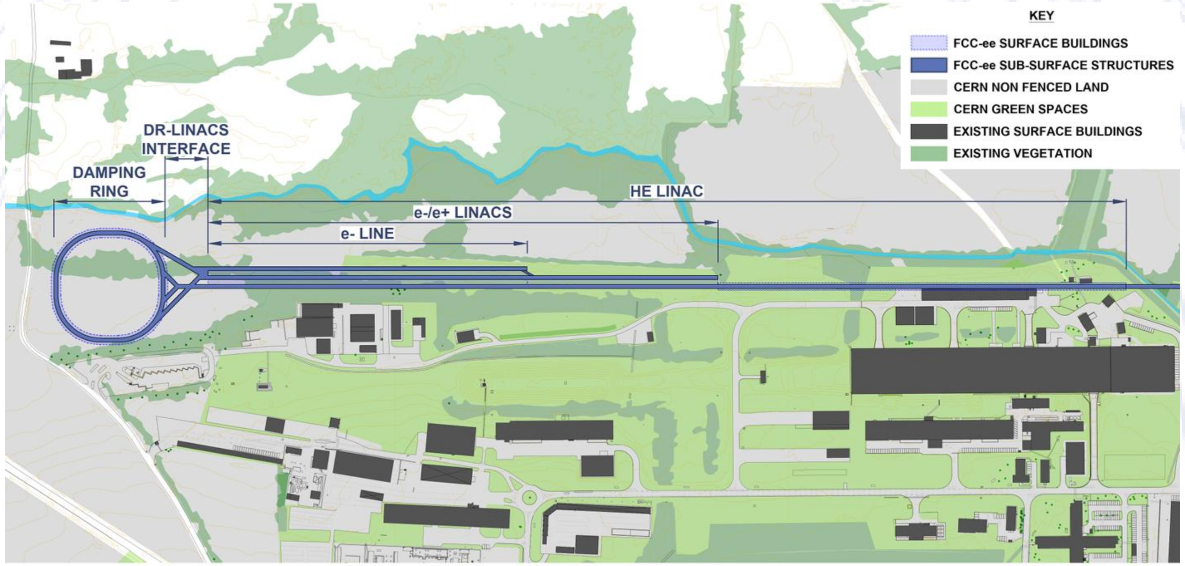
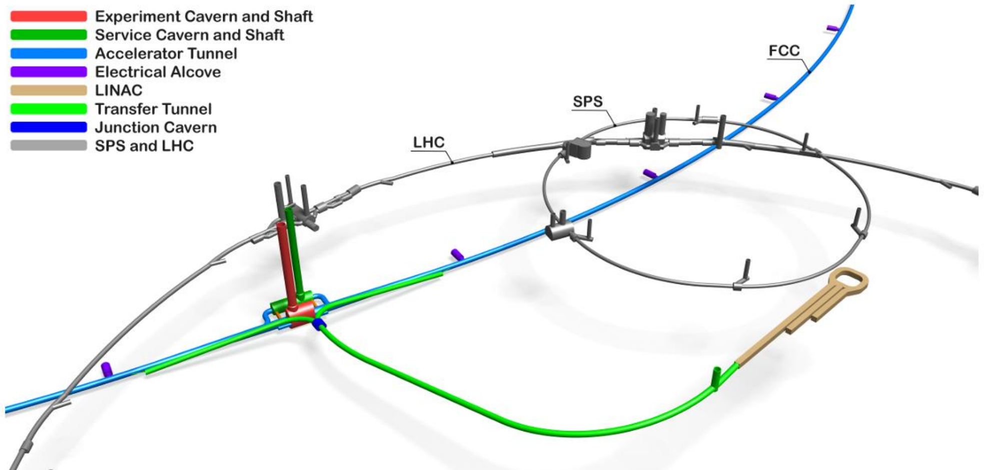
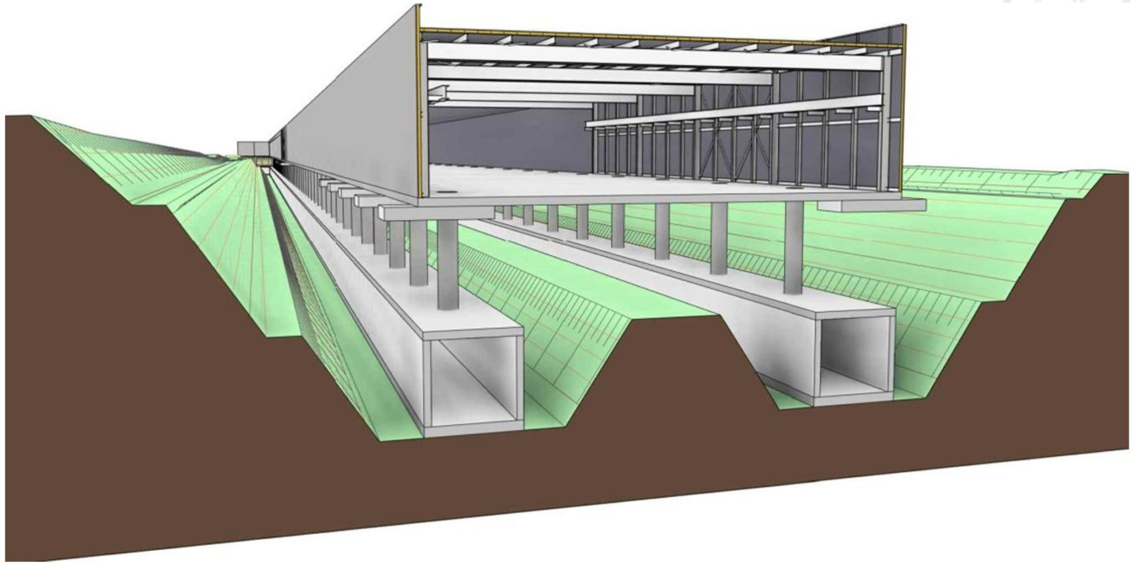


Fig. 7.35: Plan view of high energy linac civil engineering.



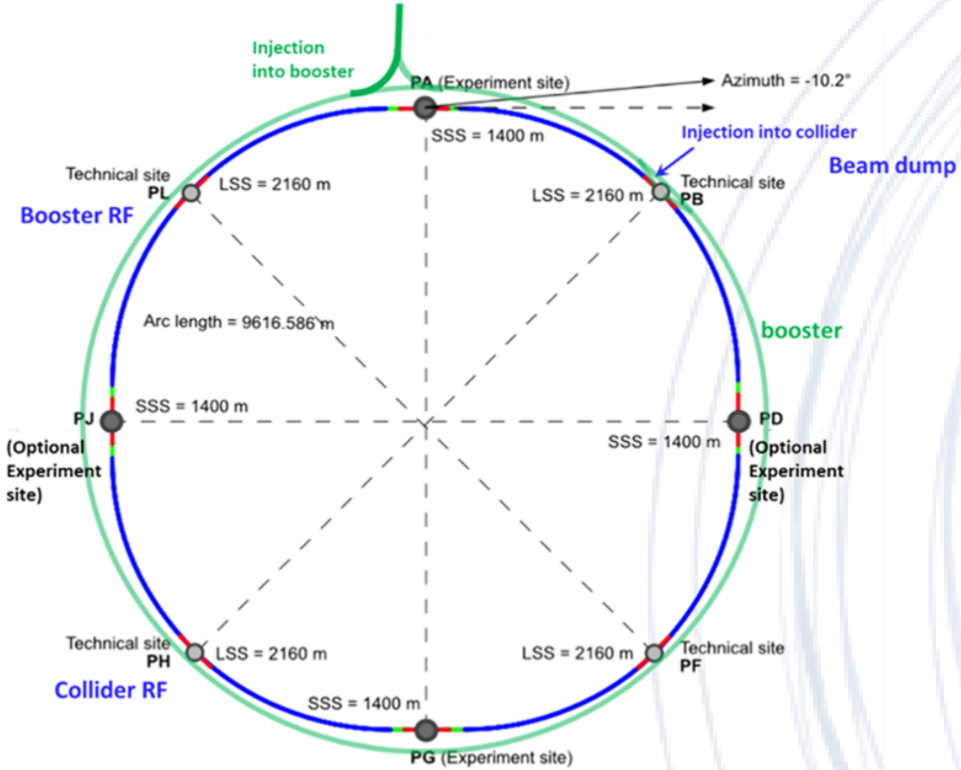
The tunnel will have a slope of 4.9%

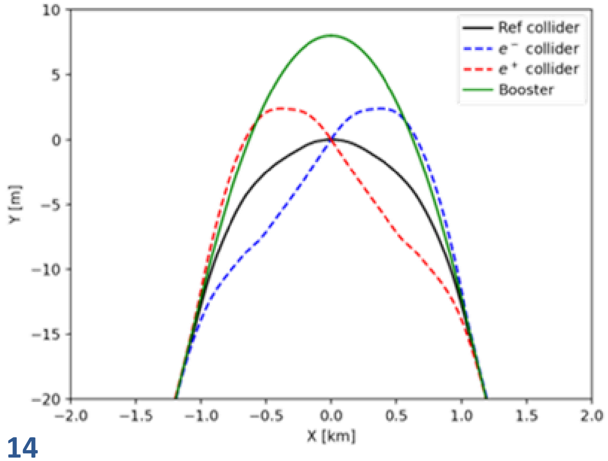
[Not to scale]



IPM
پژوهشگاه دانش‌های بنیادی

FCC-ee Booster





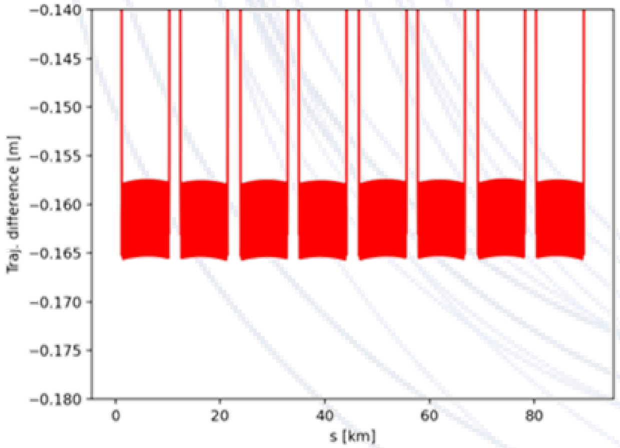
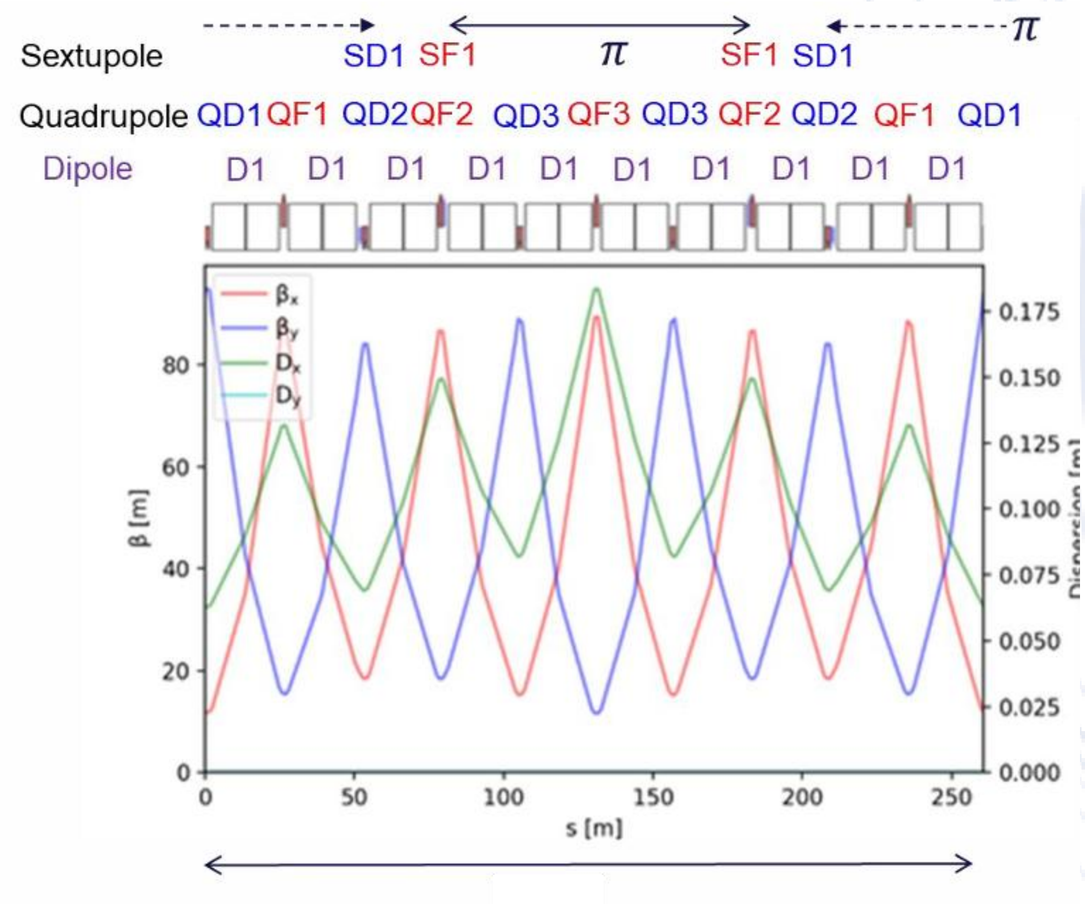


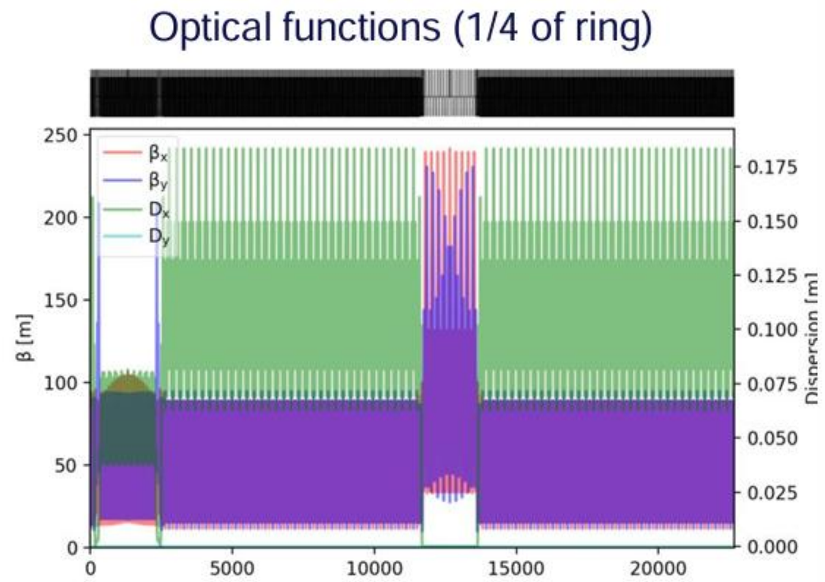
Table 4.1: Preliminary key parameters of the high-energy booster of FCC-ee. We consider here a linac of 20 GeV as a pre-injector and a high-energy damping ring.

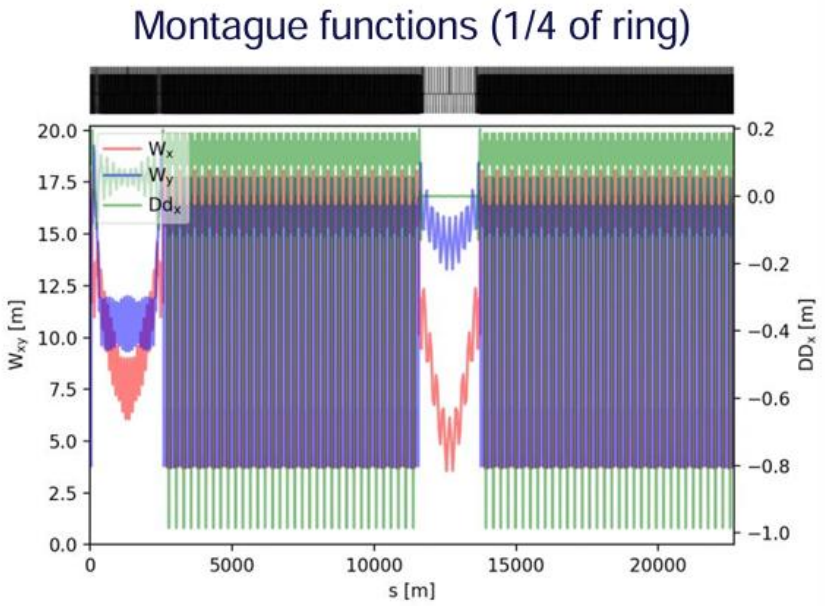
Running mode		Z	WW	ZH	$t\bar{t}$
Circumference	[km]	90.65871376			
Injection energy	[GeV]	20			
Extraction energy	[GeV]	45.6	80	120	182.5
Number booster ramps per cycle		10	2	1	1
Number of stored bunches		1120	928	300	64
Particle number/bunch (filling)†	$[10^{10}]$	2.725	1.268	1.268	1.268
Particle number/bunch (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
Filling time	[s]	2.8	2.315	3	0.64
Up-Ramp time	[s]	0.706	0.857	1.429	2.321
Flat top	[s]	0.1	0.1	0.1	0.1
Down-Ramp time	[s]	0.334	0.689	1.148	1.866
Total cycling time	[s]	39.4	7.922	5.68	4.927

Baseline Optics : FODO



- Made of 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 at QF
  - Vertical at QD
- Cell length adjusted to follow the collider arc periodicity





- 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 between 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.
- **Tune Q_x/Q_y : 414.225/410.290**
- **Momentum compaction: 7.12e-6**

- In the **vertical** plane, a closed orbit **bump of 10mm** at the septum is foreseen to bring the circulating trajectory closer to the injected one in order to reduce the required kicker strength.

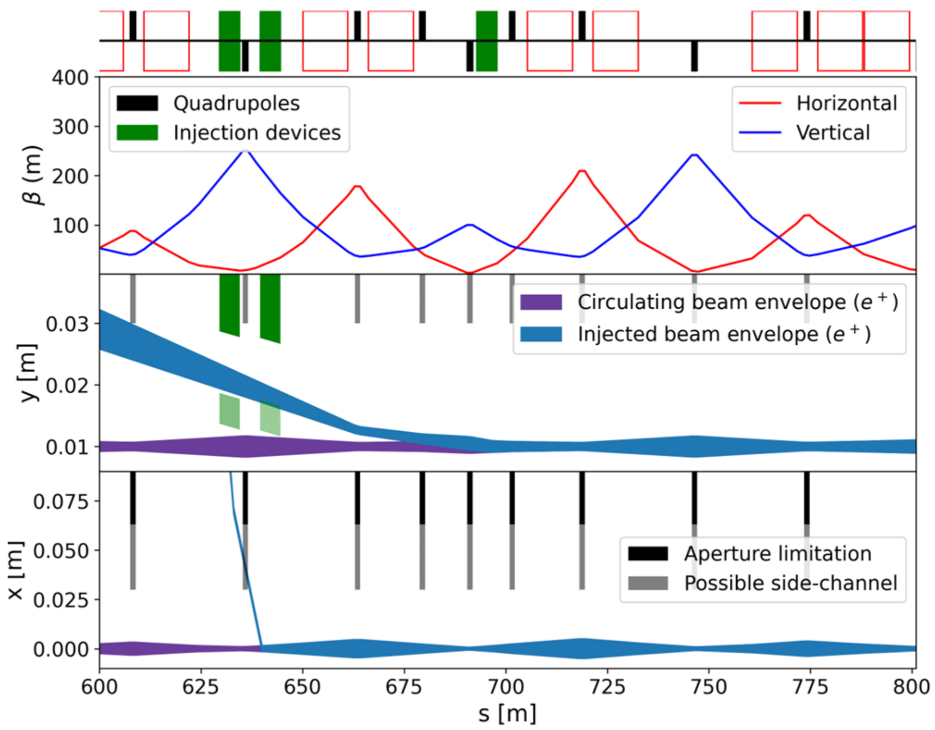


Table 4.2: Summary of the booster injection scheme hardware requirements

	Kicker	Septum
Beam energy (GeV)	20	
Deflection angle per system (mrad)	0.09	4.5
Maximum repetition frequency (Hz)	100	DC
Rise/Fall time (ns)	25[†]	–
flattop time (ns)	80	–
Blade thickness (mm)	–	7
Aperture (H×V mm)	–	5×10
Longitudinal available space (m)	5.5	20

The circulating beam is moved closer to the extraction septum using a closed-orbit bump of 10mm in **horizontal** plane.

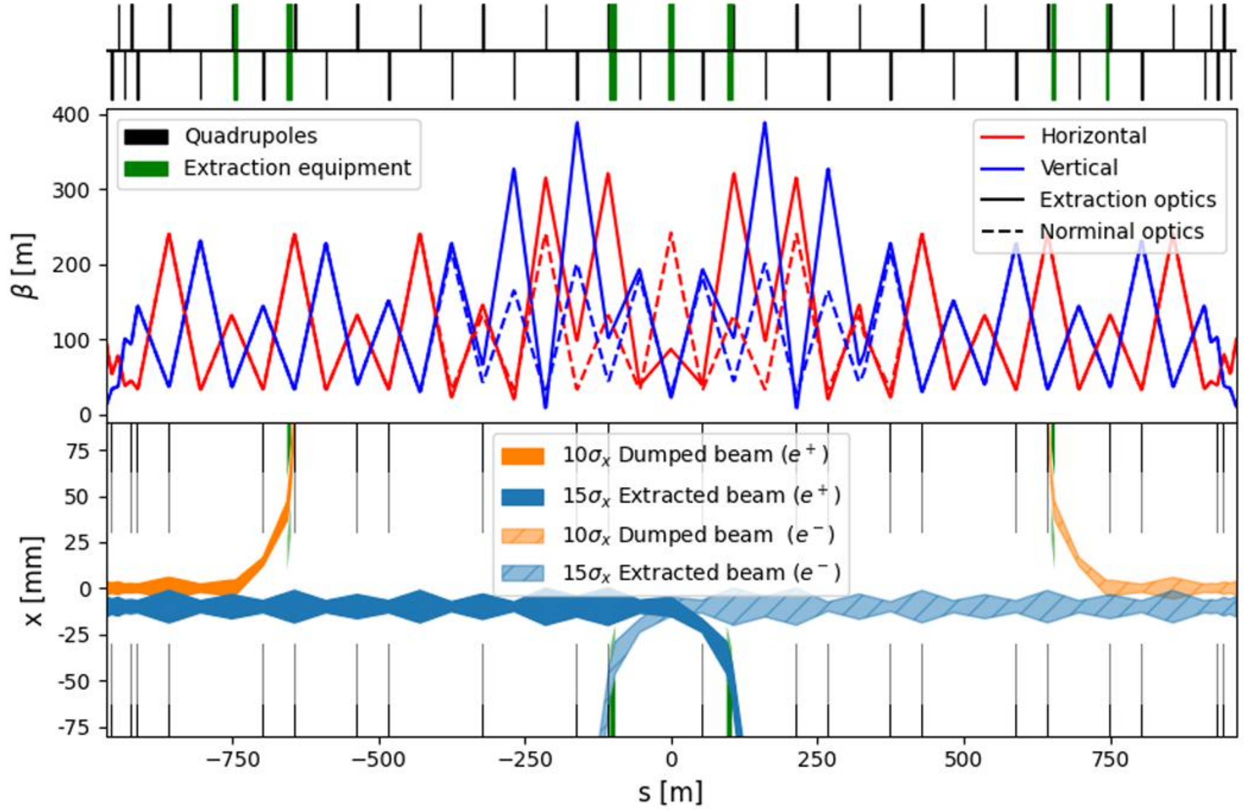


Table 4.3: Summary of the booster extraction scheme hardware requirements

	Kicker	Septum
Beam energy (GeV)	45.6 – 182.5	
Deflection angle per system (mrad)	0.2	2
Maximum repetition frequency (Hz)	0.3	0.3
Rise/fall time (μs)	1.1	N/A
flattop time (μs)	304	N/A
Blade thickness (mm)	N/A	8
Aperture (H×V mm)	N/A	18×10
Longitudinal available space (m)	15	15

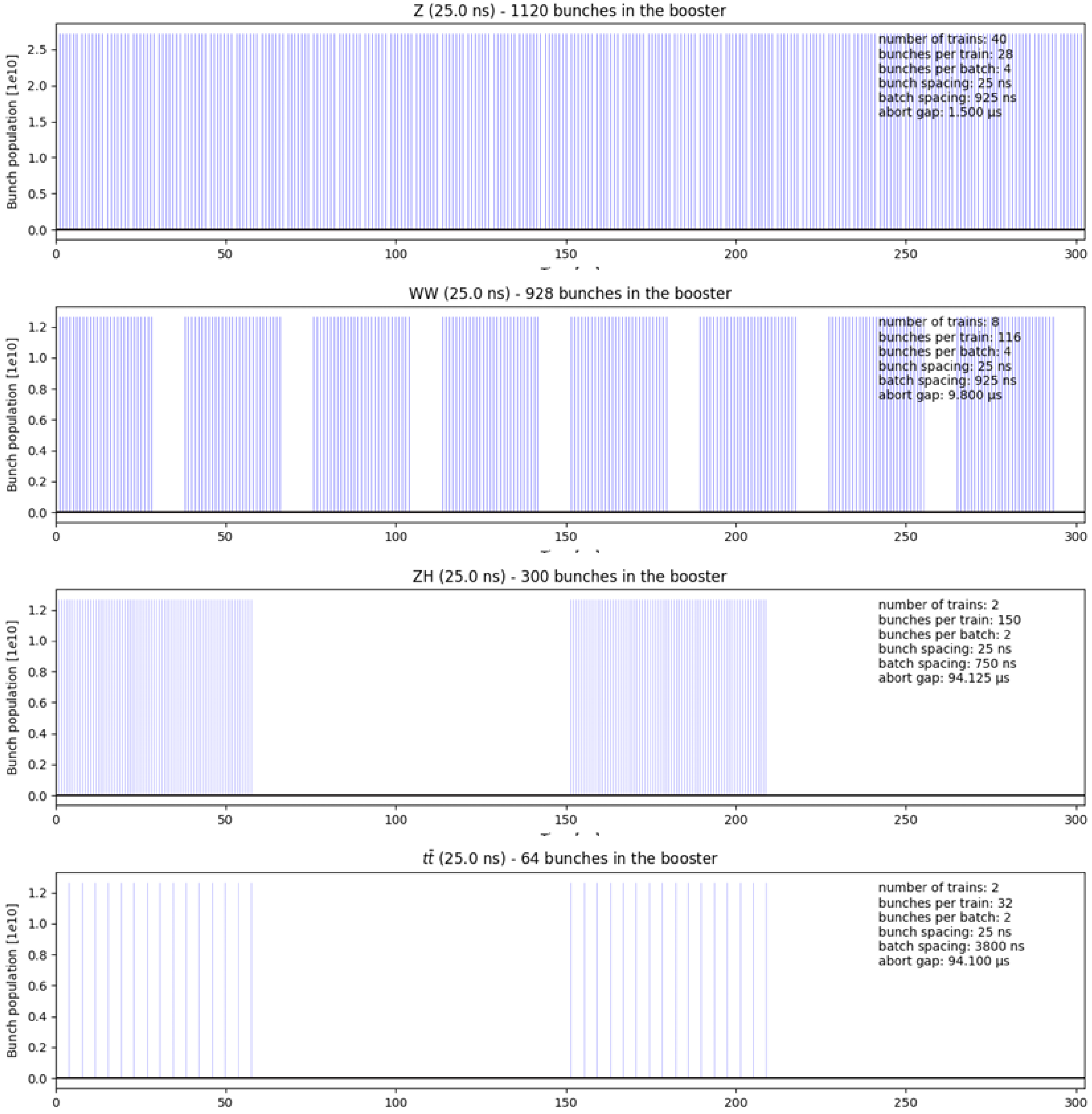
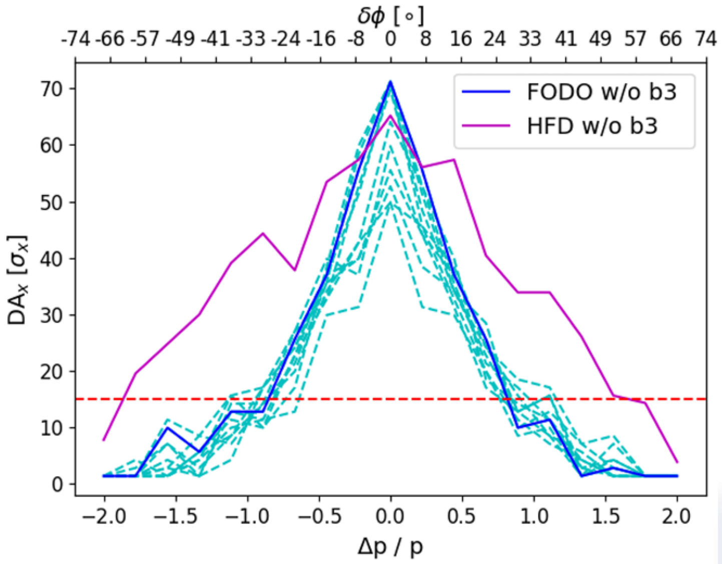
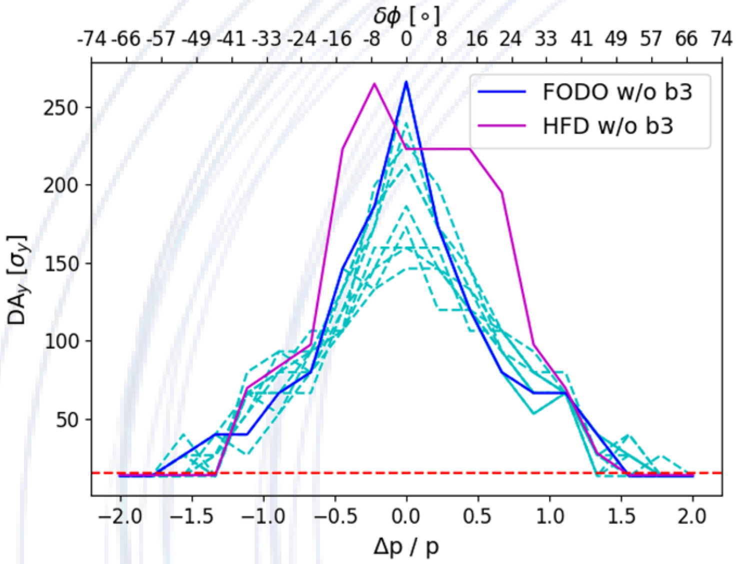
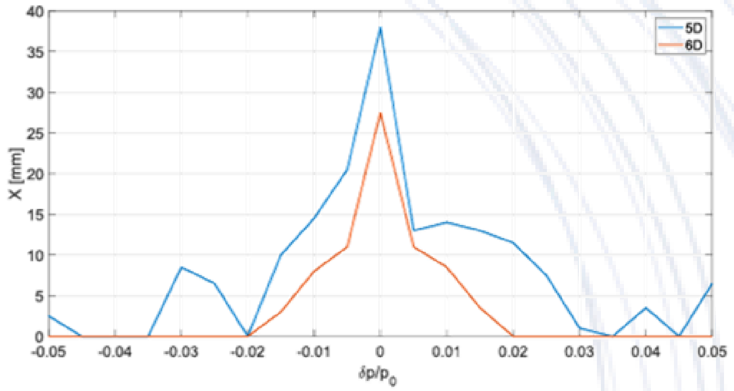


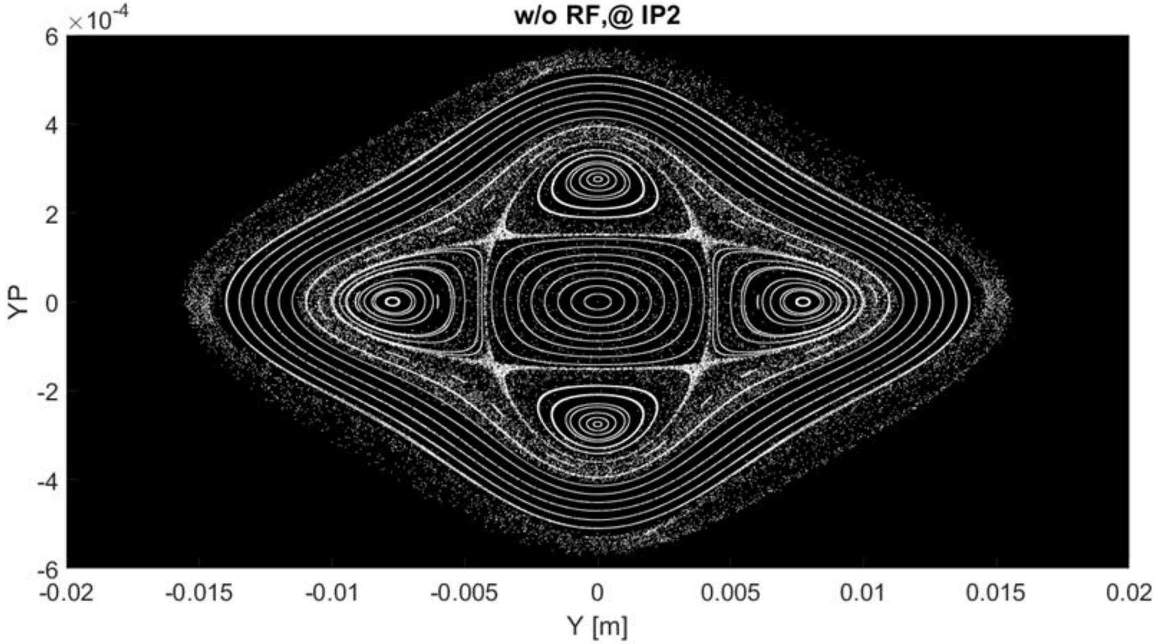
Table 5.1: Filling parameters

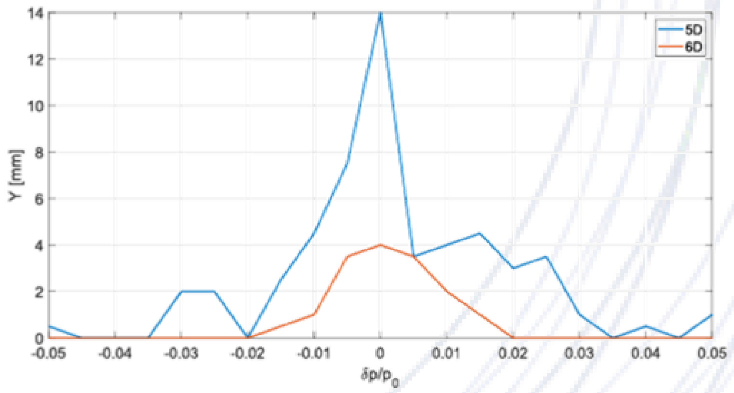
		Z	WW	ZH	$t\bar{t}$
Linac repetition rate	[Hz]	100	100	50	50
Bunches per Linac pulse		4	4	2	2
Linac bunch spacing	[ns]	25	25	25	25
Booster accumulation time	[s]	2.8	2.32	3.0	0.64
Booster total ramping time	[s]	1.0	1.6	2.6	4.3
Booster cycle length	[s]	3.8	3.92	5.6	4.94
Bunches per booster cycle		1120	928	300	64
Number of bunches in collider		11 200	1856	300	64
Max. bunch intensity injected in collider	10^{10}	2.725	1.268	1.268	1.268
Nominal bunch intensity in collider	10^{10}	21.5	13.8	16.9	14.8
Allowable charge imbalance	[%]	5	3	3	3
Beam lifetime: lumi 4 IPs, (q,BS,lattice)/4	[s]	916	517	428	497


δϕ [∘]
FODO w/o b3
HFD w/o b3
DA_x [σ_x]
Δp / p

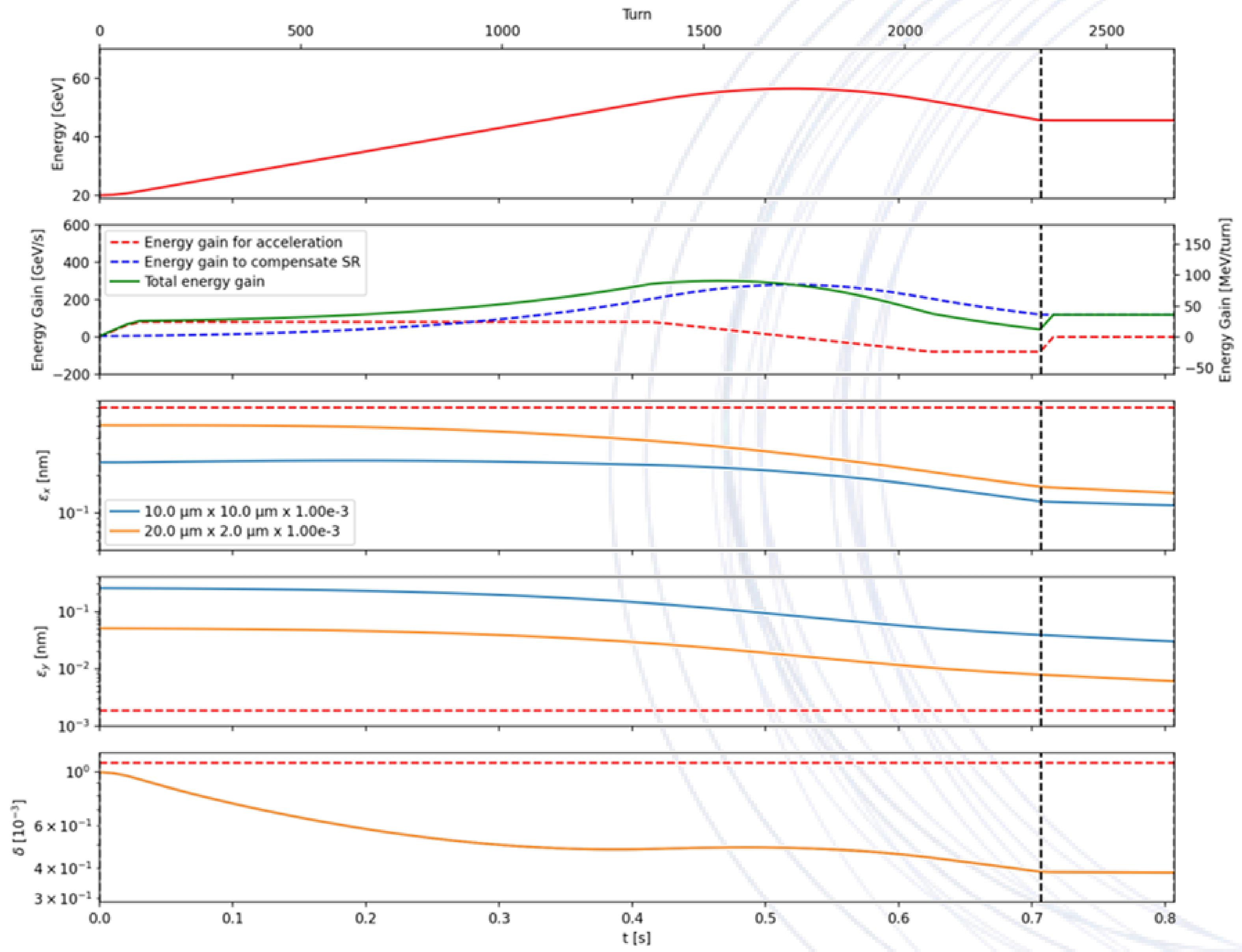

δϕ [∘]
FODO w/o b3
HFD w/o b3
DA_y [σ_y]
Δp / p


5D
6D
X [mm]
$\delta p/p_0$


w/o RF,@ IP2
×10^-4
YP
Y [m]

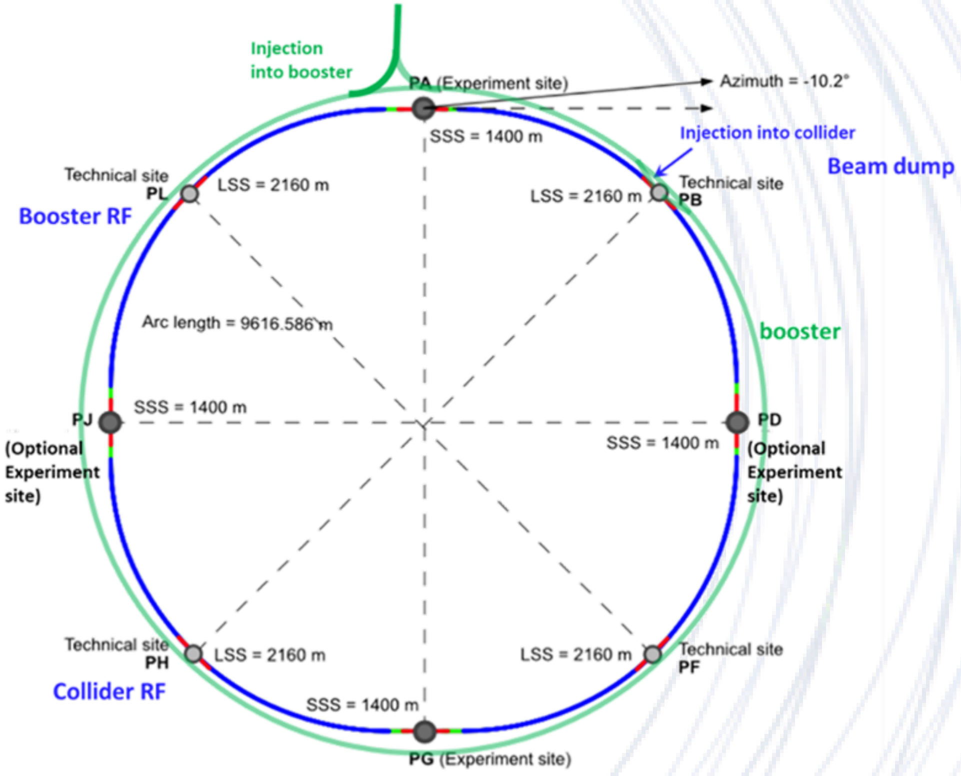

5D
6D
Y [mm]
$\delta p/p_0$

Booster Energy Ramp



- The start of the ramp shall be adiabatic to avoid shaking the bunches.
- The energy gain per turn is limited by **Eddy currents** in the magnets.
- A conservative maximum ramp rate of **80 GeV/s** is considered.
- When approaching high energies, the energy gain is dominated by the energy provided to compensate for losses due to synchrotron radiation.

parameter	Z	WW	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	145	20	7.5	1.4
total integrated luminosity / IP / year [ab^{-1} / yr]	17	2.4	0.9	0.17
beam lifetime [min]	21	13	9	10



- The luminosity at one IP may be expressed as

$$\mathcal{L} = \frac{\gamma}{2er_e}\frac{I_{tot}\xi_y}{\beta_y^*} R_G$$

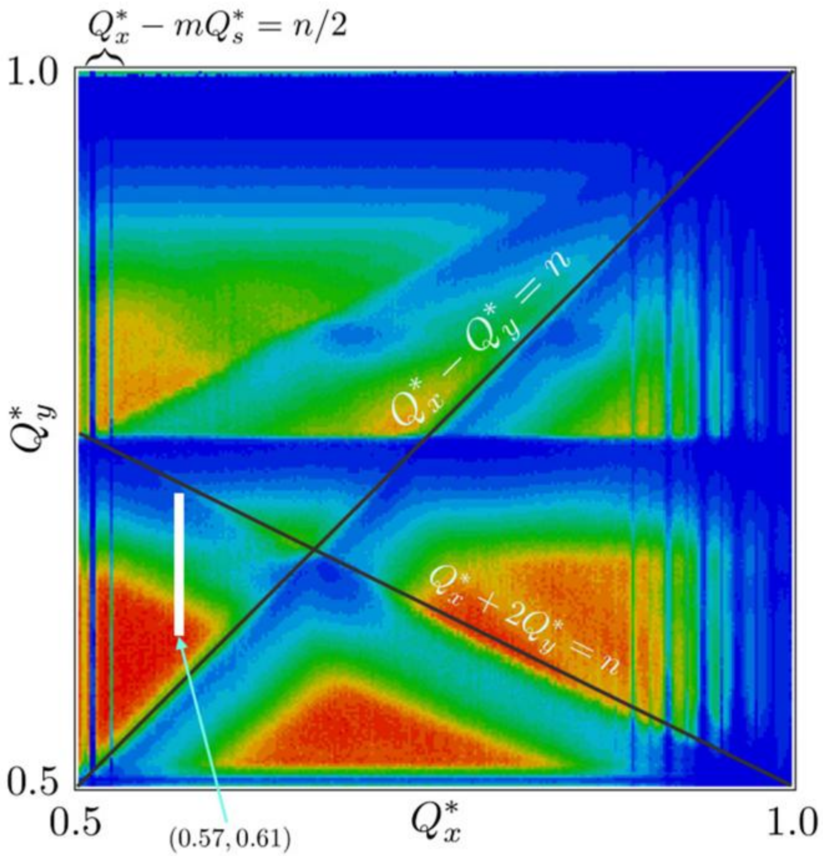
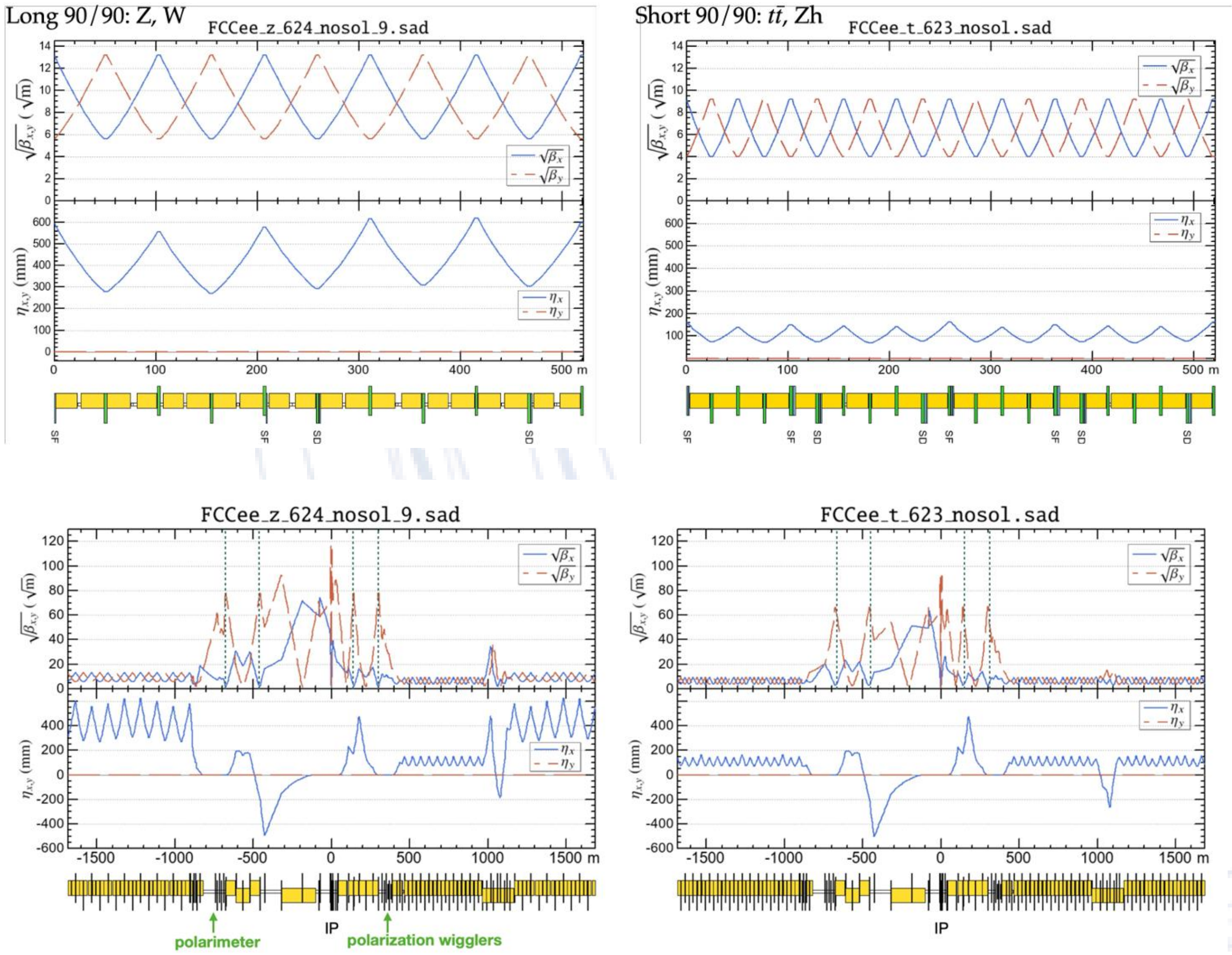


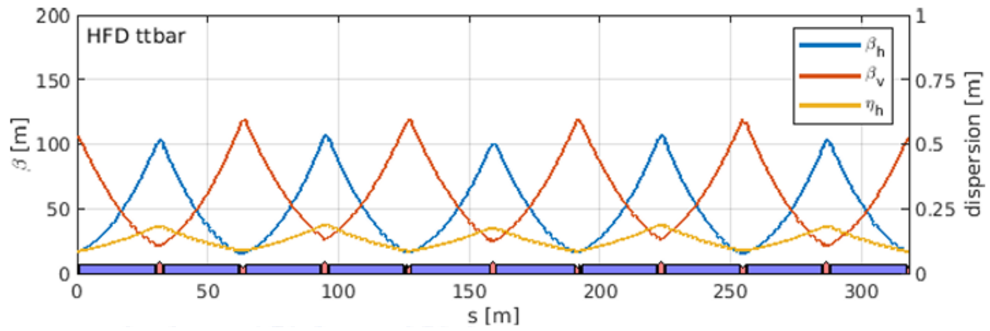
Fig. 1.1: Luminosity at the Z energy as a function of betatron tunes for the CDR configuration [13], represented by a single arc and a single IP. The colour scale extends from zero (blue) to $2.3{\cdot}10^{36}$ $cm^{-2}s^{-1}$ (red) [14]. The white narrow rectangle above (0.57, 0.61) indicates the footprint due to the beam-beam interaction

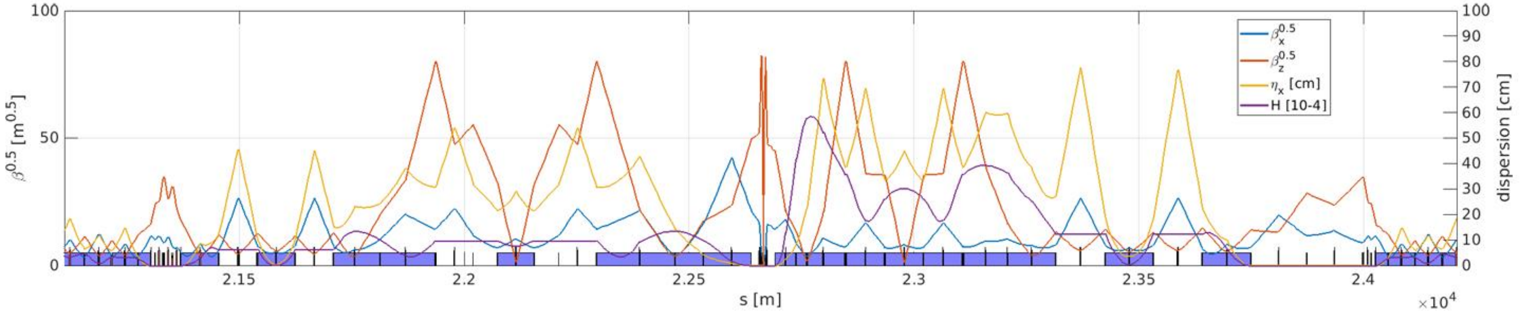
Global Hybrid Correction (GHC)

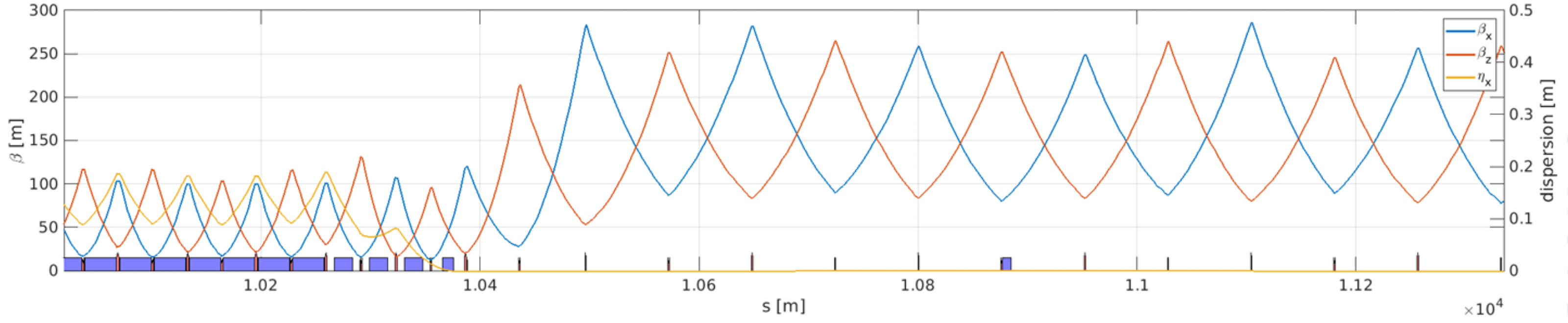
The baseline optics is called the Global Hybrid Correction (GHC) scheme, since the **vertical chromaticity** for the low beta insertion is **corrected locally**, with two sextupole magnets in the final focus, while the **horizontal chromaticity** is **corrected globally** using the arc sextupoles.



- The structure of the accelerator is the same as the baseline optics, including four final focus systems (FF) and four long straight sections (LSS) separated by eight arcs.
- The LCC optics are designed to obtain anharmonic and achromatic beam dynamics for each of these components independently.





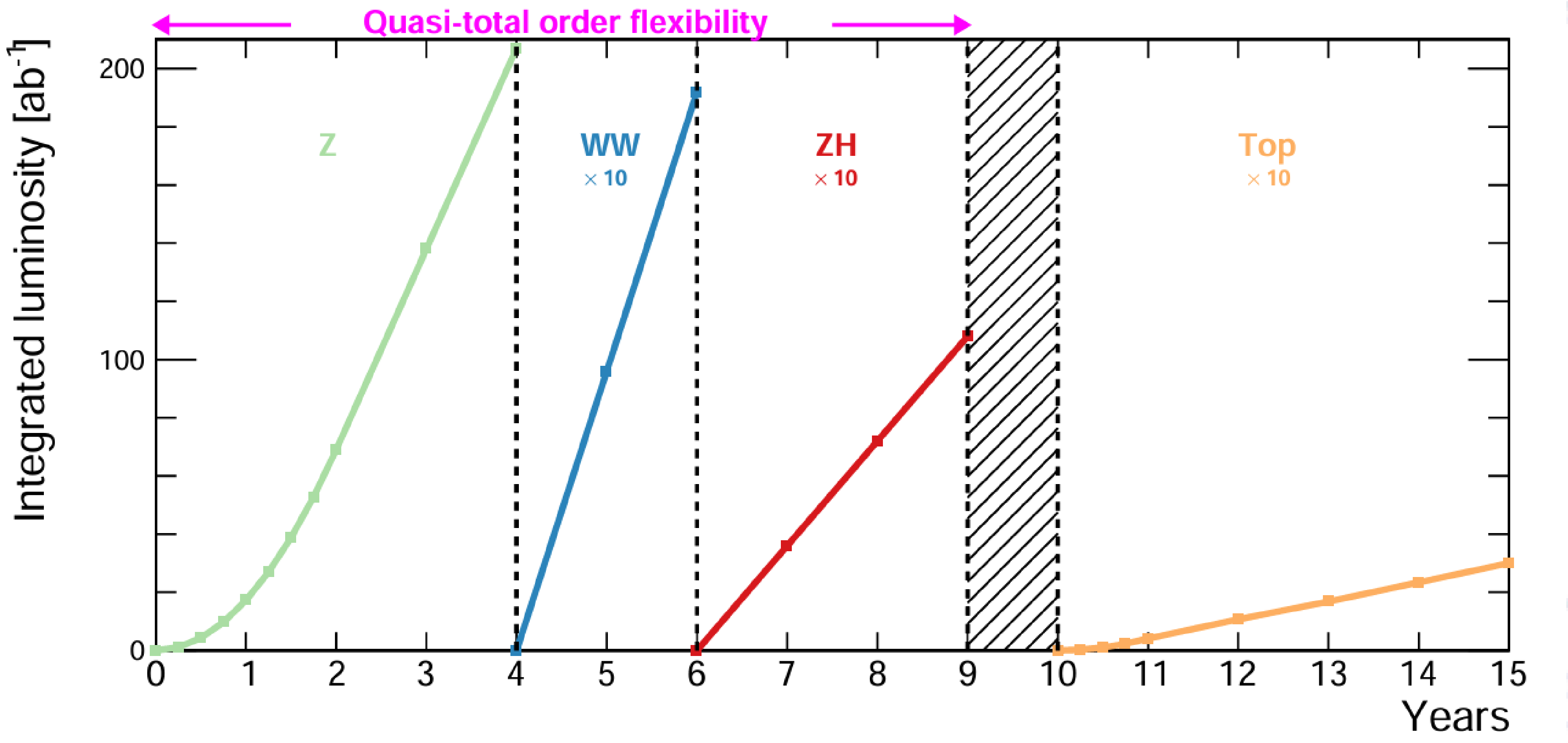


Annual integrated luminosity estimates for FCC-ee at each mode of operation are derived from three or four parameters:

- Nominal Instantaneous Luminosity $\mathcal{L}$
- Annual Scheduled Physics Time T: It is assumed that 185days per year are scheduled for physics.
- Availability A: An overall machine availability of 80% is assumed.
- Efficiency E: The target availability is at least 80% and, thereby, a corresponding efficiency E > 75% is expected.

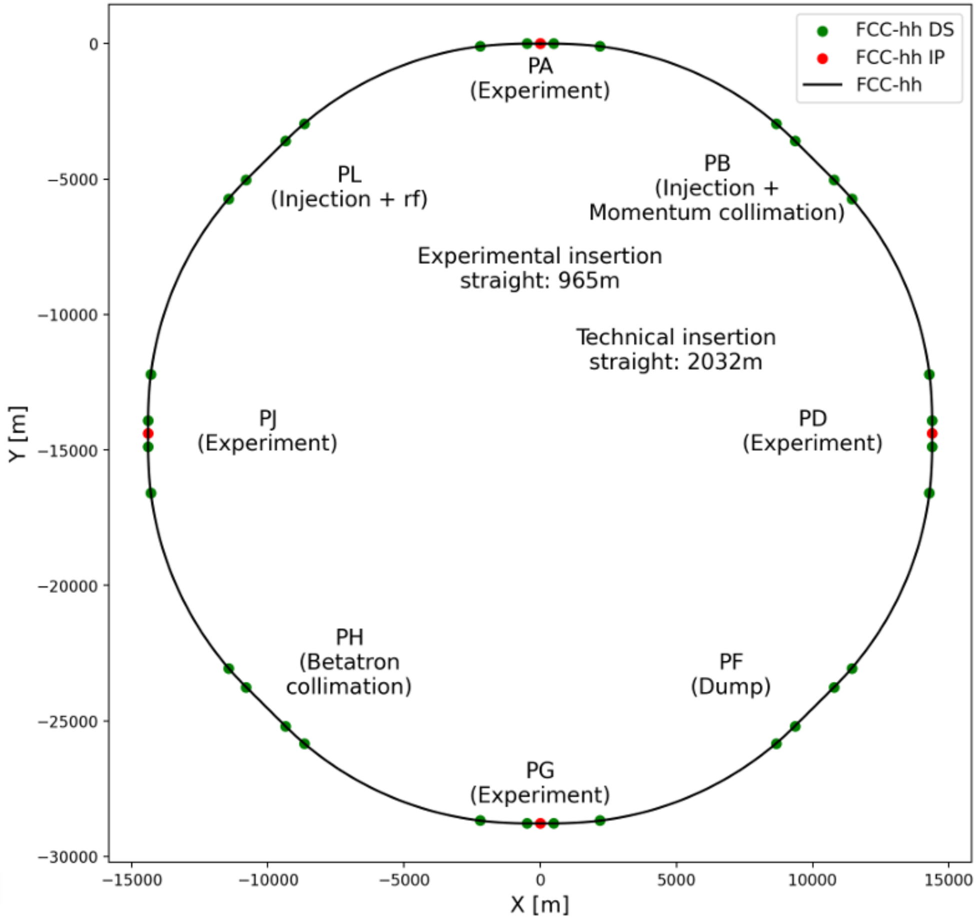
Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm^{-2}s^{-1}}$)	140	20	7.5	1.8	1.4
Lumi/year ($\mathrm{ab^{-1}}$)	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated Lumi ($\mathrm{ab^{-1}}$)	205	19.2	10.8	0.42	2.70
Number of events	$6\,10^{12}$ Z	$2.4\,10^{8}$ WW	$2.2\,10^{6}$ HZ + 65k WW $\rightarrow$ H	$2\,10^{6}$ $t\bar{t}$ +370k HZ +92k WW $\rightarrow$ H	

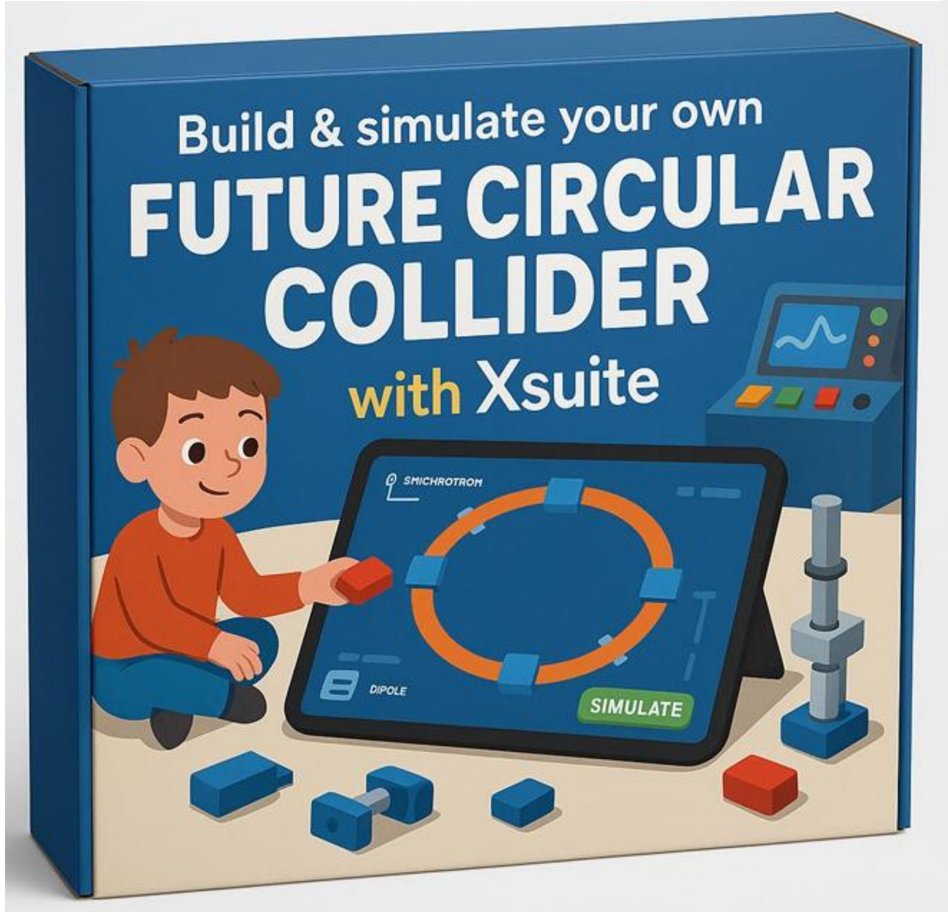
$$\mathcal{L}_{int} = \mathcal{L}\,E\,T$$

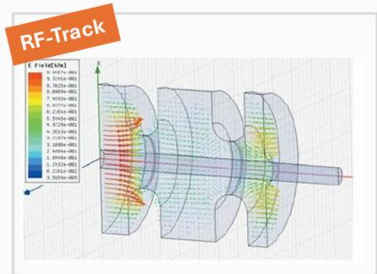

Quasi-total order flexibility
Integrated luminosity [ab^{-1}]
200
100
0
Z
WW
× 10
ZH
× 10
Top
× 10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Years

FCC-hh Parameters

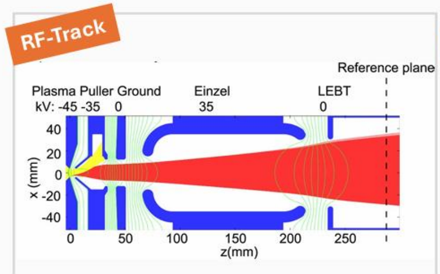
parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [10^{34} $cm^{-2}s^{-1}$]	30	30	5 (lev.)
events/bunch crossing	1000	1000	132
stored energy/beam [GJ]	6.5	8.3	0.7
integr. luminosity / IP [fb^{-1}]	20000	20000	3000



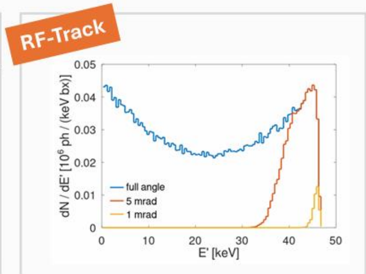




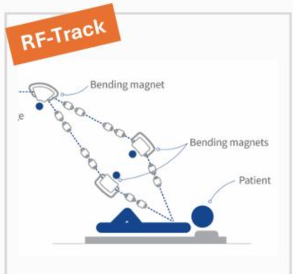
Photoinjectors and electron guns (space-charge, IBS)



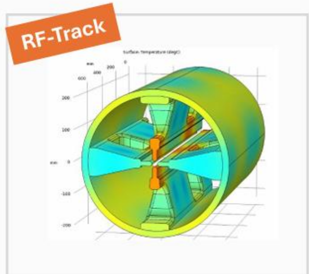
Positron, proton, and ion sources & linacs



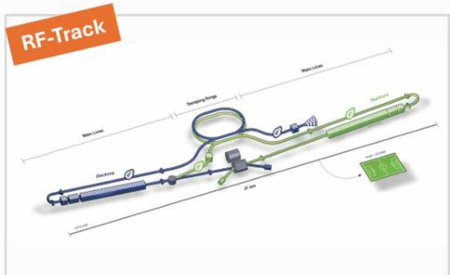
Inverse-Compton Scattering Compact X-ray sources



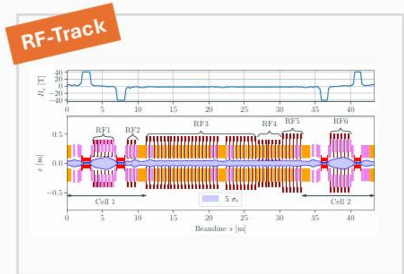
Medical e⁻ linacs for Flash therapy



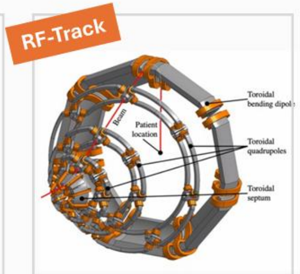
Radio-Frequency Quadrupoles (RFQ)



Linear Colliders, Free-Electron Lasers (Wakefields, beam loading, ...)



Muon Cooling (Particle-matter interaction)



GaToroid (Optics in complex fields)

Table A.1: Estimated investment costs for different construction domains in 2024 Swiss Francs.

Domain	**Cost [MCHF]**
Civil engineering	6160
Technical infrastructures	2840
Injectors and transfer lines	590
Booster and collider	4140
CERN contribution to four experiments	290
FCC-ee total	**14 020**
+ Four experiments (non-CERN part)	1300
FCC-ee total, including four experiments	**15 320**

The total average annual operating cost of FCC-ee across all stages amounts to around **600 MCHF**.

Table A.2: Estimated investment costs for different construction domains in 2024 Swiss Francs.

Domain	**Cost (MCHF)**
Civil engineering	520
Technical infrastructures	3960
Injectors and transfer lines	1000
Collider	13 400
FCC-hh total	**18 880**

Thanks for your attention!