Future Circular Colliders at CERN

Jacqueline Keintzel

Acknowledgements: The FCC collaboration

Special Thanks to:

M. Benedikt, M. Giovannozzi, C. Grojean, J. Gutleber, P. Janot, F. Zimmermann

CERN Accelerator School

Ferney Voltaire, France

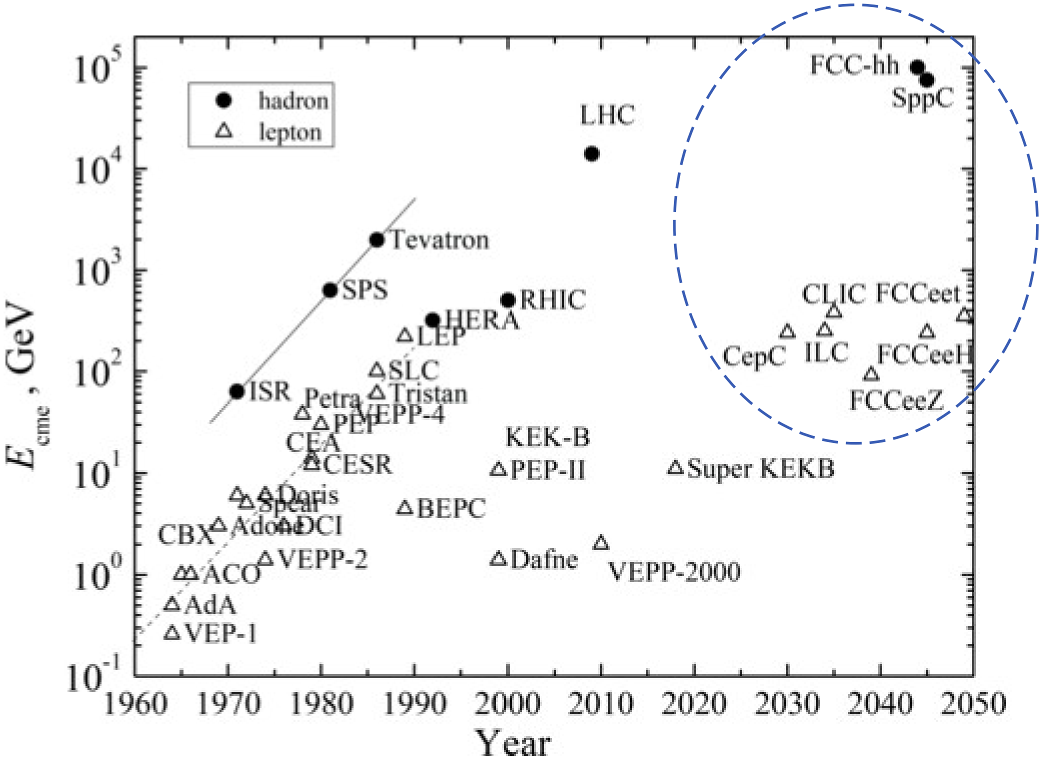
15 March 2024

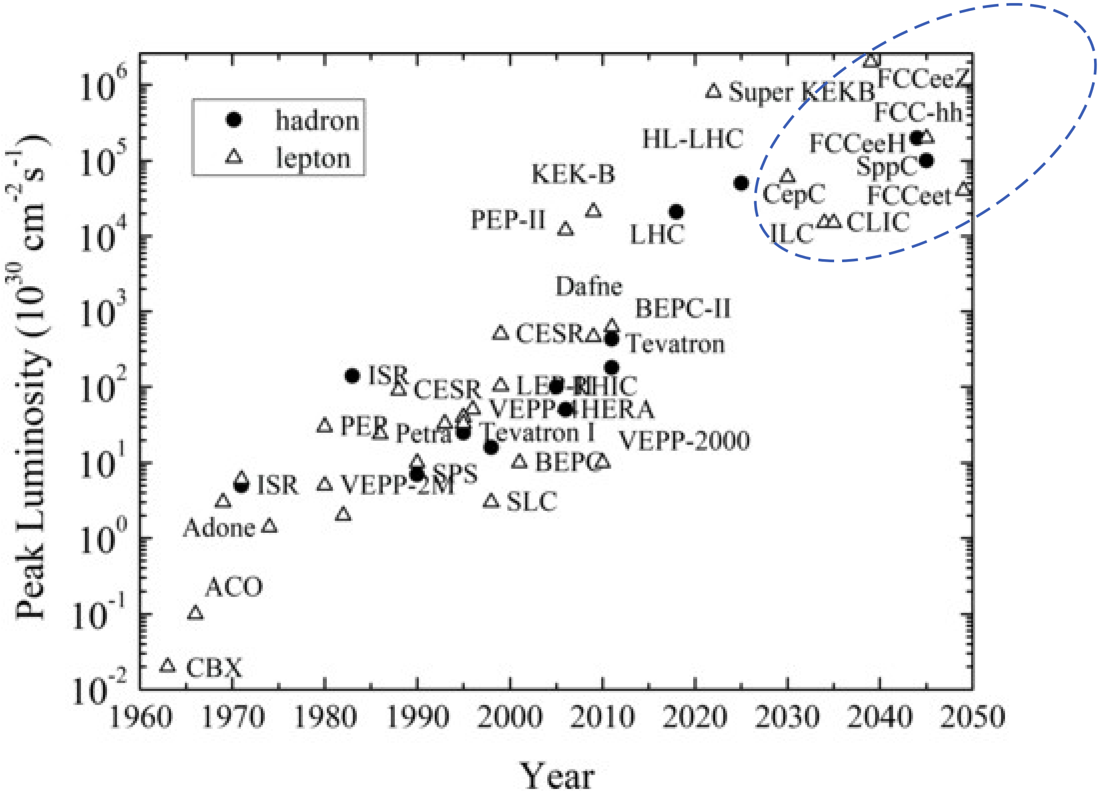
jacqueline.keintzel@cern.ch

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.

History I

- Electron-positron colliders started in the 1960s





Ref: V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006, 2021.

Note: Possible start for various future machines later than shown in plots

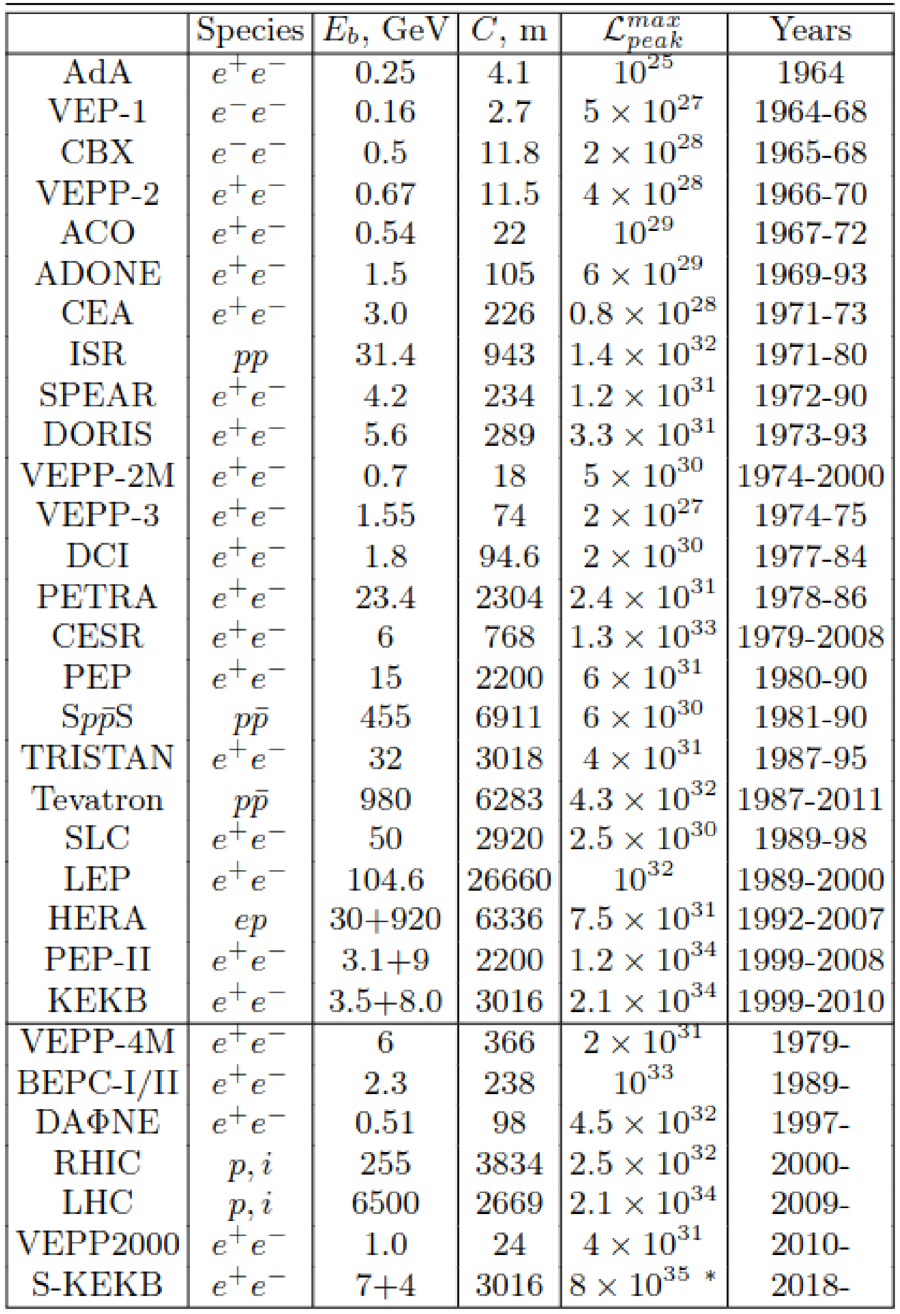
History II

- About 14 past circular electron-positron colliders
- About 3 past circular hadron colliders

- 7 colliders currently in operation
  - e.g. LHC, SuperKEKB

- Possible option for the future
  - Future Circular Collider, FCC-ee
  - Future Circular Collider, FCC-hh

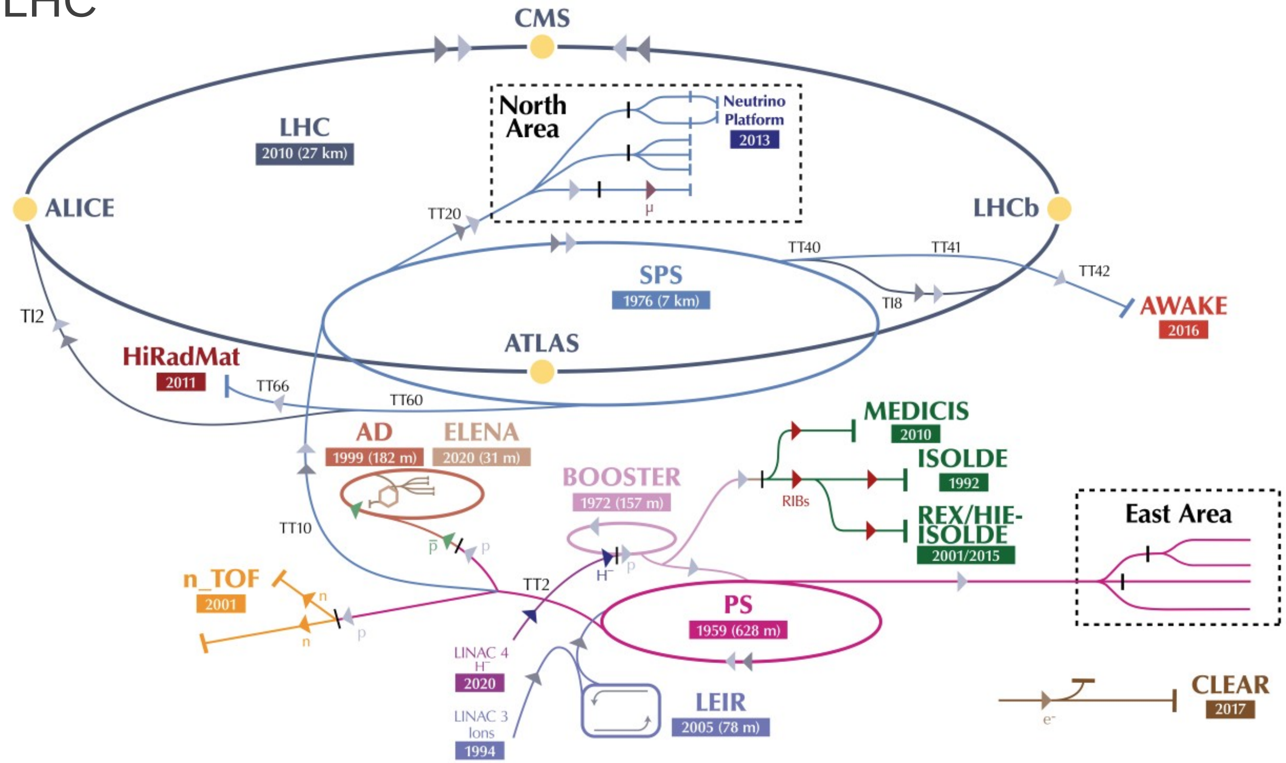
Ref: V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006, 2021.



	Species	E_b, GeV	C, m	$\mathcal{L}^{max}_{peak}$	Years
AdA	e^+e^-	0.25	4.1	10^{25}	1964
VEP-1	e^-e^-	0.16	2.7	5×10^{27}	1964-68
CBX	e^-e^-	0.5	11.8	2×10^{28}	1965-68
VEPP-2	e^+e^-	0.67	11.5	4×10^{28}	1966-70
ACO	e^+e^-	0.54	22	10^{29}	1967-72
ADONE	e^+e^-	1.5	105	6×10^{29}	1969-93
CEA	e^+e^-	3.0	226	0.8×10^{28}	1971-73
ISR	pp	31.4	943	1.4×10^{32}	1971-80
SPEAR	e^+e^-	4.2	234	1.2×10^{31}	1972-90
DORIS	e^+e^-	5.6	289	3.3×10^{31}	1973-93
VEPP-2M	e^+e^-	0.7	18	5×10^{30}	1974-2000
VEPP-3	e^+e^-	1.55	74	2×10^{27}	1974-75
DCI	e^+e^-	1.8	94.6	2×10^{30}	1977-84
PETRA	e^+e^-	23.4	2304	2.4×10^{31}	1978-86
CESR	e^+e^-	6	768	1.3×10^{33}	1979-2008
PEP	e^+e^-	15	2200	6×10^{31}	1980-90
S$p\bar{p}$S	$p\bar{p}$	455	6911	6×10^{30}	1981-90
TRISTAN	e^+e^-	32	3018	4×10^{31}	1987-95
Tevatron	$p\bar{p}$	980	6283	4.3×10^{32}	1987-2011
SLC	e^+e^-	50	2920	2.5×10^{30}	1989-98
LEP	e^+e^-	104.6	26660	10^{32}	1989-2000
HERA	ep	30+920	6336	7.5×10^{31}	1992-2007
PEP-II	e^+e^-	3.1+9	2200	1.2×10^{34}	1999-2008
KEKB	e^+e^-	3.5+8.0	3016	2.1×10^{34}	1999-2010
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979-
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989-
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997-
RHIC	p, i	255	3834	2.5×10^{32}	2000-
LHC	p, i	6500	2669	2.1×10^{34}	2009-
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010-
S-KEKB	e^+e^-	7+4	3016	8×10^{35} *	2018-

The Biggest Colliders so far

- Large Electron Positron Collider (LEP) with 27 km circumference, in operation from 1989 to 2000
- Predecessor of the Large Hadron Collider (LHC) → same tunnel for 2 different colliders
- High Luminosity LHC (HL-LHC) → successor of the LHC



Particle Physics Future

- In 2020 the **European** strategy upgrade of particle physics (ESPP) expressed the long-term plan for particle colliders:
  - An **electron-positron Higgs factory is the highest-priority** next collider.
  - Europe, together with its international partners, should investigate the technical and financial feasibility of a **future hadron collider at CERN** with a center-of-mass energy of at least 100 TeV and with **an electron-positron Higgs and electroweak factory as a possible first stage**.
- Particle Physics Project Prioritization Panel **(P5)** published recommendations in 2023, high priority projects:
  - Exploitation of LHC and HL-LHC
  - Oversea **Higgs and electroweak factory**

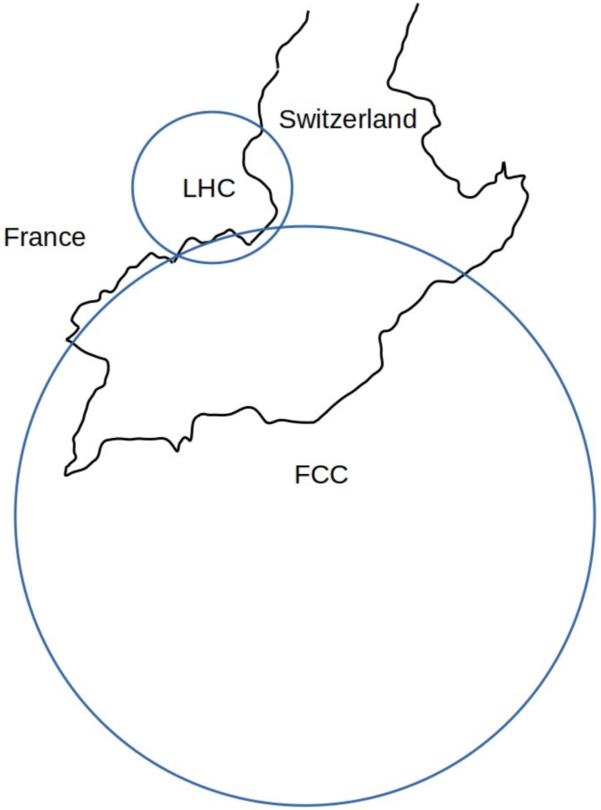
2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

Future Circular Collider

Inspired by LEP-LHC programm

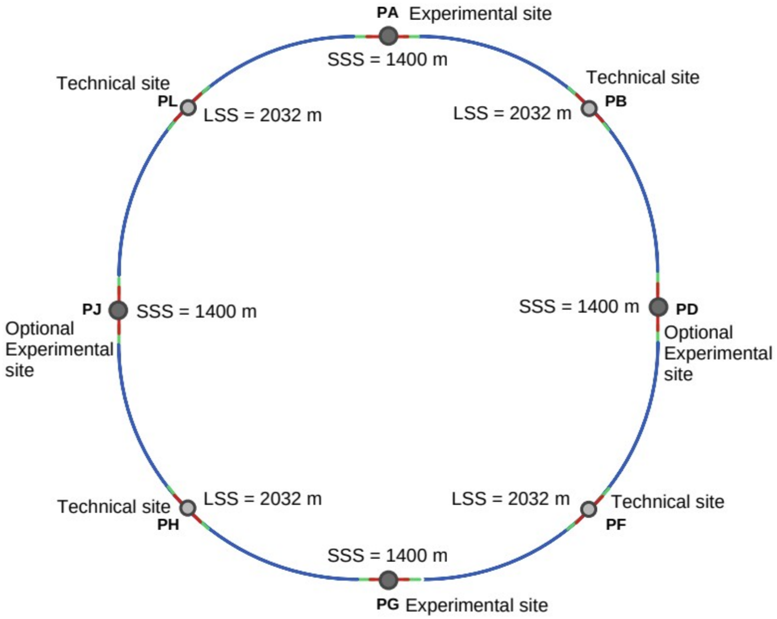
Re-using CERN infrastructure



Compatible lattice designs

FCC-ee

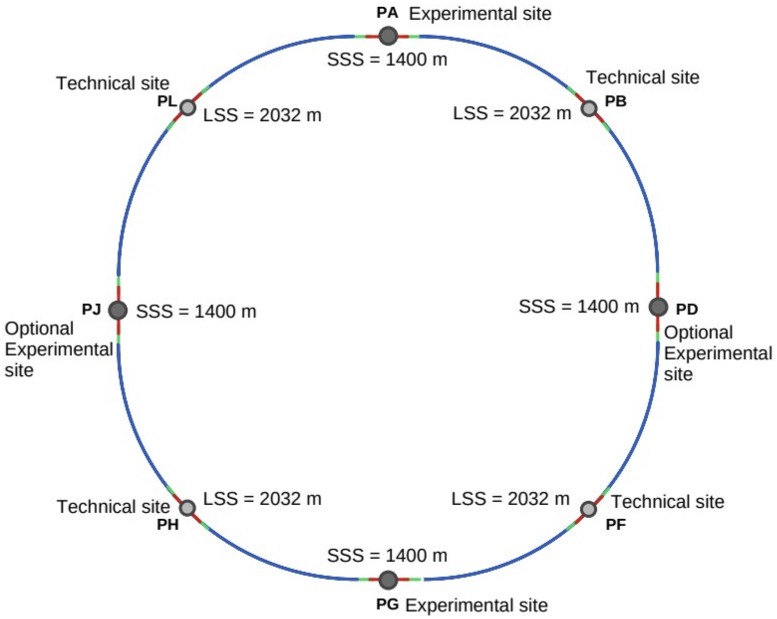
Electron-positron collider



~ 2045 - 2060

FCC-hh

Proton-proton collider



~ 2070 - 2090

FCC Collaboration

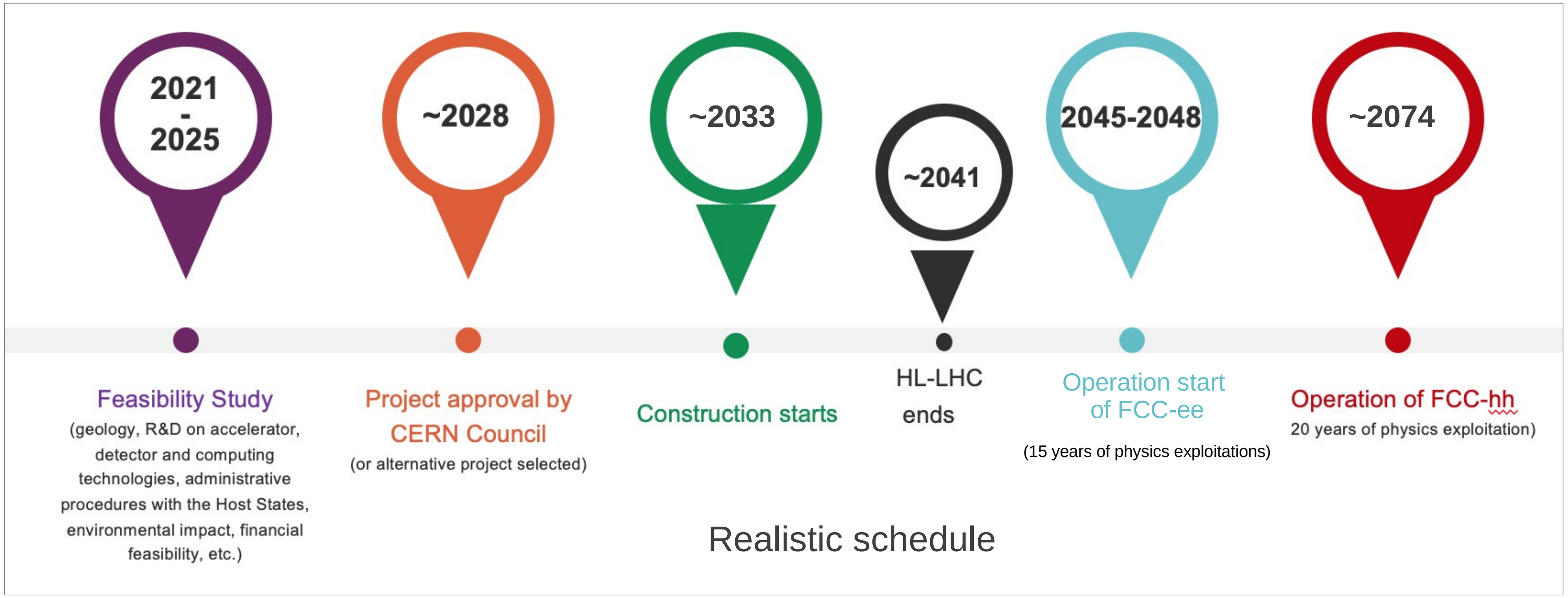
Long-Term Goal: World-leading high energy physics infrastructure for 21st century to push particle-physics precision and energy frontiers far beyond present limits → international collaboration essential

More than 140 institutes from 33 countries

Feasibility Study and Schedule

- From 2021-2025 with mid-term review end of 2023 and final Feasibility Study Report end of 2025

Goal: Demonstration of the geological, technical, environmental, financial and administrative feasibility of the FCC-ee, including its optimisation



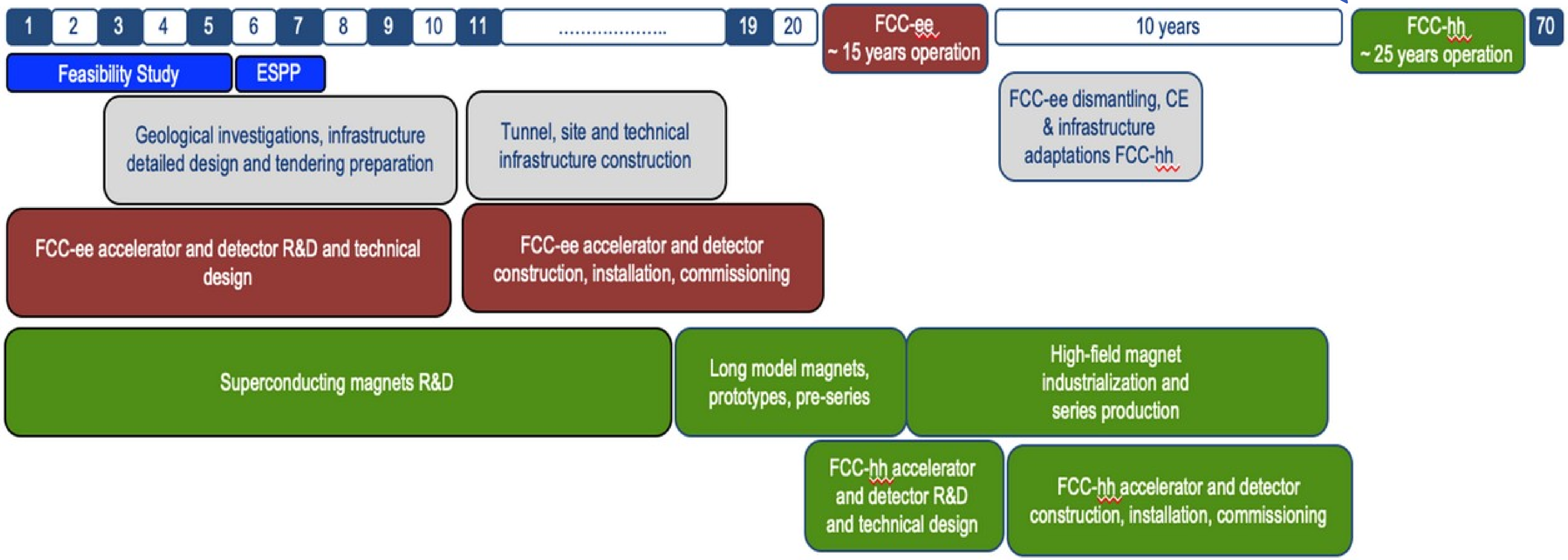
Courtesy: F. Gianotti

FCC Technical Schedule

FCC-ee commissioning second half of the 2040s

FCC-hh commissioning around 2070

Starts at 2021



Mid-Term Report

- **MTR Goal:** Asses progress of feasibility study towards the final report by February 2024

Future Circular Collider
Midterm Report

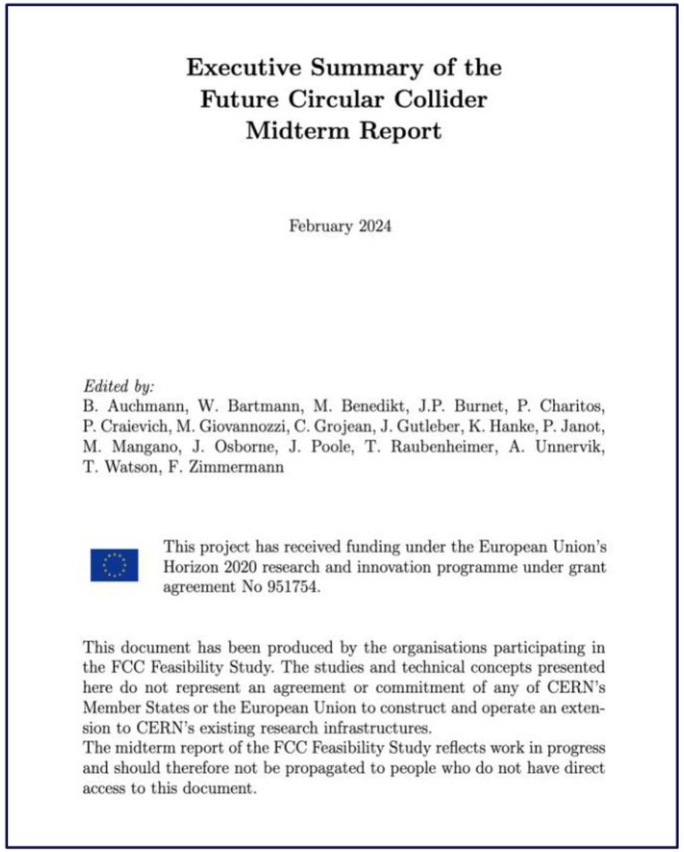
February 2024

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, T. Watson, F. Zimmermann

This project has received funding under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

8 Chapters
~ 700 pages
~ 16 editors
~ 300 contributors



Executive Summary of the Future Circular Collider Midterm Report

February 2024

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Charitos, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, A. Unnervik, T. Watson, F. Zimmermann

This project has received funding under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

This document has been produced by the organisations participating in the FCC Feasibility Study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or the European Union to construct and operate an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

8 Chapters
~ 45 pages
~ 16 editors

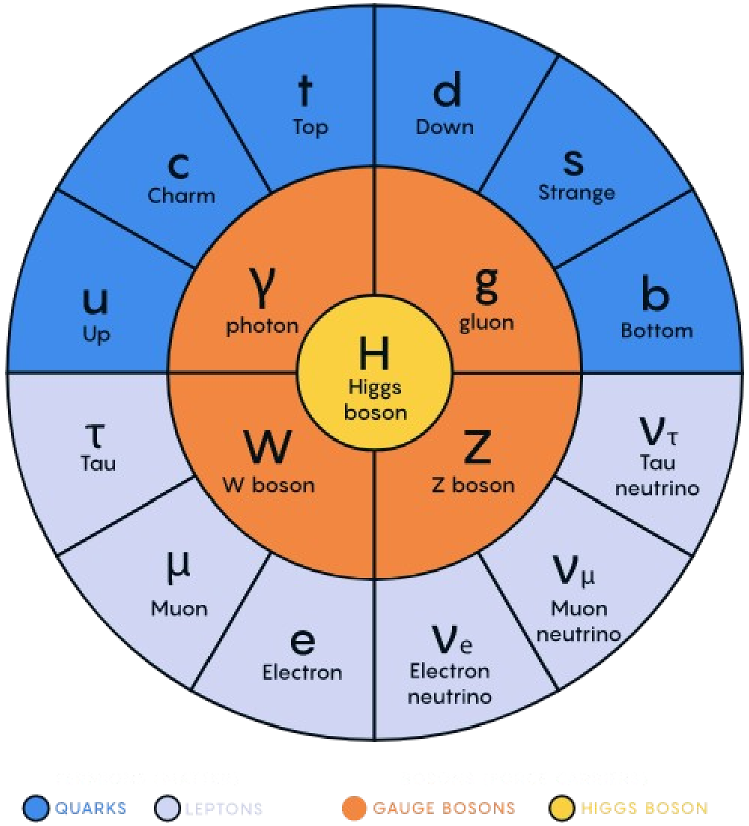
Particle Physics Thanks to the LHC

- Standard Model (SM) confirmed to high accuracy up to several TeV

- Higgs-boson discovered
  - At the mass predicted within the SM by LEP precision electro-weak measurements

- Absence of new physics at the TeV scale

Need for a new, broad and ambitious program
→ more precision
→ more energy
→ for more sensitivity for new physics

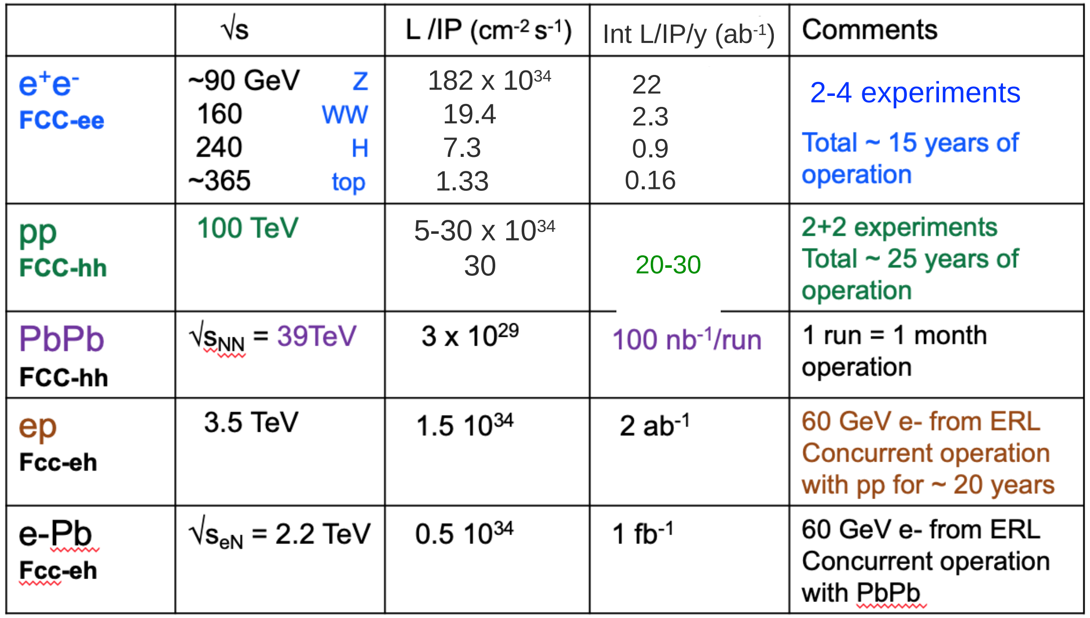


https://forumias.com/blog/the-standard-model-of-particle-physics-gets-a-jolt/#gsc.tab=0

Courtesy: F. Gianotti

FCC Physics Potential

- Integrated FCC offers multi-stage facility with broad and diverse physics potential



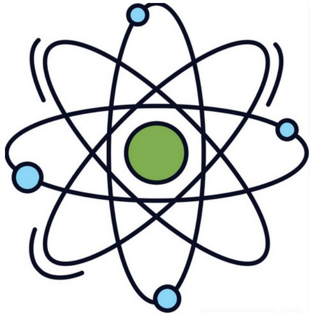
	√s	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	182 x 10^{34} 19.4 7.3 1.33	22 2.3 0.9 0.16	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5-30 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

- FCC-ee:
  - Highest luminosities at Z, W and H of all proposed Higgs and electro-weak factories
  - Indirect discovery potential up to 70 TeV
- FCC-hh:
  - Direct exploration of next energy frontier (~10x LHC)
  - Also heavy ion collision experiments possible
- FCC-eh:
  - Possibly also electron-proton (ion) collisions

Courtesy: F. Gianotti

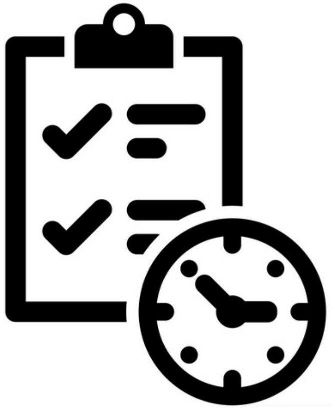
Why FCC?

Physics



- Immense physics potential for lepton and hadron colliders
- Luminosity frontier: Precision physics experimements
- Energy frontier: Discovery potential thanks to 100 TeV E_{cm} for FCC-hh

Timeline

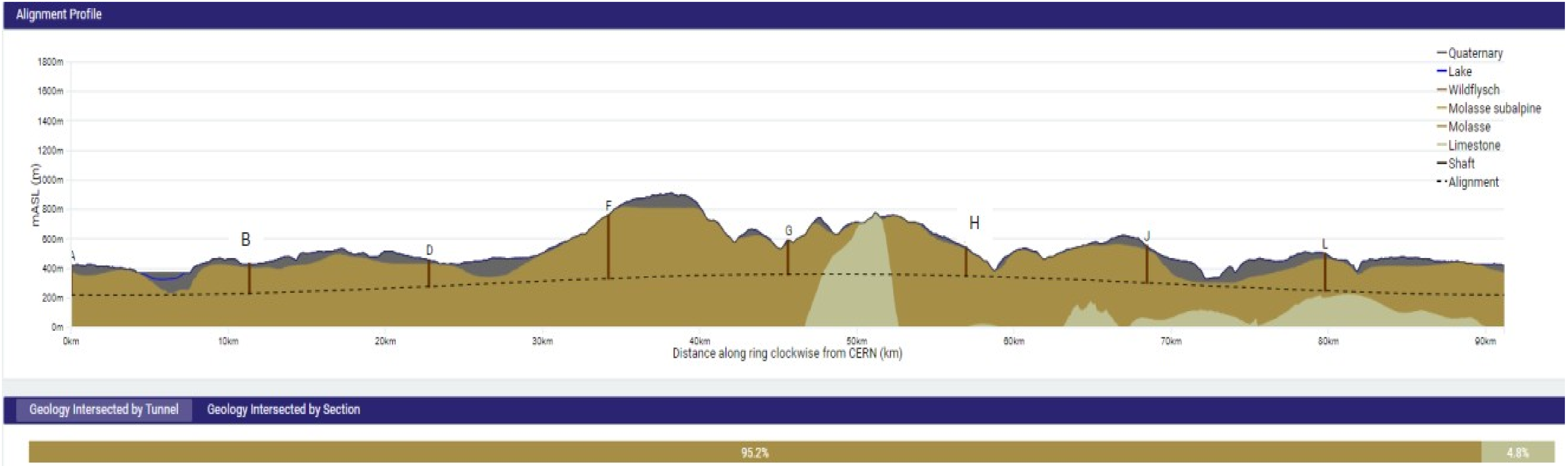


- FCC-ee technology is mature; collisions could start few years after HL-LHC
- Integrated FCC project allows for ~20 more years magnet R&D
- Optimized overall investment

Community

- 4 collision points for high-energy physics experiments
- Many other possibilities (fixed-target, use of beam dump, ..)
- Only facility to commensuate the size of the CERN community

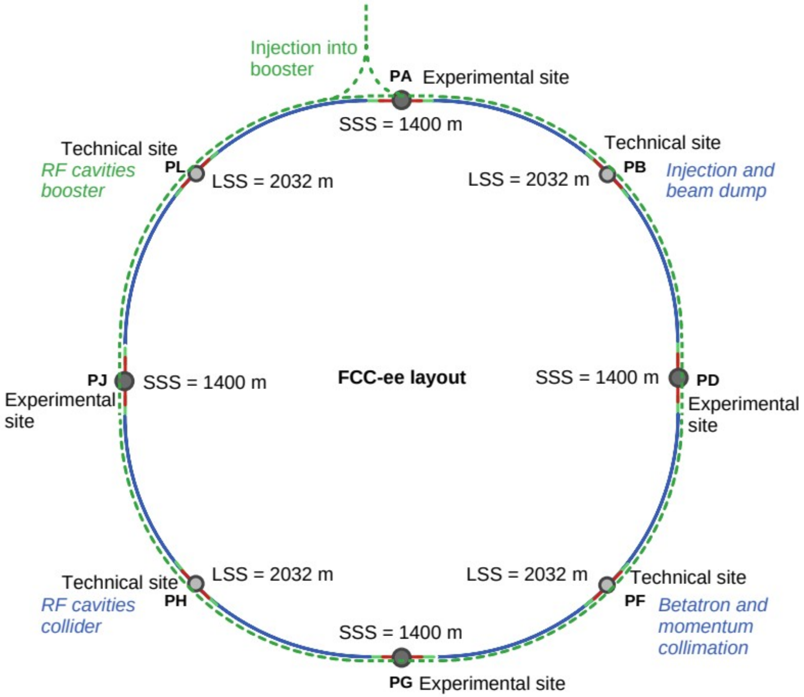
Placement Studies

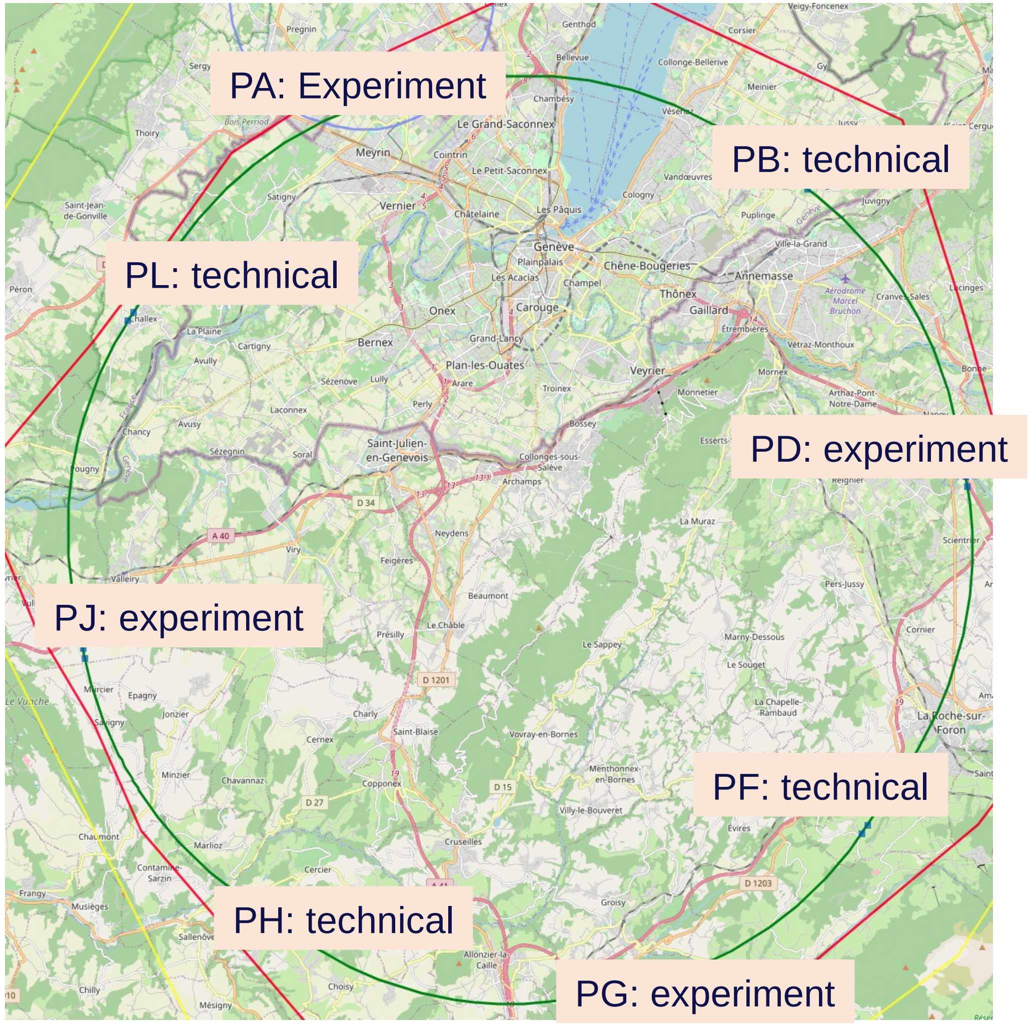


- 91 km circumference
- 95 % in molasse for minimizing tunnel construction risks
- Site investigations ongoing until end of 2025

Optimized Placement

- Optimized considering constraints on geology and surface
- **90.7 km** circumference with **8 surface points**
- **High Energy Booster** in addition to main rings



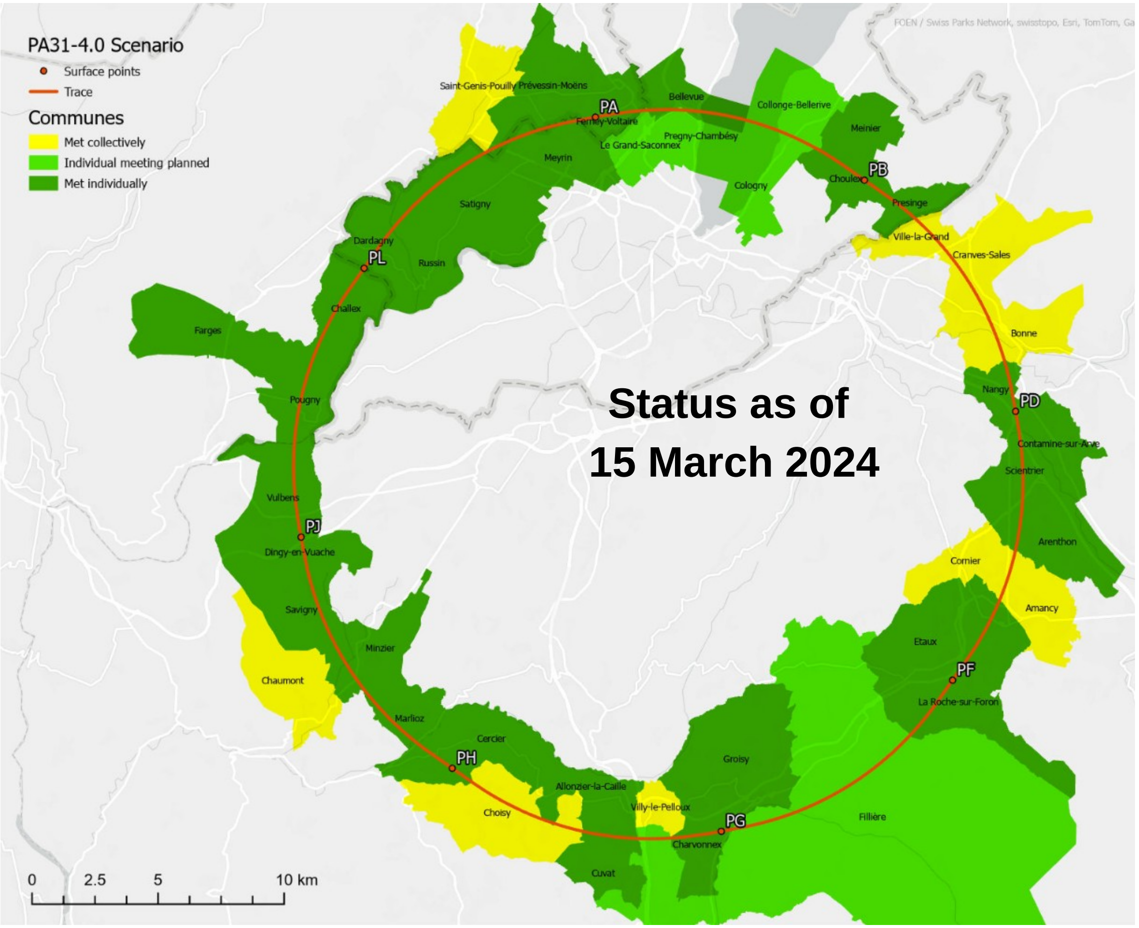


Courtesy: J. Gutleber

Progress with Baseline

Meetings with municipalities concerned:

- PA: Ferney Voltaire (FR) – experimental side
- PB: Présinge/Choulex (CH) – technical side
- PD: Nangy (FR) – experimental side
- PF: Roche sur Foron/Etaux (FR) – technical side
- PG: Charvonnex/Groisy (FR) – experimental side
- PH: Cercier (FR) – technical side
- PJ: Vulbens/Dingy en Vuache (FR) – experimental side
- PL: Challex (FR) – technical side

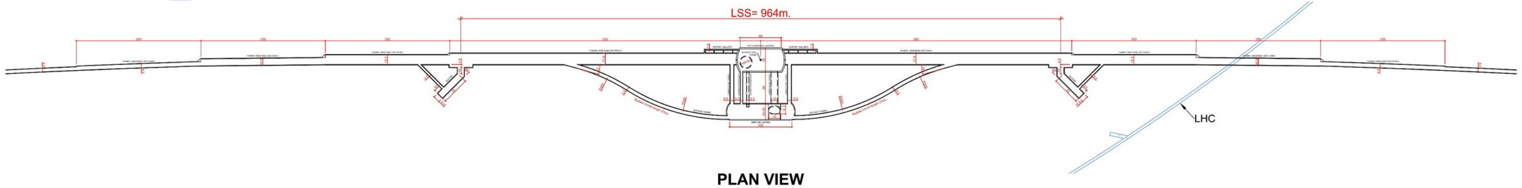


Status as of
15 March 2024

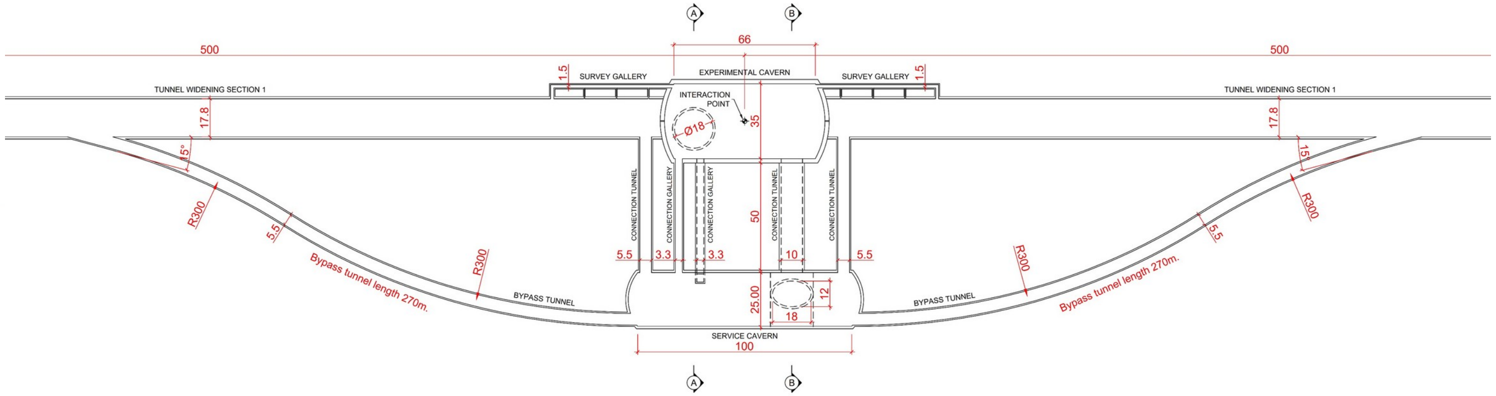
The support of the host states is greatly appreciated and essential for the study progress!

Civil Engineering

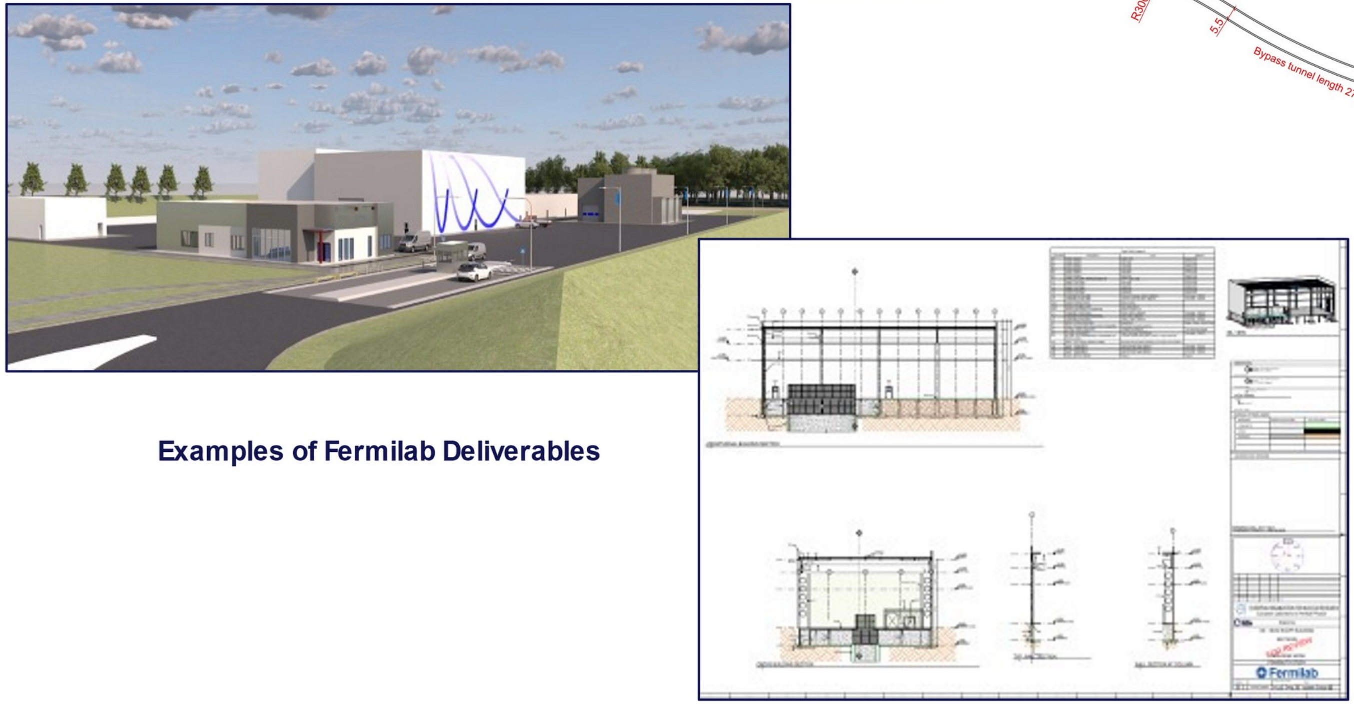
- Full 3D model of all underground structures designed



PLAN VIEW
1:3000



PLAN VIEW
1:1000



Examples of Fermilab Deliverables

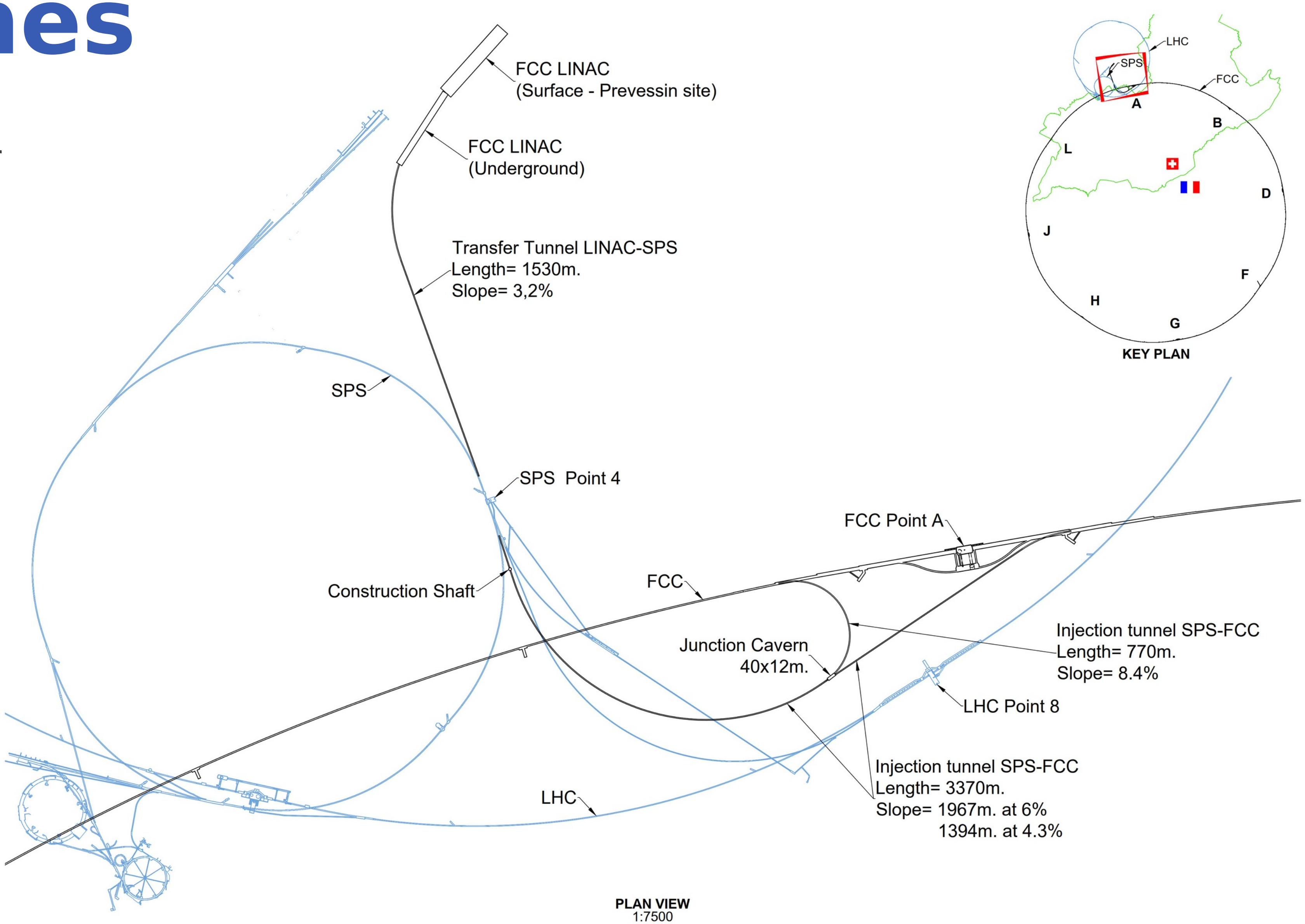
- Generic study of experimental and technical sites

Transfer Lines

- Designed to enable injection either from SPS as pre-booster or from a new linac sited at Prevessin

- Single tunnel with spur for clock-wise and anit-clockwise injection

- Design allows re-use for FCC-hh if injector in the SPS tunnel

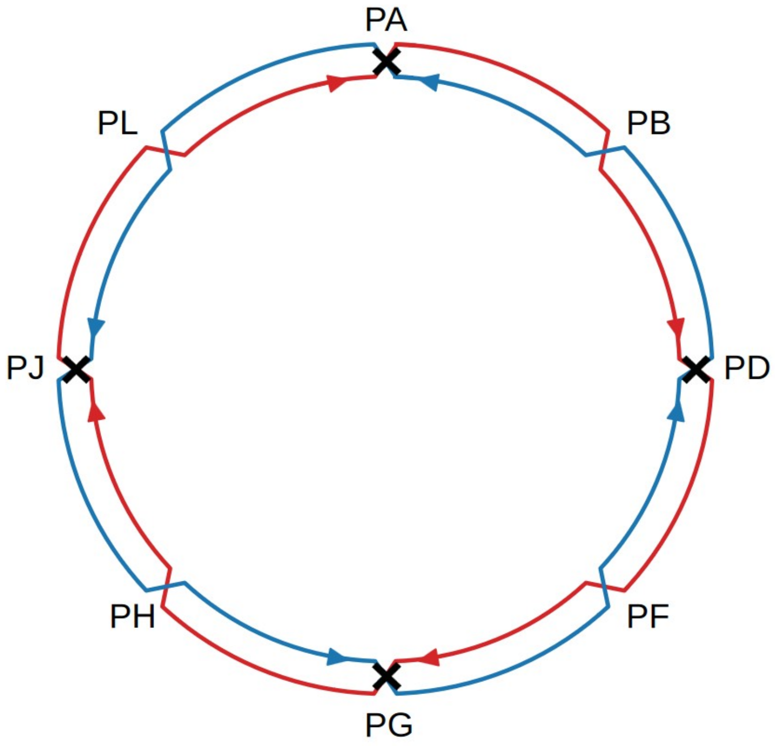


PLAN VIEW
1:7500

FCC-ee Overview

Particle Physics:

- Higgs EW, top and flavour factory
- 4 baseline beam energies and diverse particle physics program
  - 45.6 GeV: Z-pole
  - 80 GeV: W-pair-threshold
  - 120 GeV: ZH-production
  - 182.5 GeV: top-pair-threshold
- High statistics



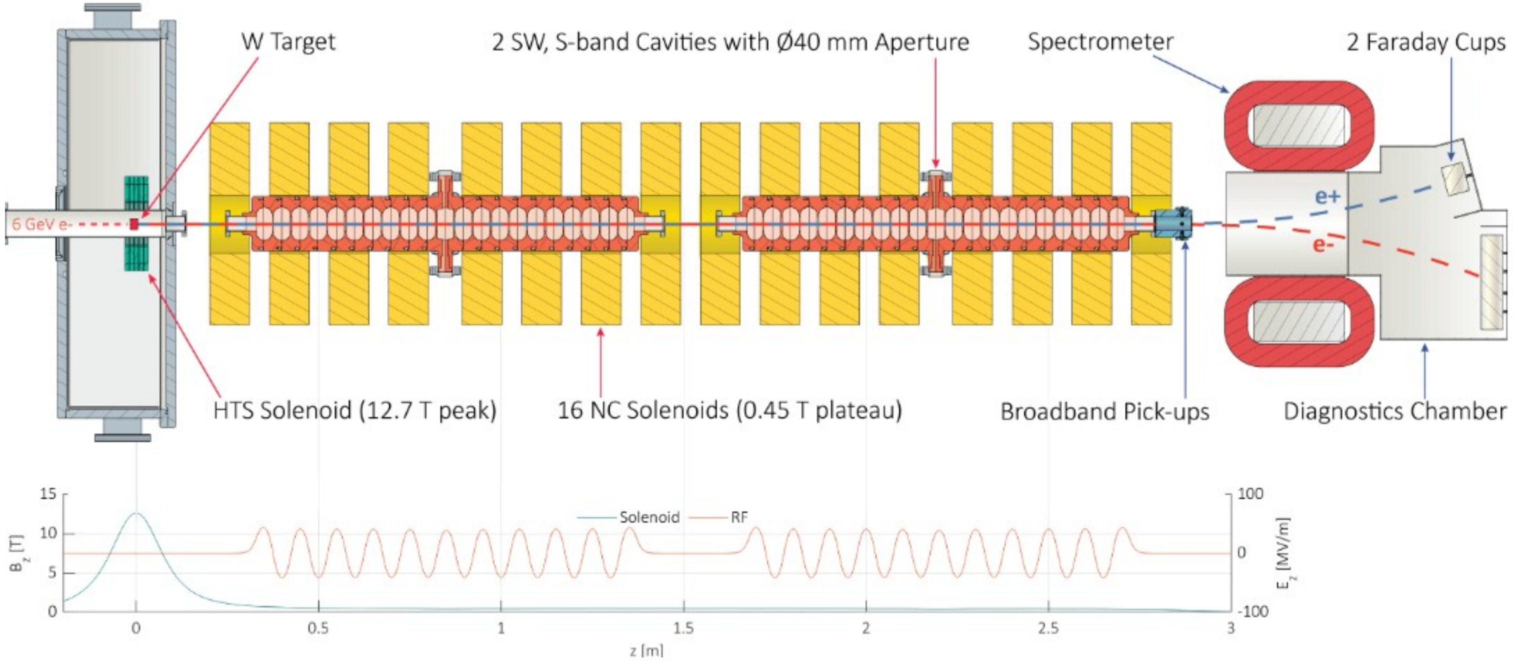
Accelerator Physics:

- 4-fold super-symmetric layout
  - Up to 4 Interaction Points (IPs)
  - 1 RF-section per beam
  - 1 collimation section
  - 1 section for injection and dump
- 10s of nm beam size at IPs
- Strong synchrotron radiation

Precision particle physics experiments ⟺ **Excellent and robust accelerator design**

Positron Production

- Positrons generated by electrons hitting high-Z-target
- Generated positrons have **large emittance and energy spread** → must be reduced
- Novel capture techniques tested at **P³** (PSI Positron Production), relevant for future colliders



N. Vallis et al, arXiv:2308.16803v2, 2023.

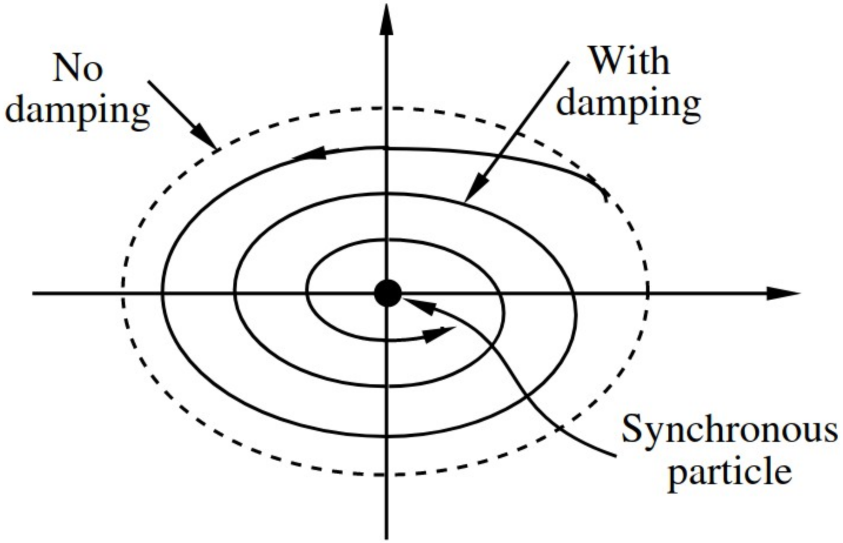
Synchrotron Radiation (SR)

- Electrons/Positrons about 2000 times lighter than protons → 10^{13} greater radiation losses

$$P_\gamma = \frac{2}{3} r_0 E_0 c \frac{\gamma_{\mathrm{rel}}^4 \beta_{\mathrm{rel}}^4}{\rho^2}$$

- Leads to a **natural damping** of the emittance over time

$$\varepsilon(t) = e^{-2\, t/\tau_{\mathrm{SR}}} \qquad \tau_{\mathrm{SR}} = \frac{T_0 E}{j_{x,y} U}$$



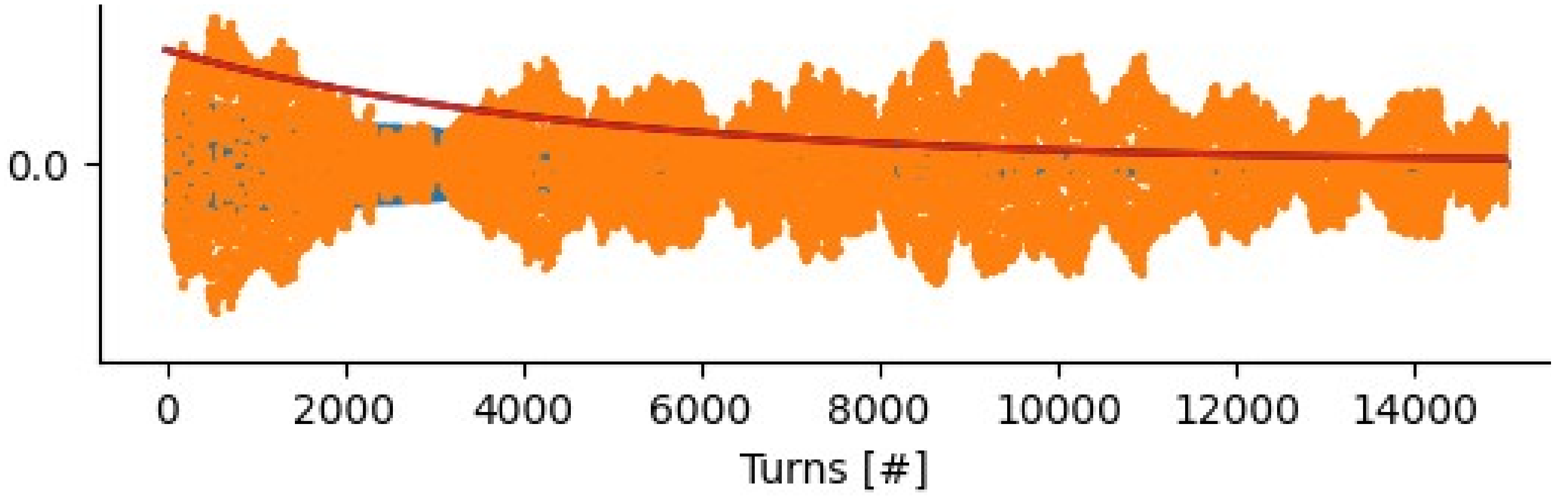
W. Barletta, USPAS lectures on synchrotron radiation, 2009.

Quantum Excitation

- Photons emitted in discrete quanta following a **random Poisson process**
- Sudden loss leads to an instantaneous jump of the particle if emitted in dispersive region
- Introduced **noise** leads to emittance growth towards equilibrium

$$\epsilon_0 = C_q \gamma_0^2 \frac{I_5}{j_x I_2}$$

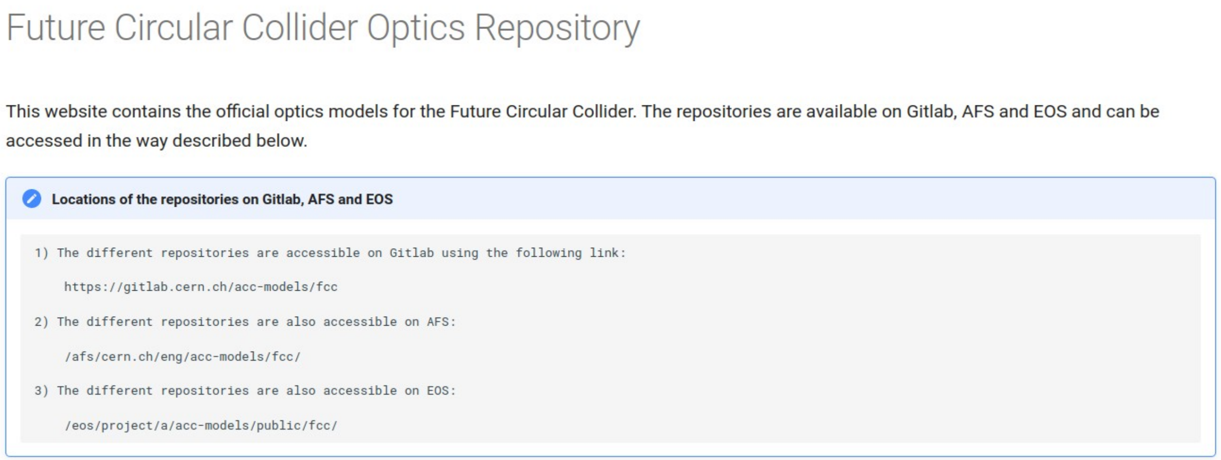
Cq… quantum radiation constant
I_2/I_5 … radiation integrals
jx … partition number



Blue: only synchrotron radiation; Orange: with quantum excitation

Lattice Designs

- 2 lattice designs with different features being investigated
  - Global Hybrid Correction optics
    K. Oide et al.
    Phys. Rev. Accel. Beams 19, 111005
  - Local Chromaticity Correction optics
    P. Raimondi and S. Liuzzo
    Phys. Rev. Accel. Beams 26, 021601
- Lattices can be found in the repository
  - *https://acc-models.web.cern.ch/acc-models/fcc/*

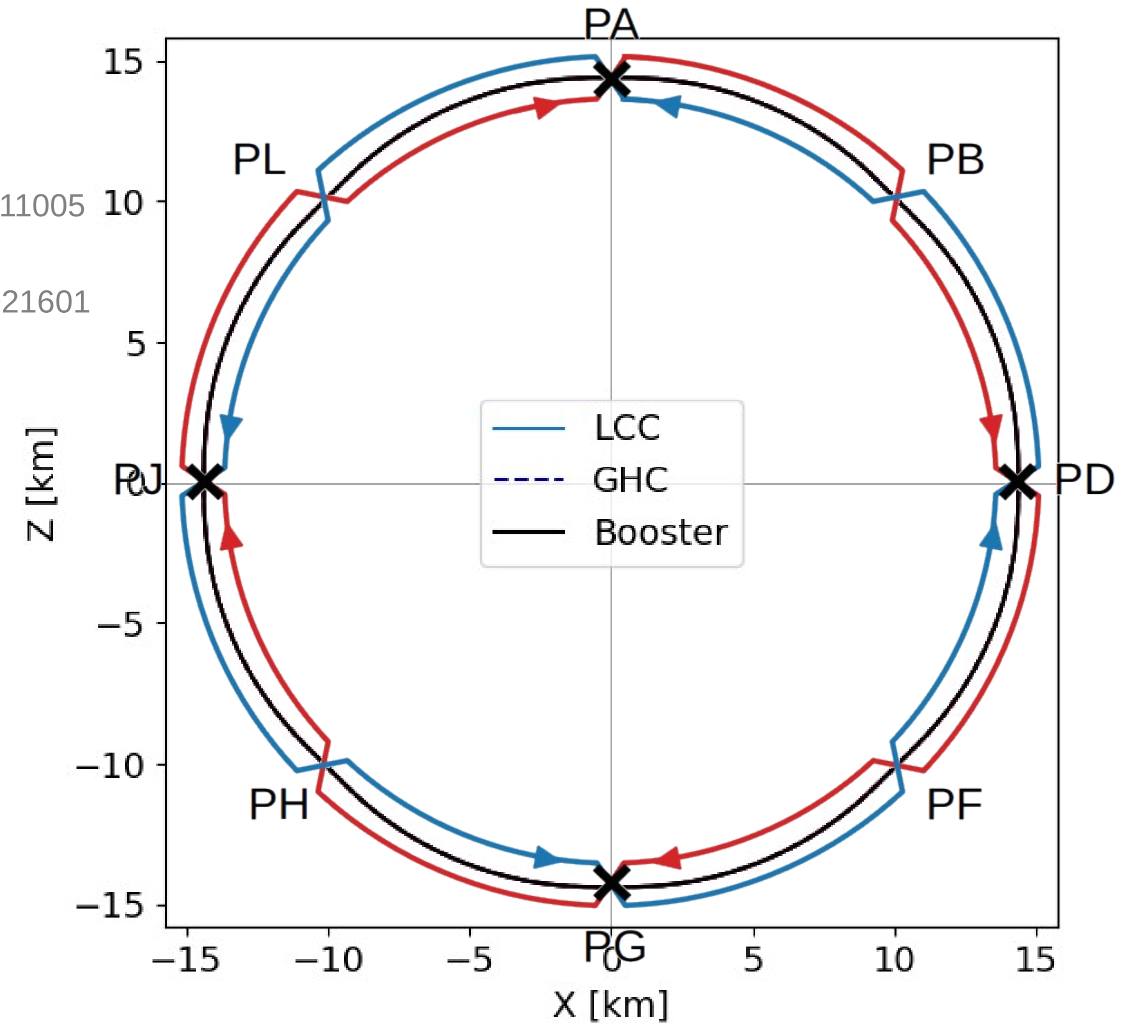


Future Circular Collider Optics Repository

This website contains the official optics models for the Future Circular Collider. The repositories are available on Gitlab, AFS and EOS and can be accessed in the way described below.

Locations of the repositories on Gitlab, AFS and EOS

```
1) The different repositories are accessible on Gitlab using the following link:

    https://gitlab.cern.ch/acc-models/fcc

2) The different repositories are also accessible on AFS:

    /afs/cern.ch/eng/acc-models/fcc/

3) The different repositories are also accessible on EOS:

    /eos/project/a/acc-models/public/fcc/
```



FCC-ee Parameters

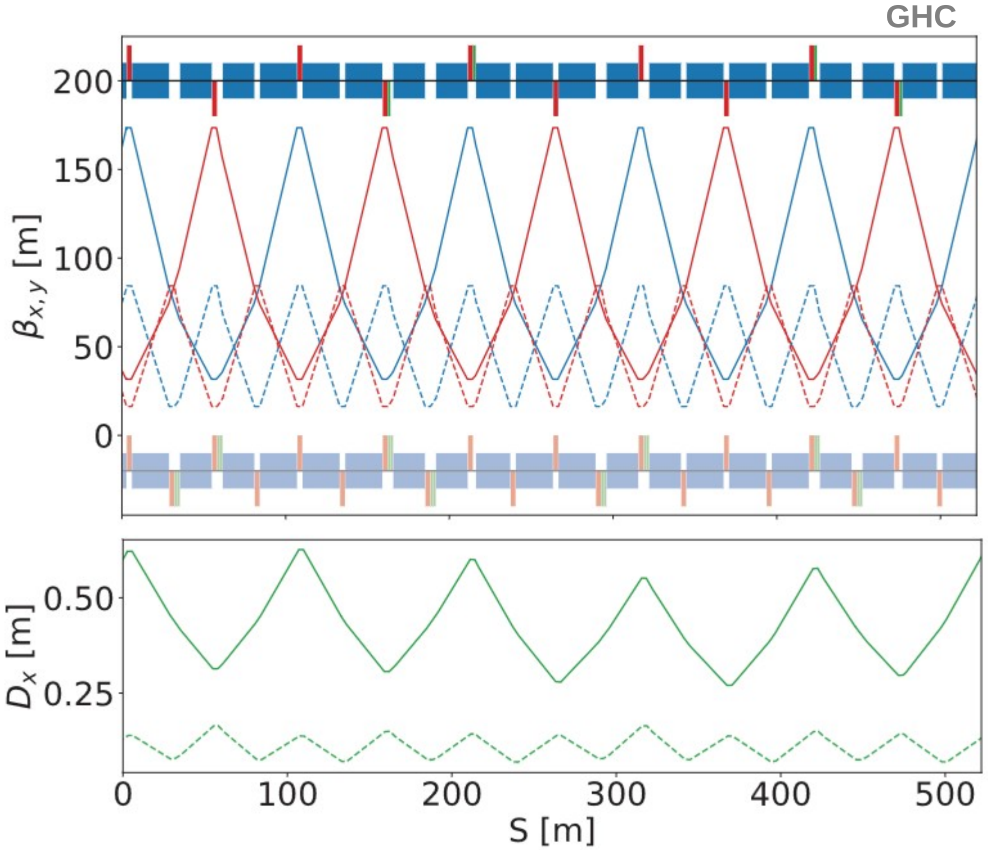
	Z	WW	ZH	ttbar
Beam energy [GeV]	45.6	80	120	182.5
SR power/beam [MW]	50			
SR losses/turn [GeV]	0.0394	0.374	1.89	10.42
Beam current [mA]	1270	137	26.7	4.9
Bunches/beam [-]	11200	1780	440	60
Bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
RF voltage 400/800MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Horizontal β-function at IP [mm]	110	200	240	1000
Vertical β-function at IP [mm]	0.7	1.0	1.0	1.6
Horizontal emittance [nm]	0.71	2.17	0.71	1.59
Vertical emittance [pm]	1.9	2.2	1.4	1.6
Luminosity/IP [10^{34}cm^{-2}s^{-1}]	141	20	5	1.25
Integrated luminosity/IP/year [ab^{-1}]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 ttbar pairs

Design and parameters dominated by choice to allow for 50 MW synchrotron radiation power per beam

Defines
→ RF system
→ Beam parameters

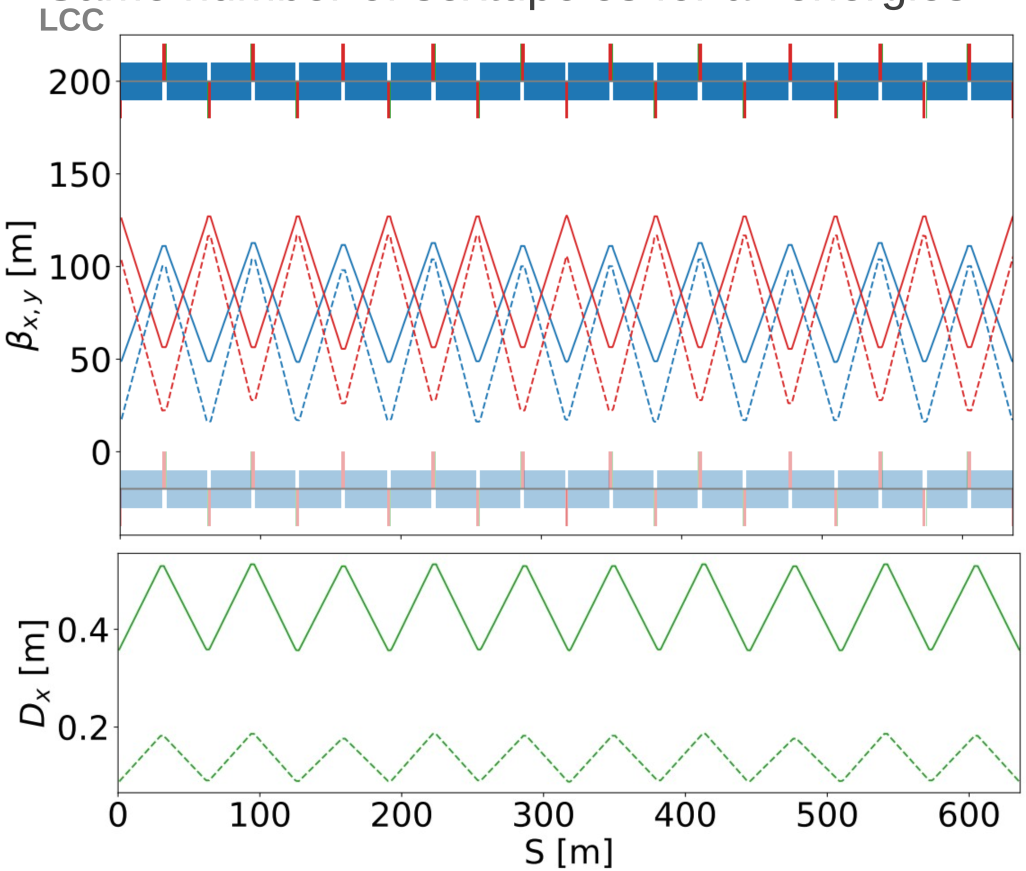
FCC-ee Arc Designs

- 260 m FODO cell
- More quadrupoles and sextupoles at ZH and ttbar



Blue: dipoles
Red: quadrupoles
Green: sextupoles

- 300 m Hybrid FODO cell
- Same number of sextupoles for all energies

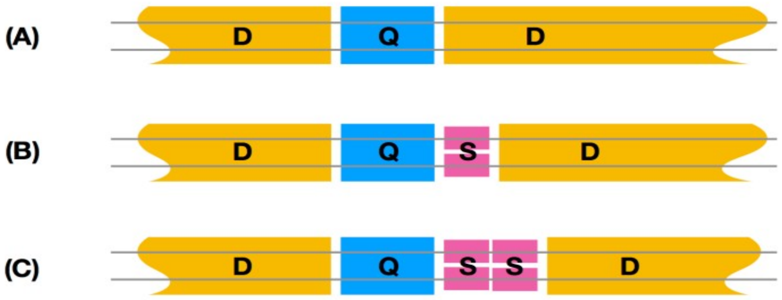


Solid: Z; Dashed: ttbar

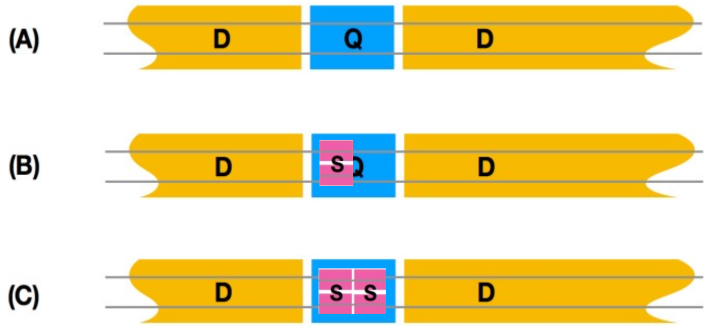
Courtesy: M. Koratzinos, B. Auchmann

HTS Optics for FCC-ee Arcs

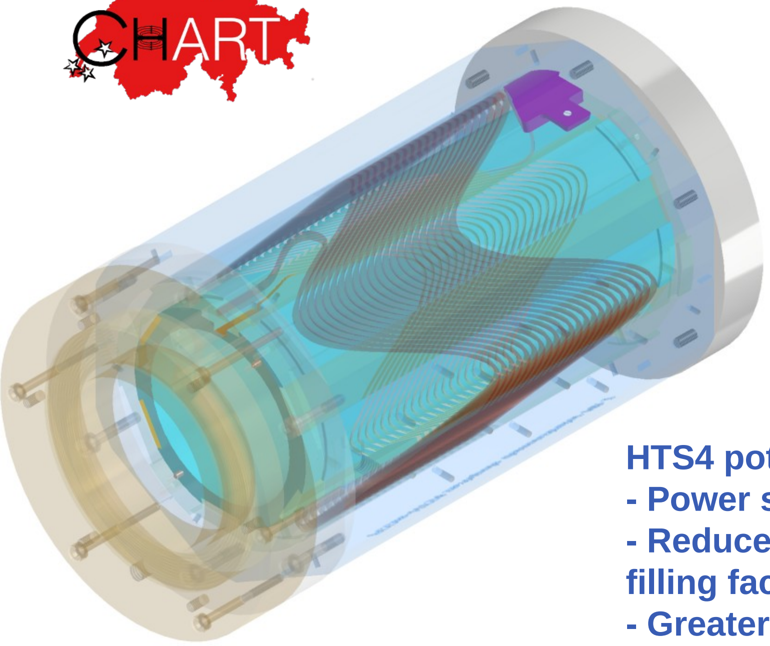
- Baseline design: normal conducting arc quadrupoles and sextupoles

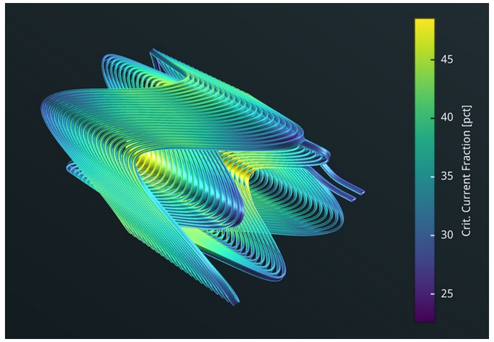


- HTS: High Temperature Superconducting magnets



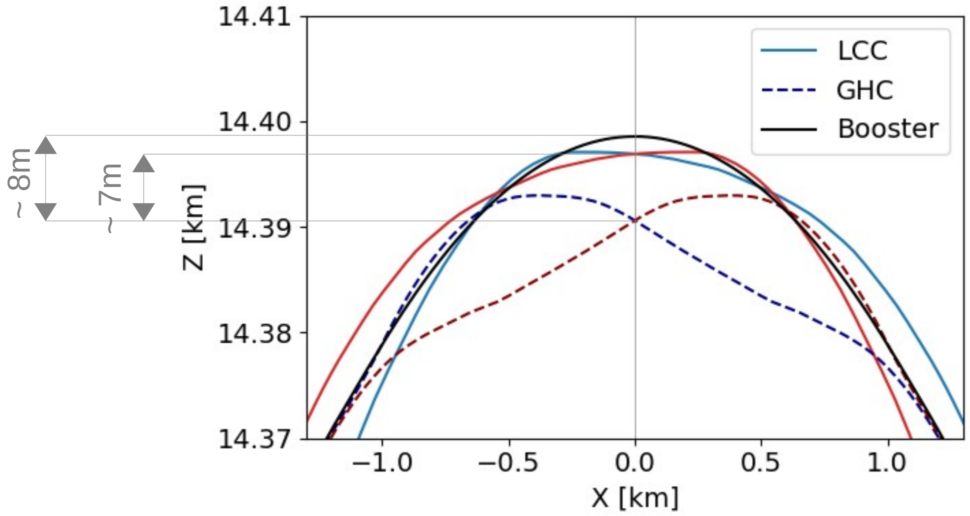
- HTS4 project within CHART collaboration
  - Nested quadrupoles and sextupoles
  - HTS superconductor operating at 40K





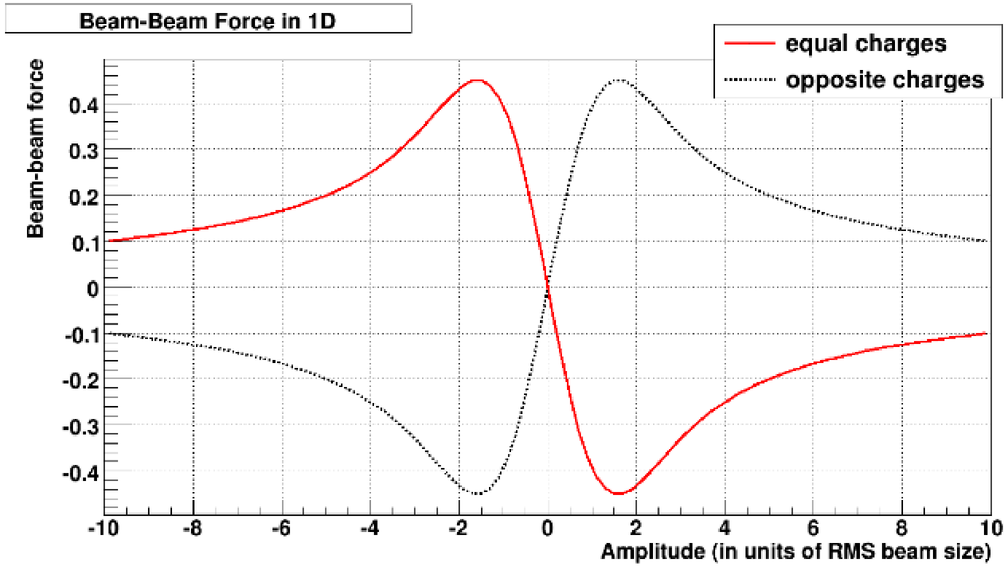
HTS4 potential:
- Power saving
- Reduced length and increased dipole filling factor
- Greater optics flexibility

Collision Point and Beam-Beam



- Limit SR photons to 100 keV
- Crossing from inside outwards at each IP
- Crossing from outside inwards at other insertions
- Booster needs to surpass main rings

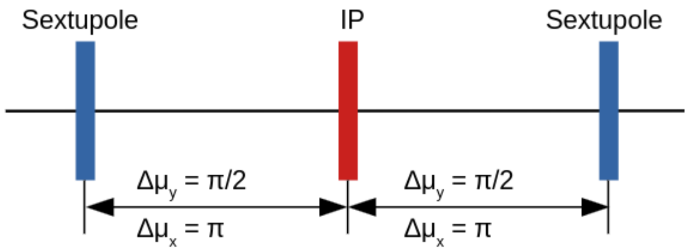
- Small emittance and beta-function
- Large beam currents → beam-beam effects
- For small amplitudes effect similar to focusing quadrupole for e^+e^- collisions
- Leads to **beam-beam tune shift**



M. Schaumann, Master Thesis, 2011.

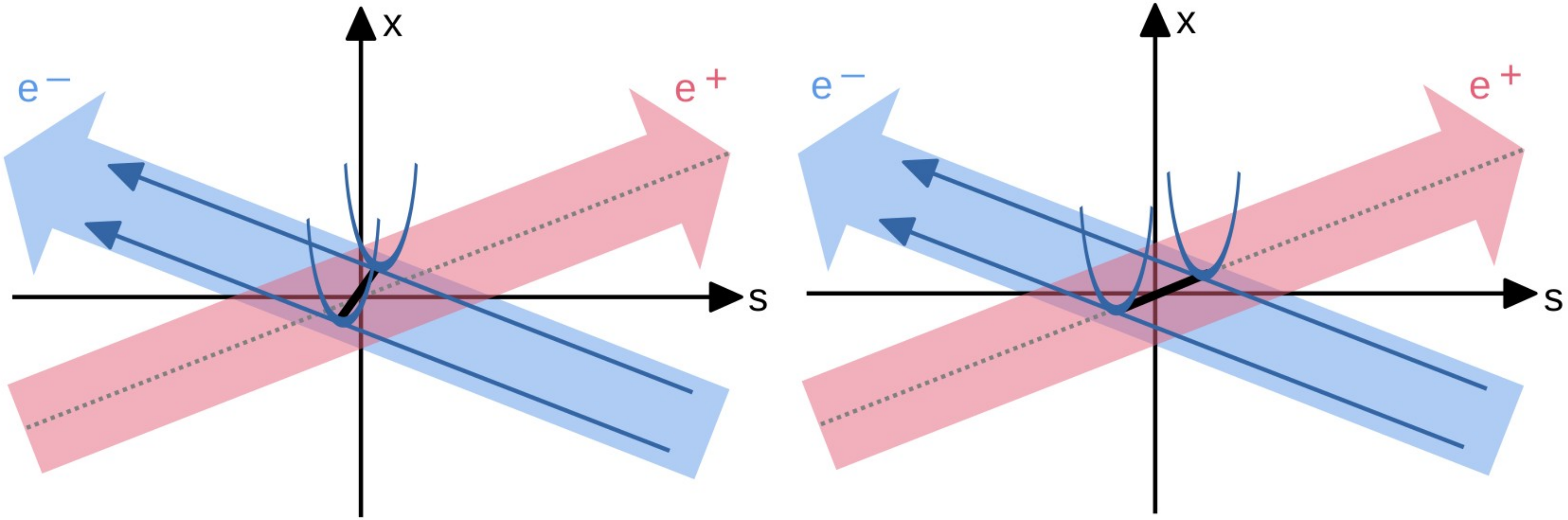
Crab-Waist Scheme

- Large crossing angle and horizontal beam size
- Vertical β-function comparable to overlap area
- **Crab-waist** transformation with **sextupoles**



Powering sextupoles rotates the vertical β-function and aligns the minimum on the longitudinal axis on the other beam

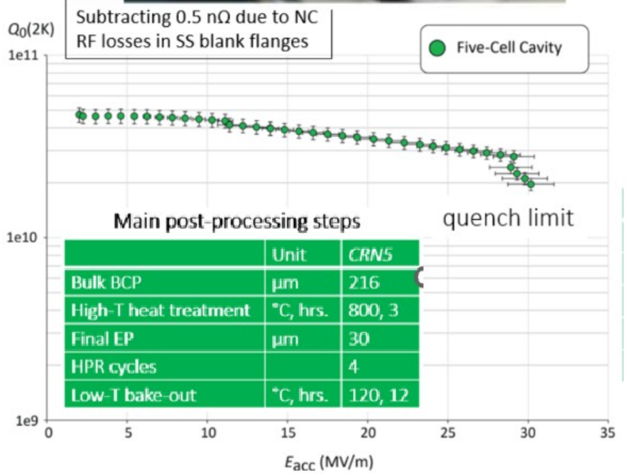
Without crab-waist transformation **With crab-waist transformation**



RF R&D Activities

- RF system is key technology for the FCC-ee
- Nb on Cu 400 MHz cavities (KEK as R&D partner), seamless cavity production and coating techniques
- RF power source R&D in synergy with HL-LHC

5-cell 800 MHz cavity development collaboration with JLAB

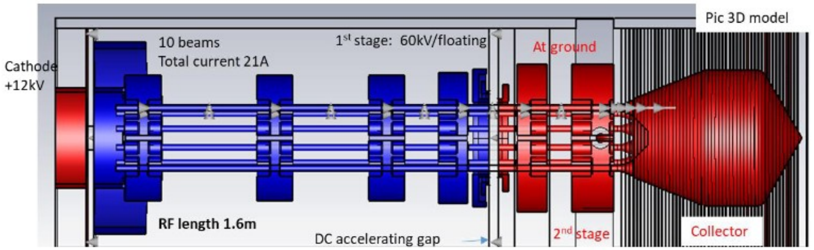


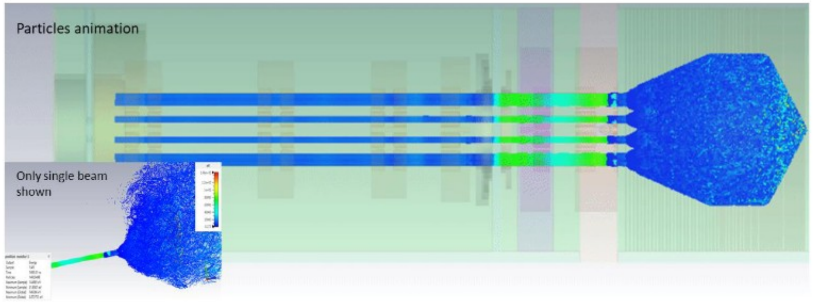
Main post-processing steps

	Unit	CRN5
Bulk BCP	µm	216
High-T heat treatment	°C, hrs.	800, 3
Final EP	µm	30
HPR cycles		4
Low-T bake-out	°C, hrs.	120, 12

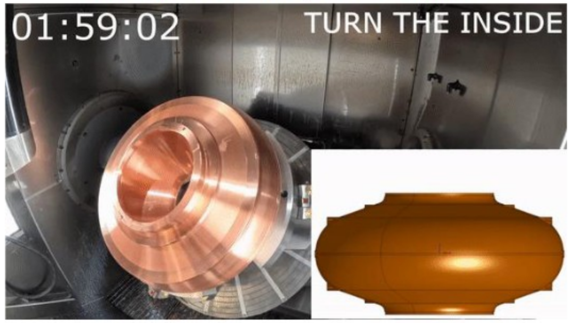
high-efficiency klystron R&D

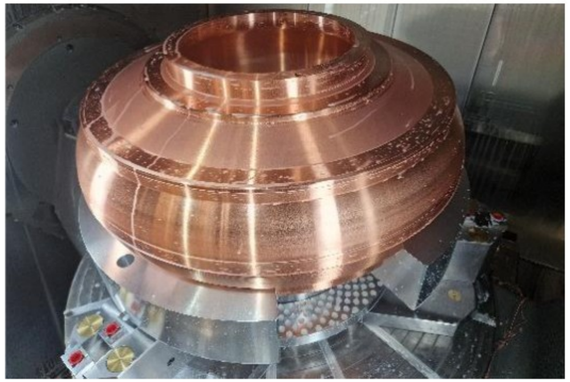
Novel two-stage MBK klystron: CW, 400MHz, 1.28MW.





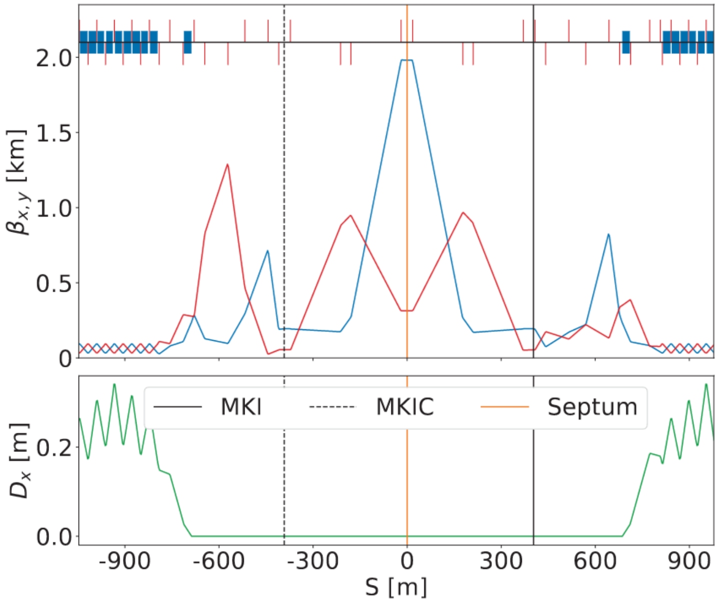
400 MHz monoblock prototype

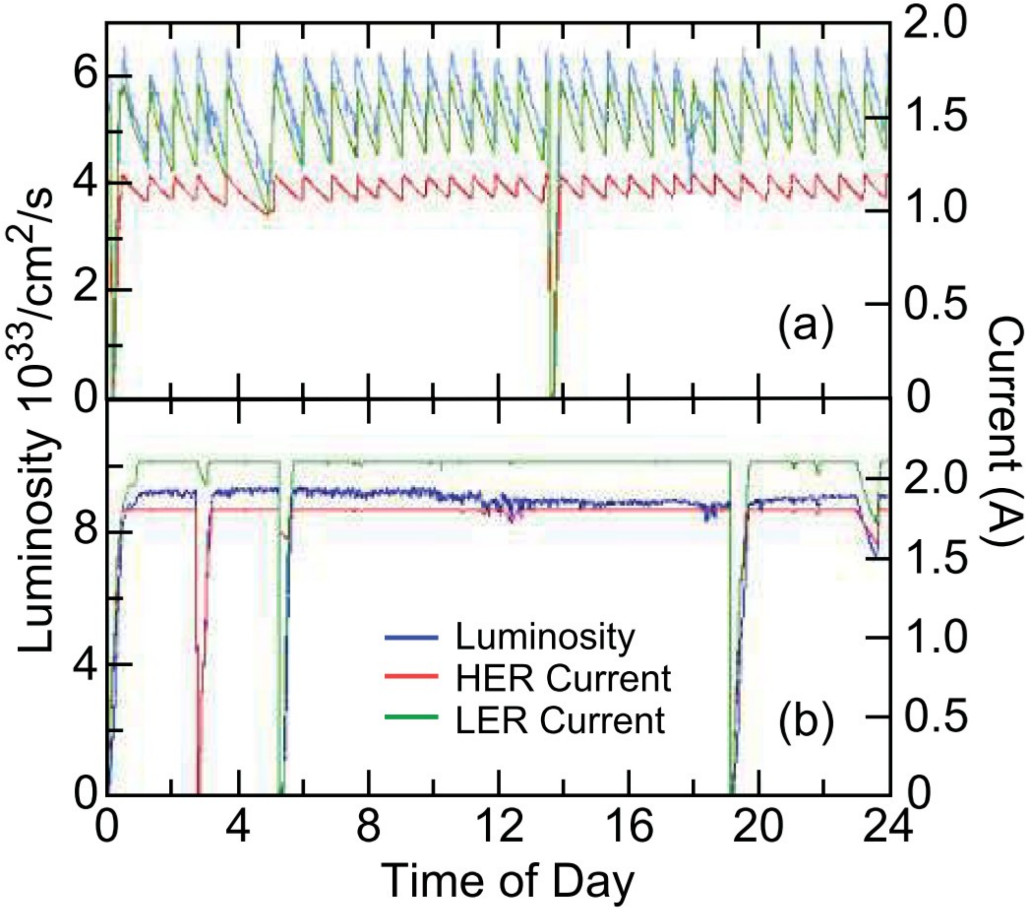




Top-Up Injection

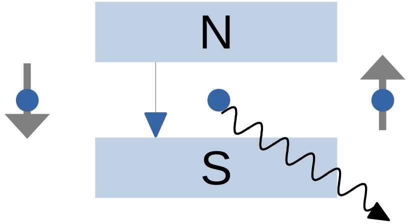
- Used already at other facilities, e.g. SuperKEKB
- **Injection at collision energy** into collider rings
- Continous injection to keep **constant beam current**
- Average luminosity ~ peak luminosity



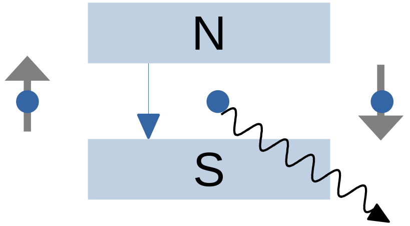


Top-up injection at KEKB (predecessor of SuperKEKB)

Polarization Build-Up



More likely
(by factor ~25)



Less likely

- Statistically every $10^{10\text{th}}$ emitted synchrotron photon flips the spin
- Probability depends on the initial spin orientation

- Leads to a natural **polarization build-up** over time
- Orientation is **anti-parallel** to the guiding magnetic field (e^-)
- In a flat synchrotron only vertical bending → vertical spin orientation
- Known as Sokolov-Ternov-Effekt

- Maximum theoretical polarization of **92.4 %**
- Decreases typically with orbit and optics errors

Spin Tune and Beam Energy

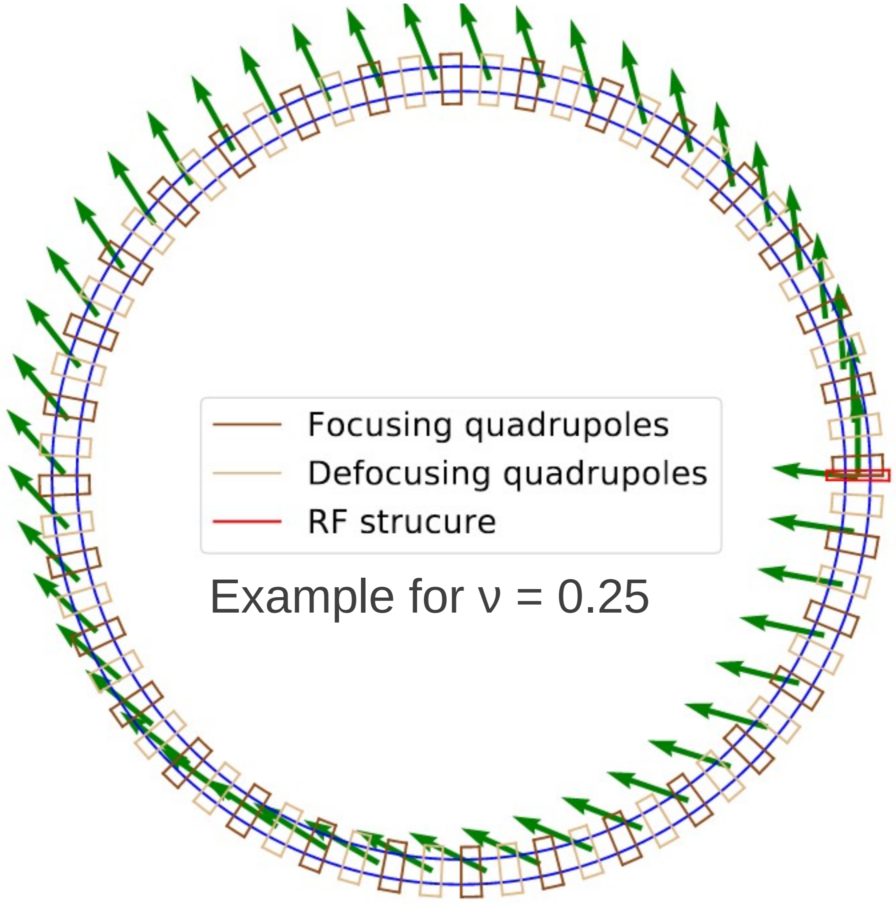
- Spin precesses through the lattice
- Spin tune ν: Number of spin precessions per turn

- In an error-free flat machine without solenoids:
- 45.6 GeV e^+/e^- –> 103.5 spin tune
- Purely vertical spin orientation

a … gyro-magnetic anomaly
γ_{Rel} … Lorentz-factor

$$\boxed{\nu = a * \gamma_{Rel}}$$

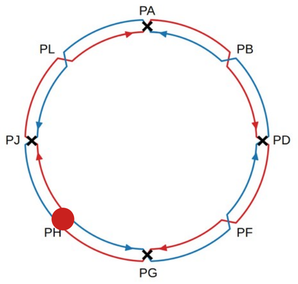
Spin tune measurement ⟺ **Beam energy determination**



Example for ν = 0.25

Courtesy: V. Caudan

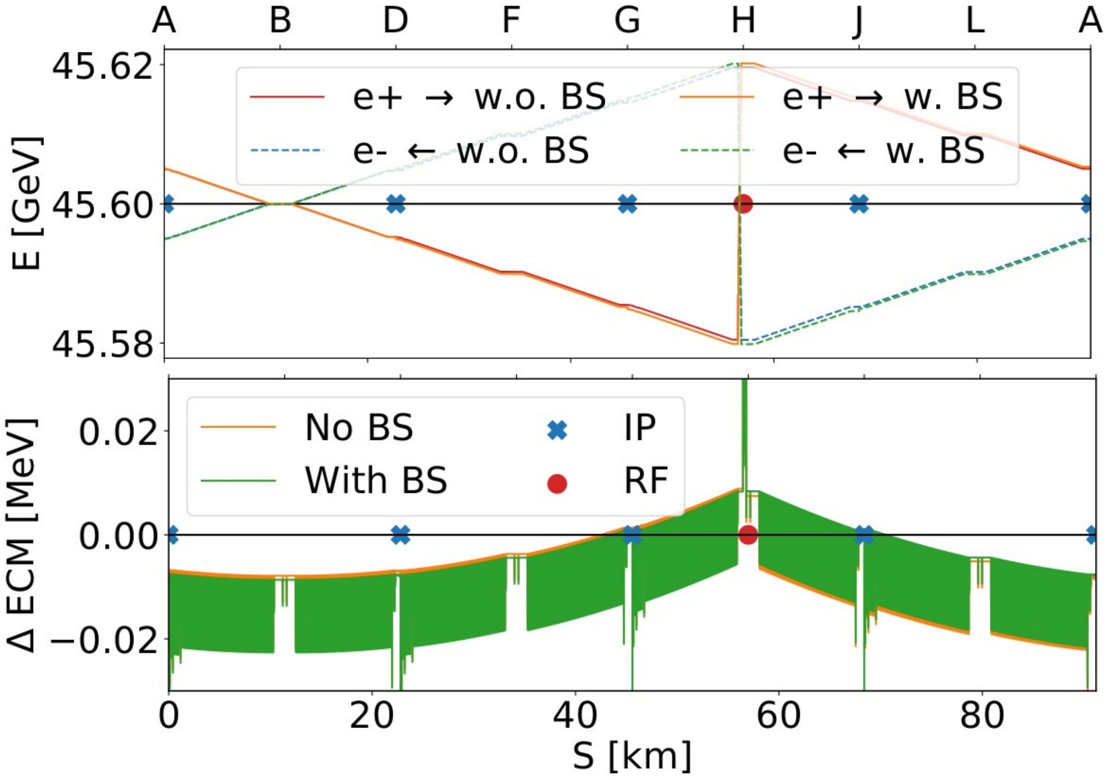
Beam Energy



- At 45.6 GeV beam energy 40 MeV synchrotron radiation losses per turn
- At 182.5 GeV beam energy 10 GeV synchrotron radation losses per turn (~5.5 % of beam energy)
- Additional losses from Beamstrahlung (BS), impedance, …

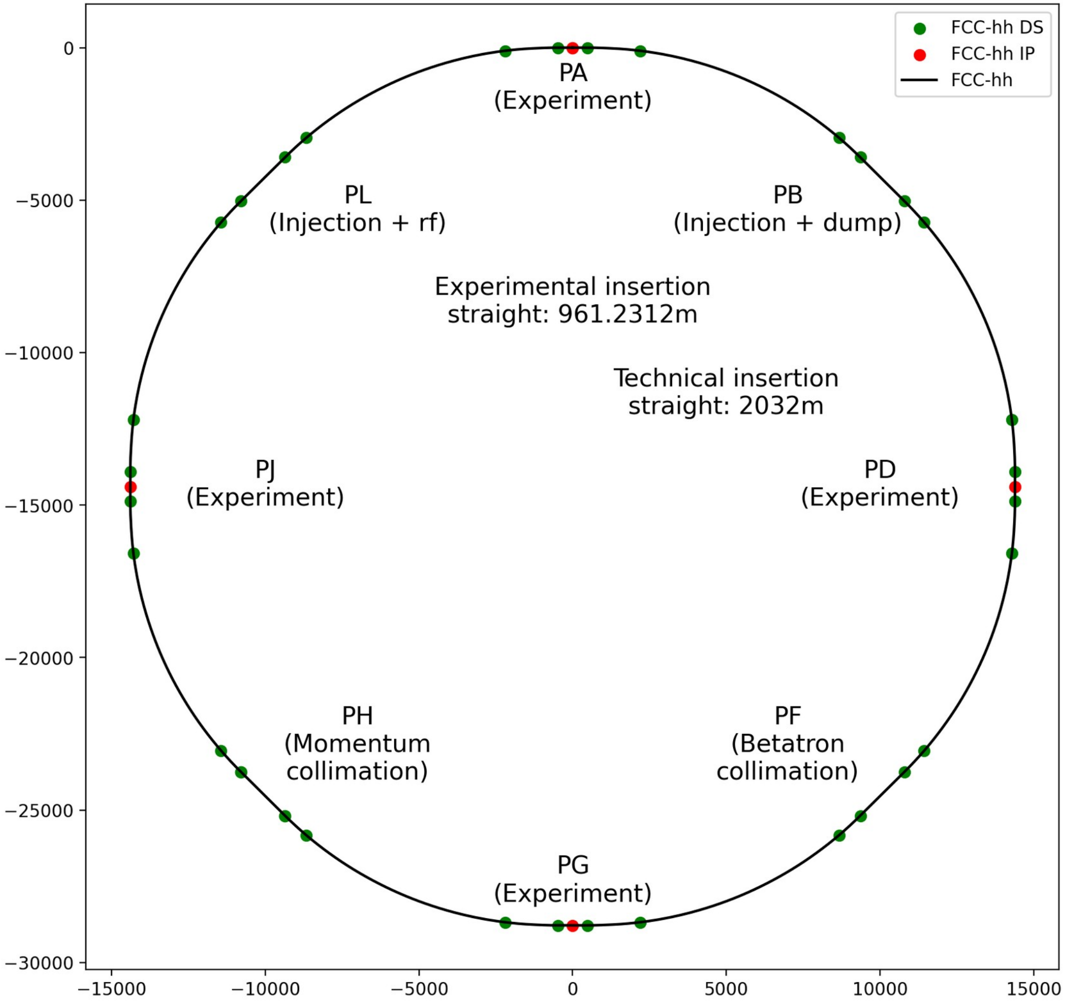
- Large beam energy variation over the circumference
  - **Tapering** for adjusting element strength to local energy

- Center-of-mass energy from measured beam energies
  - Precise models required to link average beam energy to center-of-mass energy



FCC-hh Overview

- PA, PD, PG, PJ: Experimental insertions
- PF, PH: Collimation insertions
- PB: extraction both beams + injection
- PL: RF both beams + injection
- Compatible injector from LHC or SPS tunnel



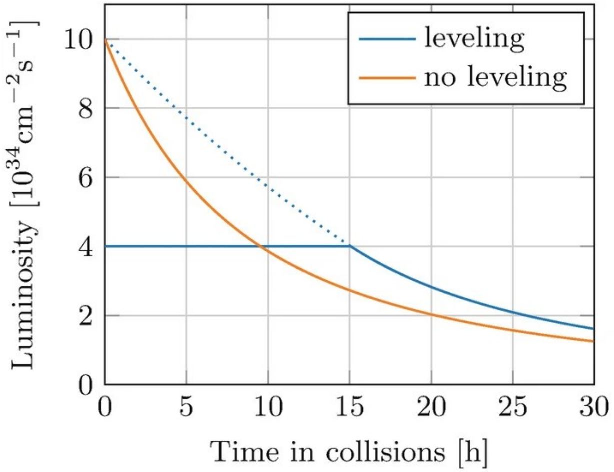
FCC-hh Parameters

	FCC-hh	HL-LHC	LHC
Collision energy [TeV]	81 - 115	14	
Dipole field [T]	14 - 20	8.33	
Circumference [km]	90.7	26.7	
Beam current [A]	0.5	1.1	0.58
Bunch intensity [10^{11}]	1	2.2	1.15
SR power/ring [kW]	1020 - 4250	7.3	3.6
SR power/length [W/m/A]	13-54	0.33	0.17
Events/bunch crossing [#]	~1000	132	27
Stored beam energy [GJ]	6.1 – 8.9	0.7	0.36
Luminosity/IP [10^{34}cm^{-2}s^{-1}]	~30	5*	1
Integrated luminosity/IP/year [ab^{-1}]	20000	3000	300

* with levelling to keep luminosity constant

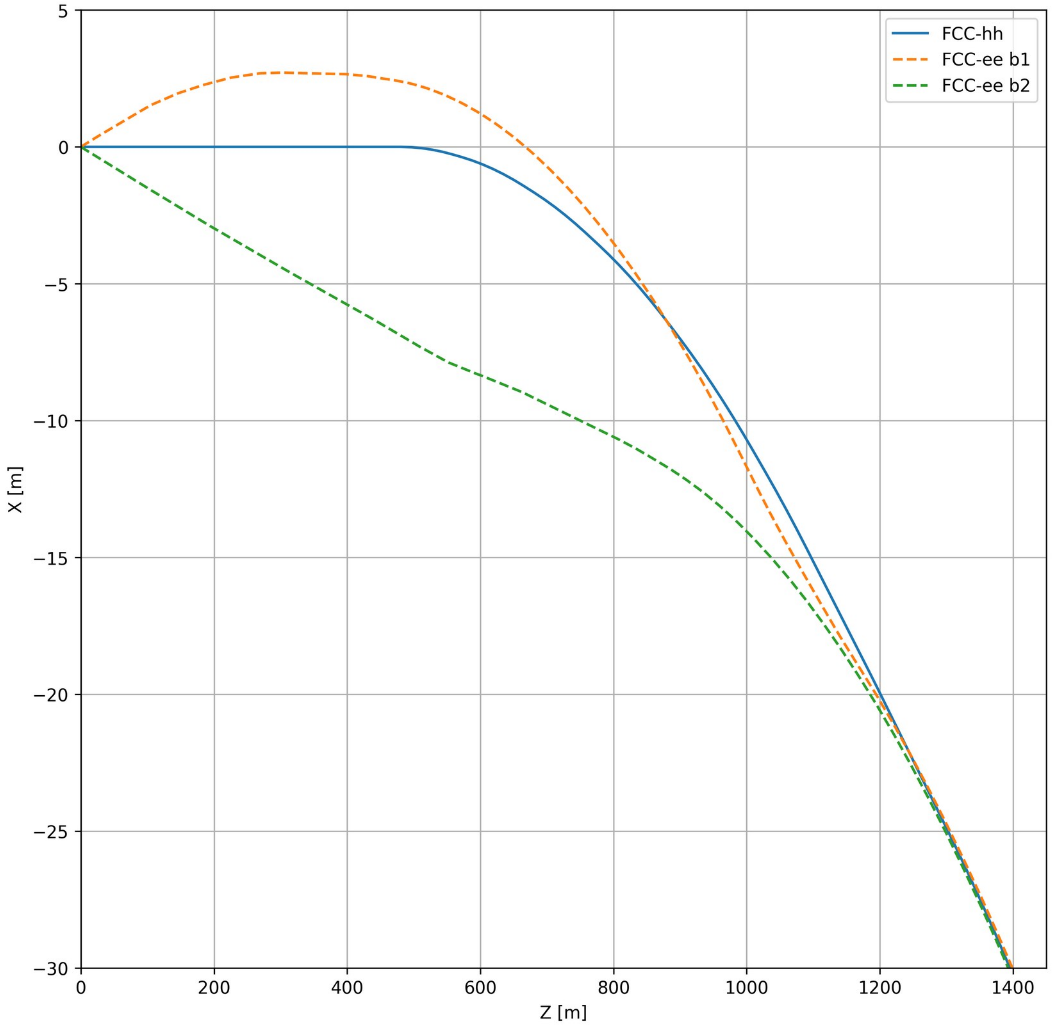
Challenges
- High field superconducting magnets up to 20 T
- Power load from SR (cryo, vacuum, ..)
- Stored beam energy 9 GJ
- Number of events in detectors
- ...

With FCC-hh after FCC-ee significantly more time for high-field magnet R&D

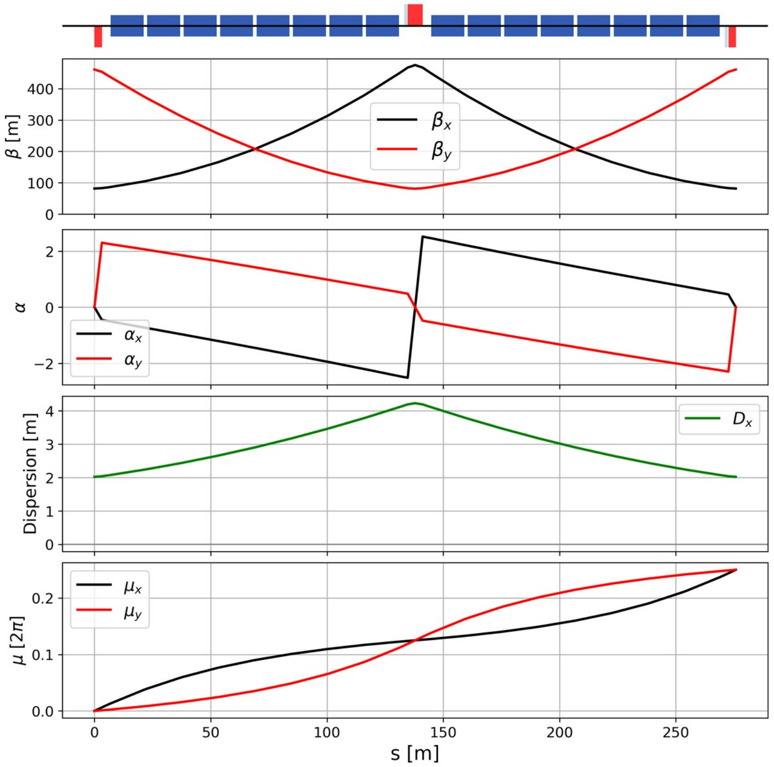


https://doi.org/10.1007/978-3-030-34245-6_9

FCC-hh Layout and Arcs

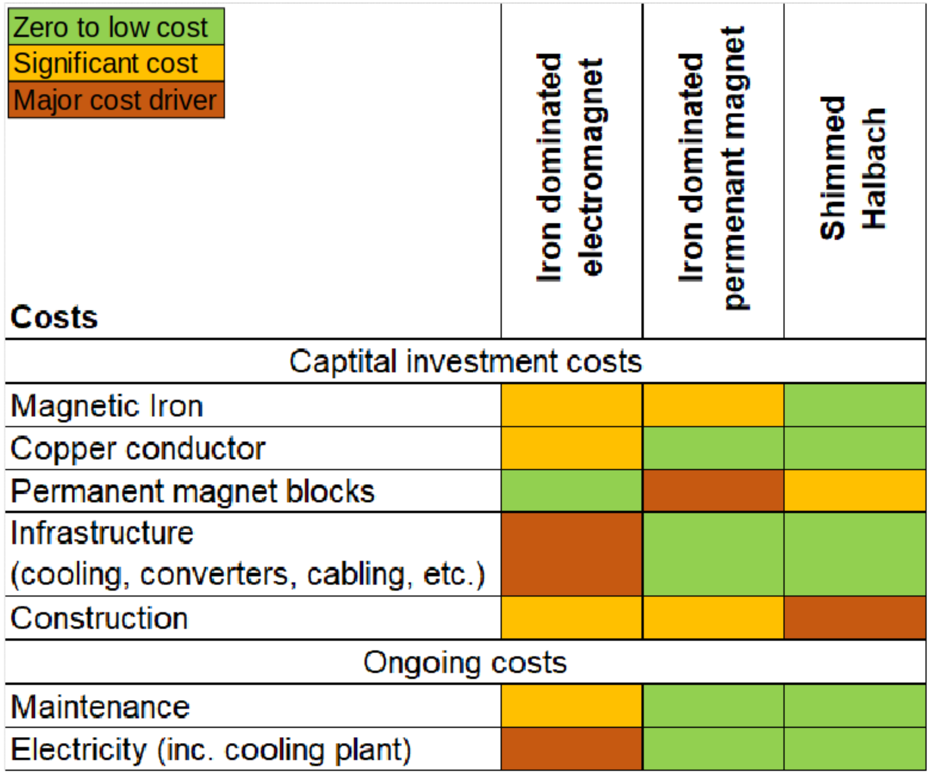


- FCC-hh follows FCC-ee GHC lattice
- New design optimized in all straight sections
- Arcs follow FODO cell design



Permanent Magnets

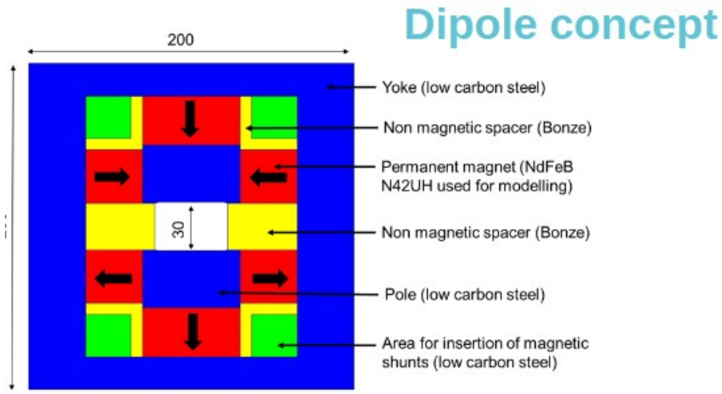
- Permanent magnets highly suitable for transfer line specifications
  - Less stringent field requirements
  - Already used in accelerators, although smaller scale
  - Small temperature dependence
  - Could be more cost effective



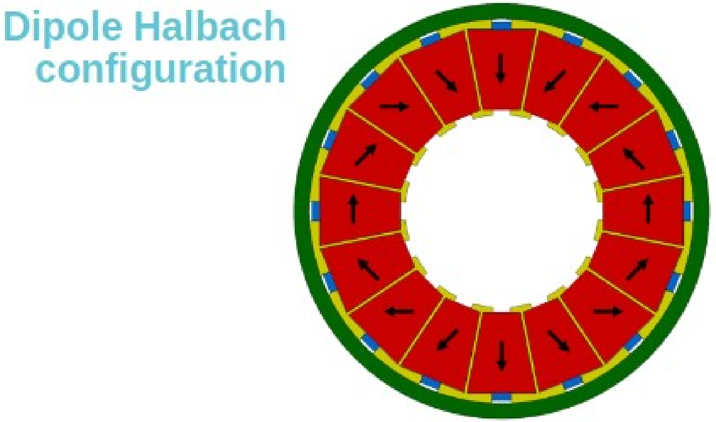
🟩	Zero to low cost
🟨	Significant cost
🟧	Major cost driver

Costs	**Iron dominated electromagnet**	**Iron dominated permenant magnet**	**Shimmed Halbach**
Captital investment costs			
Magnetic Iron	🟨	🟨	🟩
Copper conductor	🟨	🟩	🟩
Permanent magnet blocks	🟩	🟧	🟨
Infrastructure (cooling, converters, cabling, etc.)	🟧	🟩	🟩
Construction	🟨	🟨	🟧
Ongoing costs			
Maintenance	🟨	🟩	🟩
Electricity (inc. cooling plant)	🟧	🟩	🟩

Iron dominated concept



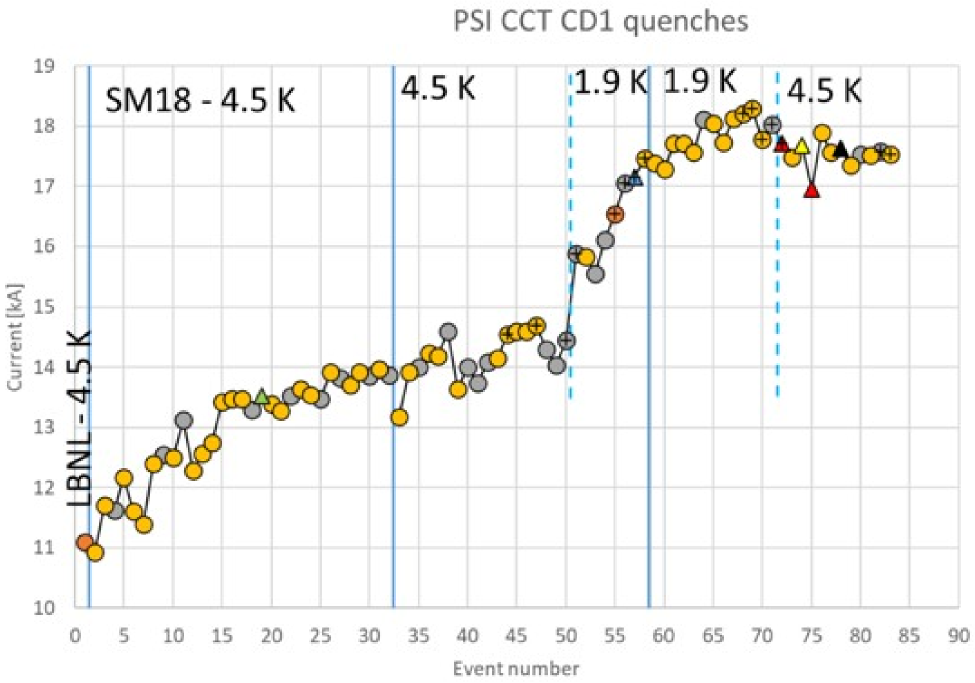
Shimmed Halbach Concept



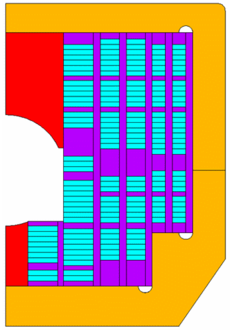
Courtesy: B. Auchmann

High Field Magnets: Nb_3Sn

- PSI Nb_3Sn main test carried out in 2022/2023
- Training via quenches (loss of superconductivity)
  - Controlled quenches help to achieve full field
- 100 % of maximum field achieved at 4.5 K
- Goal: demonstrate robust and cost efficient Nb_3Sn technology for next ESPPU



B_0 target of 14 T, at T_{op}: 4.2 K
Eng margin of 10%
B_0 short sample @ 1.9 K: 16 T

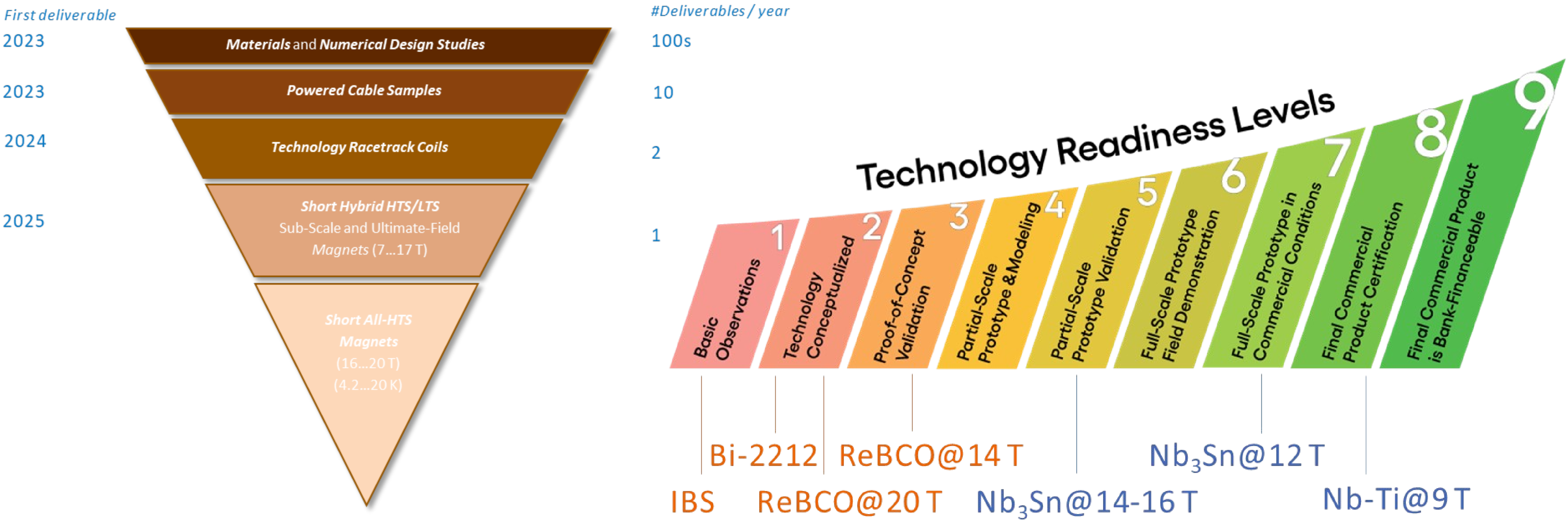


Stainless steel shell
Iron yoke
Coil collar
Former
Non-magnetic poles
Nb_3Sn conductor

Courtesy: B. Auchmann

High Field Magnets: HTS

- **Bottom line:** HTS technology must catch up over the coming 10 years



First deliverable		*#Deliverables / year*
2023	***Materials* and *Numerical Design Studies***	100s
2023	***Powered Cable Samples***	10
2024	***Technology Racetrack Coils***	2
2025	***Short Hybrid HTS/LTS*** Sub-Scale and Ultimate-Field *Magnets* (7…17 T)	1
	Short All-HTS Magnets (16…20 T) (4.2…20 K)	

Technology Readiness Levels

1. Basic Observations
2. Technology Conceptualized
3. Proof-of-Concept Validation
4. Partial-Scale Prototype &Modeling
5. Partial-Scale Prototype Validation
6. Full-Scale Prototype Field Demonstration
7. Full-Scale Prototype in Commercial Conditions
8. Final Commercial Product Certification
9. Final Commercial Product is Bank-Financeable

IBS

Bi-2212

ReBCO@20 T

ReBCO@14 T

Nb_3Sn@14-16 T

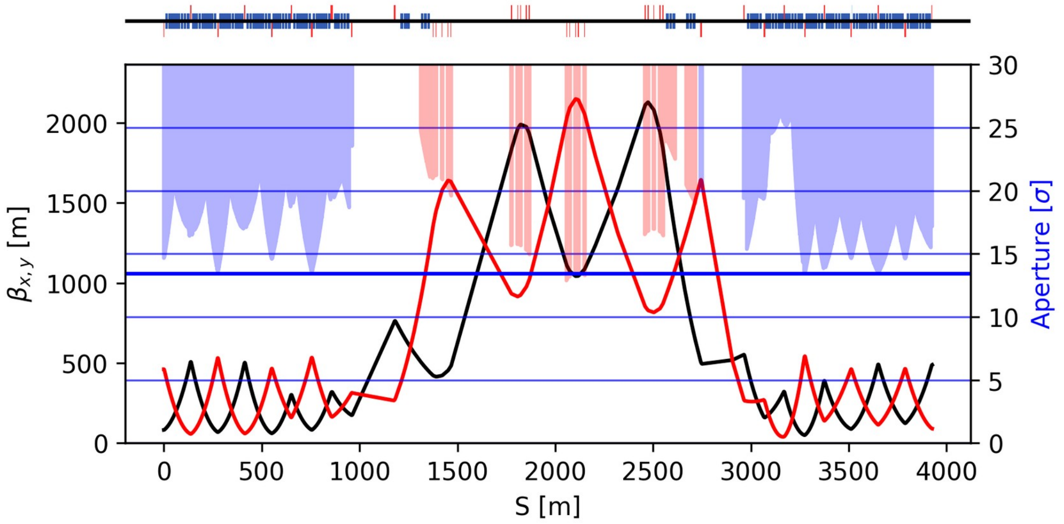
Nb_3Sn@12 T

Nb-Ti@9 T

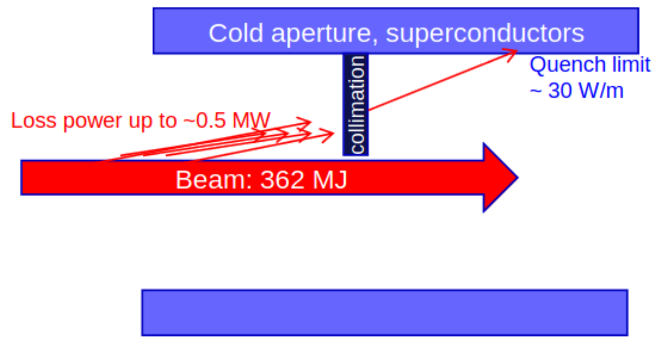
Courtesy: A. Abramov, R. Bruce, M. Giovannozzi

Collimation

- LHC: **362 MJ** and FCC: **8.3 GJ** stored beam energy
- Loss of even very small fraction of the beam could cause
  - Damage to impacted elements
  - Heating of superconducting magnets and quench
- Collimator robustness to be addressed



LHC



Cold aperture, superconductors

collimation

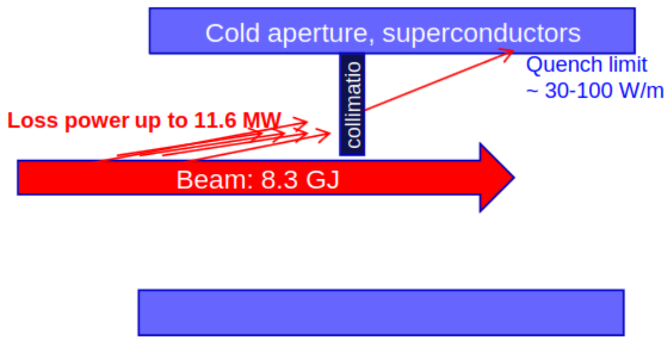
Quench limit
~ 30 W/m

Loss power up to ~0.5 MW

Beam: 362 MJ

Needed loss attenuation: factor ~2×10^4

FCC-hh



Cold aperture, superconductors

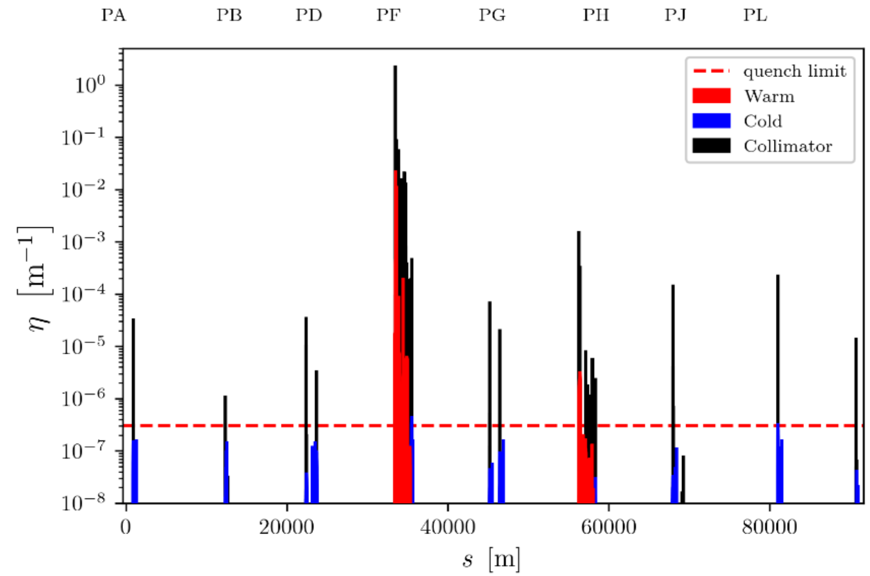
collimatio

Quench limit
~ 30-100 W/m

Loss power up to 11.6 MW

Beam: 8.3 GJ

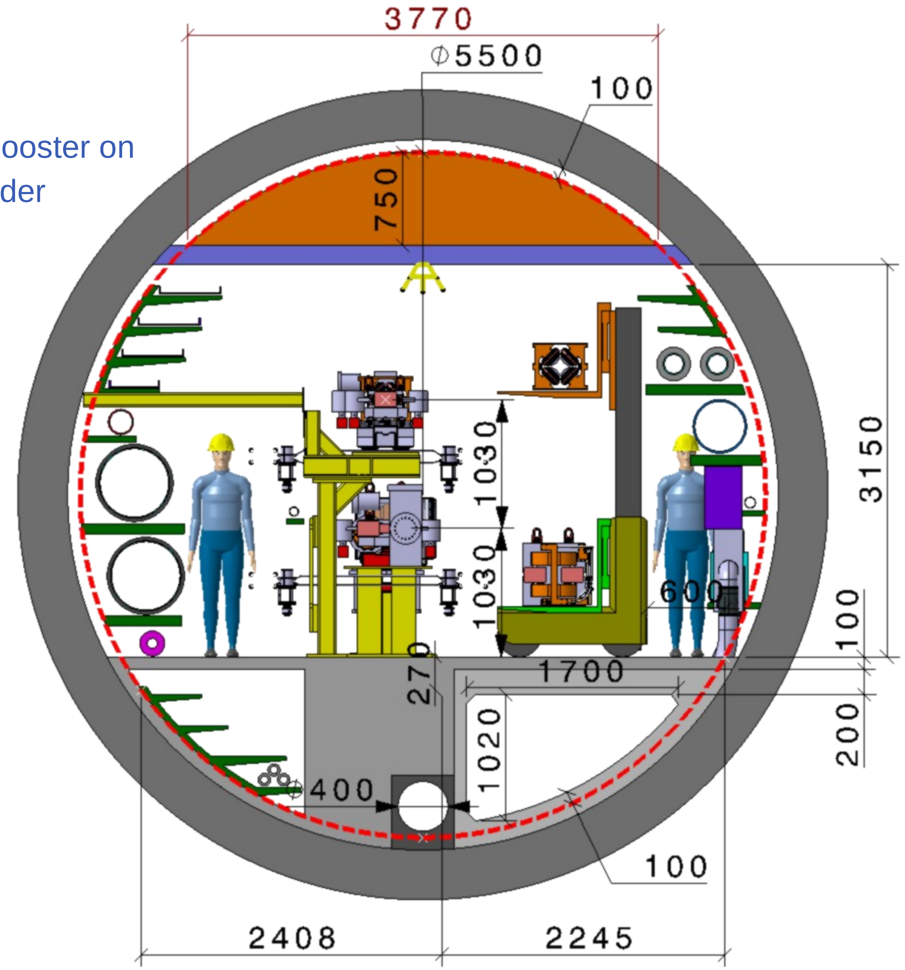
Needed loss attenuation: factor >10^5
Higher energy ➔ smaller collimator gaps



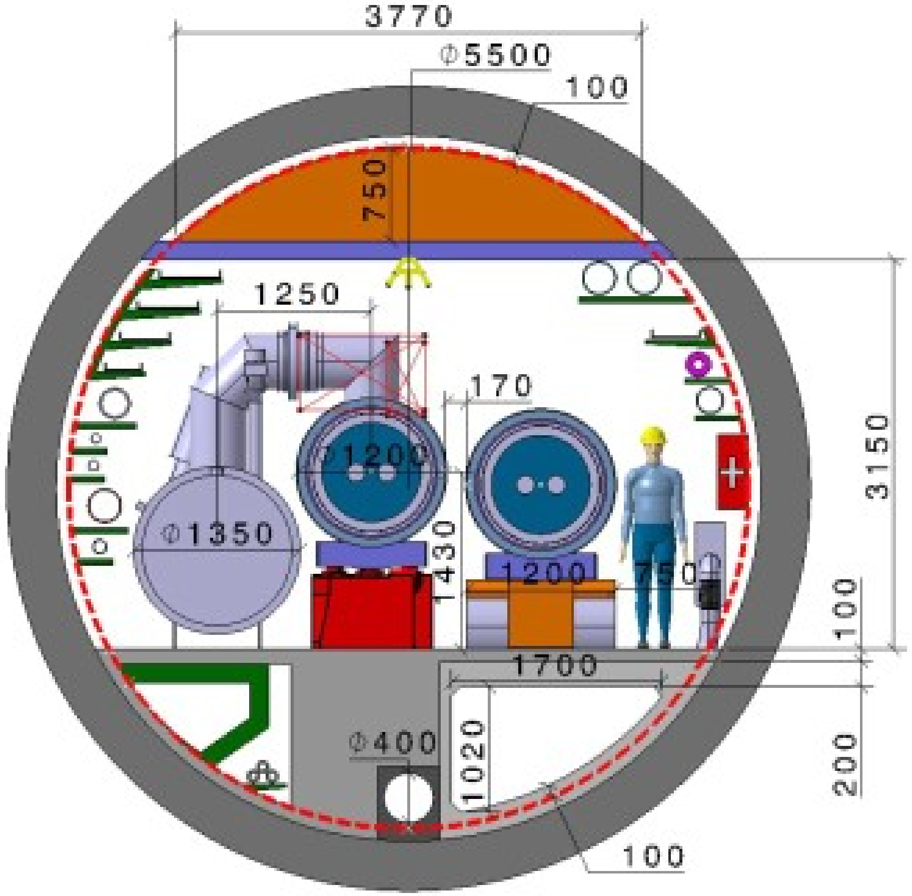
Tunnel Integration

FCC-ee

High energy booster on top of the collider

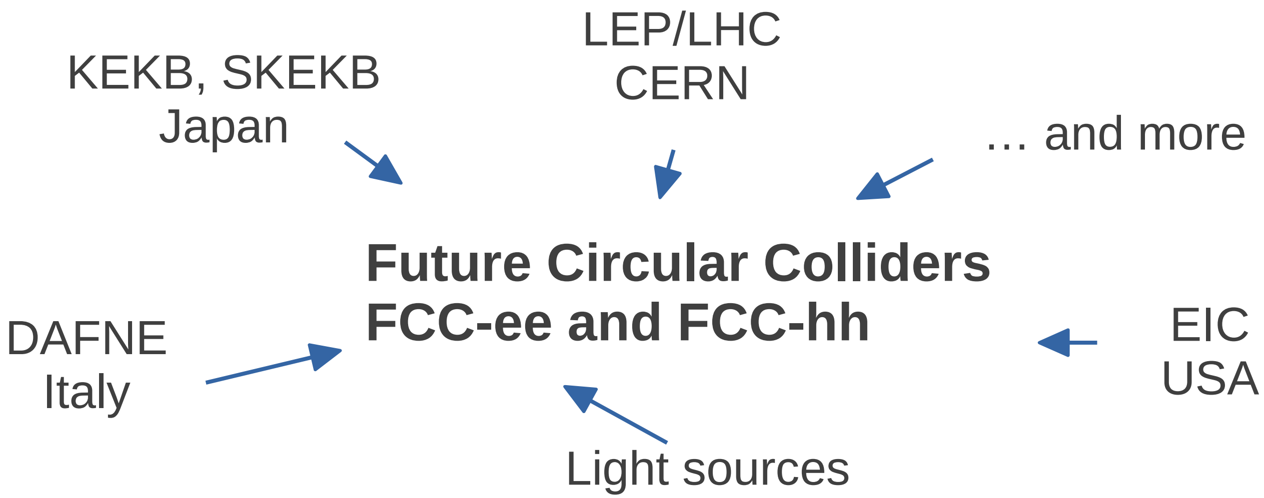


FCC-hh



Summary and Outlook

- Experice of **more than 60 years** circular colliders and lightsources
- Many interesting questions and challenges for accelerator and particle physics still to be solved
- **Higgs and electroweak factory** highest priority **next collider** after completion of HL-LHC
- **Proton-proton collider** with a center-of-mass energy of **100 TeV long term goal** of this century



KEKB, SKEKB
Japan

LEP/LHC
CERN

… and more

Future Circular Colliders
FCC-ee and FCC-hh

DAFNE
Italy

EIC
USA

Light sources

Let’s make the FCC OUR Future !

Thank you!

Future Circular Colliders

Jacqueline Keintzel

Acknowledgements: The FCC collaboration

Special Thanks to:

M. Benedikt, M. Giovannozzi, C. Grojean, J. Gutleber, P. Janot, F. Zimmermann

CERN Accelerator School

Ferney Voltaire, France

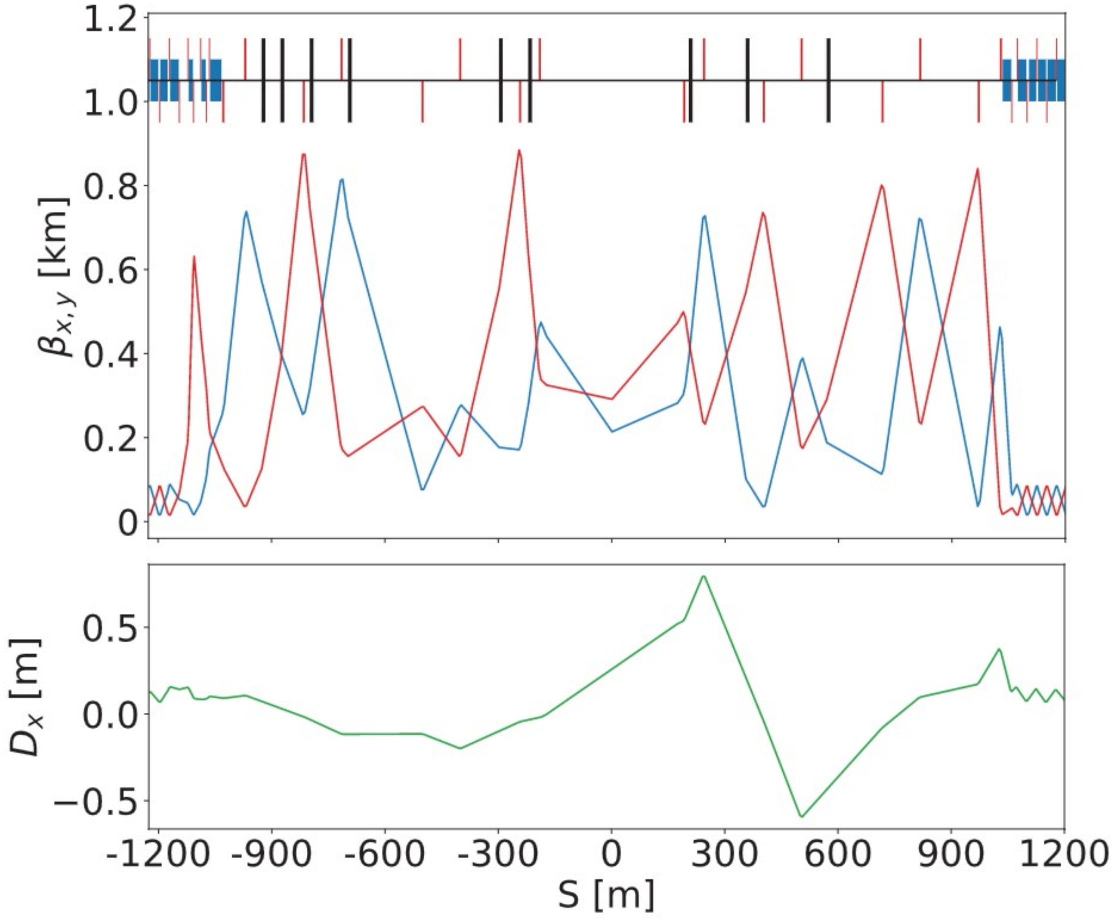
15 March 2024

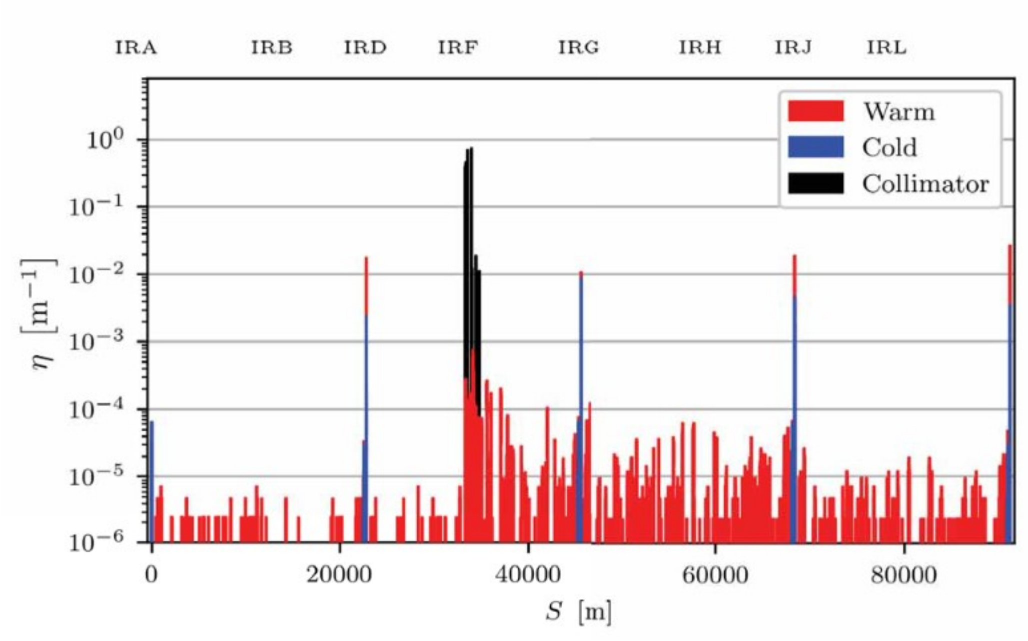
jacqueline.keintzel@cern.ch

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.

Collimation FCC-ee

- Stored beam in FCC-ee reaches up to **20.7 MJ** → comparable to heavy ions in the LHC
- Combined collimation insertion for
  - Betatron collimation (upstream)
  - Off-momentum collimation (downstream)





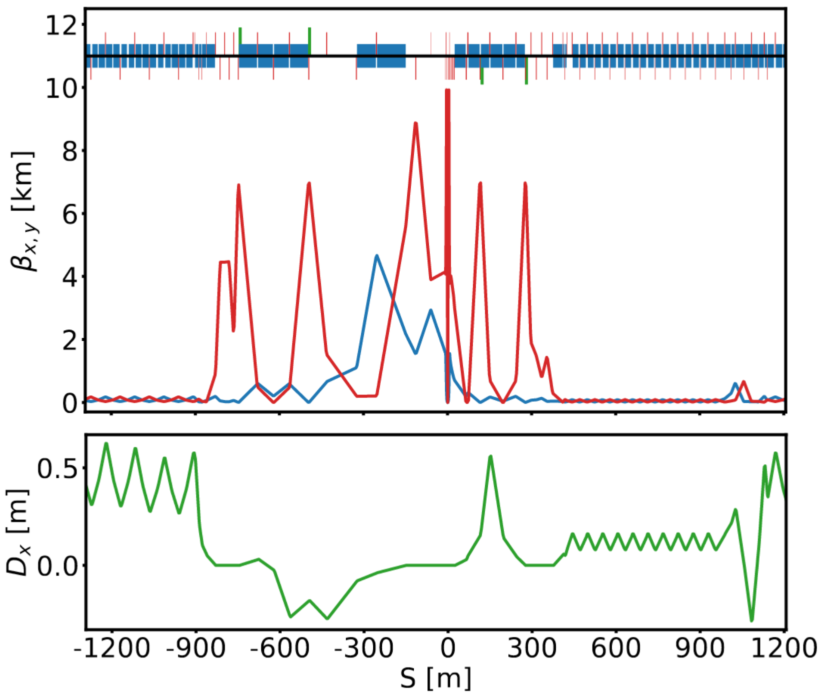
Loss studies at 182.5 GeV; Courtesy: A. Abramov

Experimental IR – FCC-ee

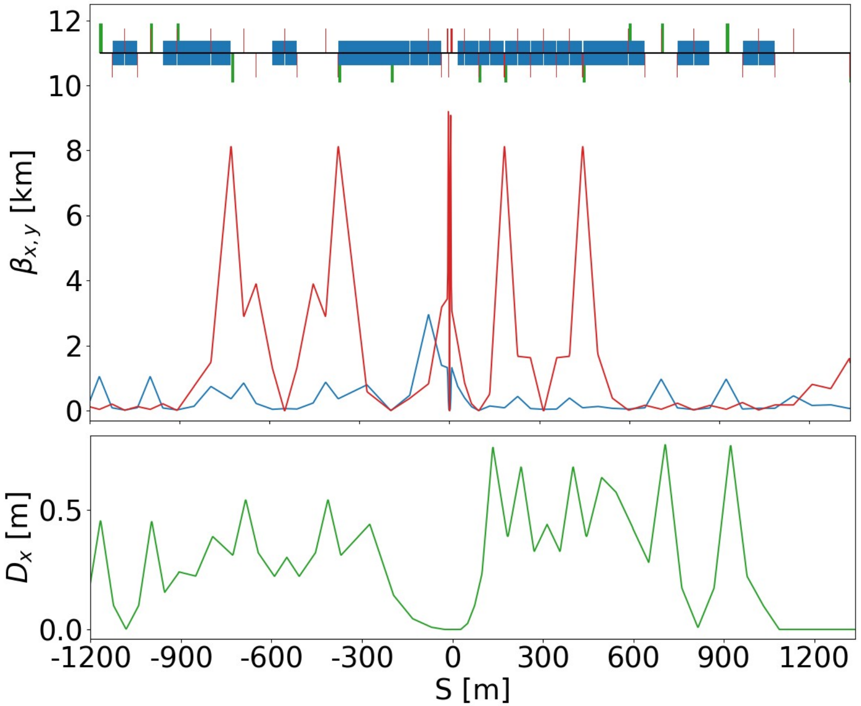
- Local vertical chromaticity correction
- Global horizontal chromaticity correction
- Virtual crab-waist scheme

- Local vertical chromaticity correction
- Local horizontal chromaticity correction
- Dedicated crab-waist sextupoles

GHC



LCC

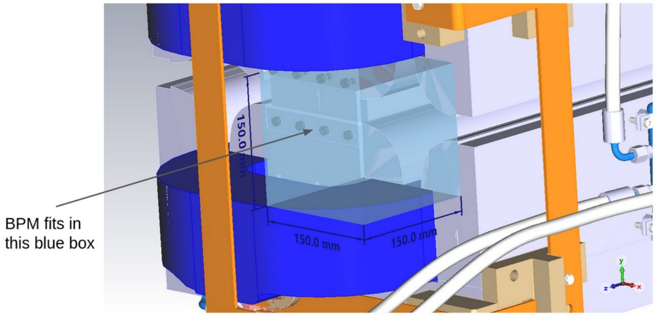


Optics Measurements

Beam Position Monitors

Used for optics measurements

Placement and number currently being studied

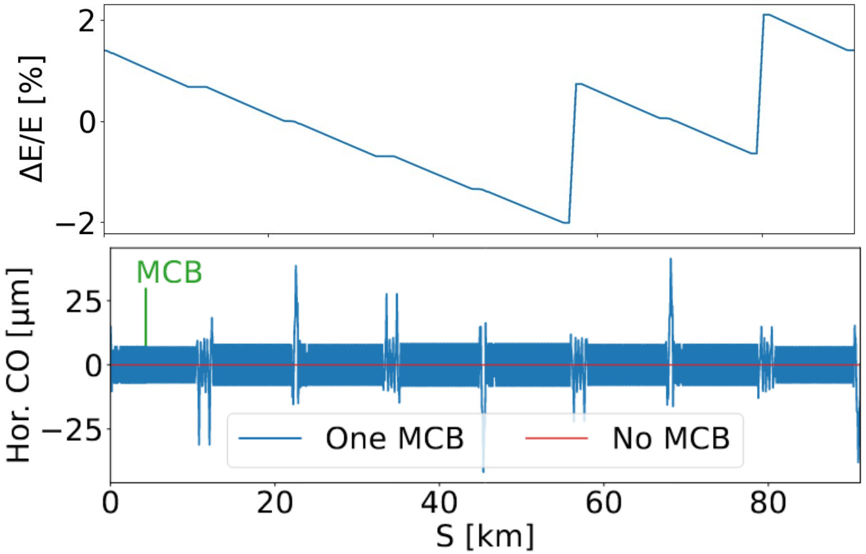


Courtesy: M. Wendt

Record orbit over several turns

Used for orbit measurements

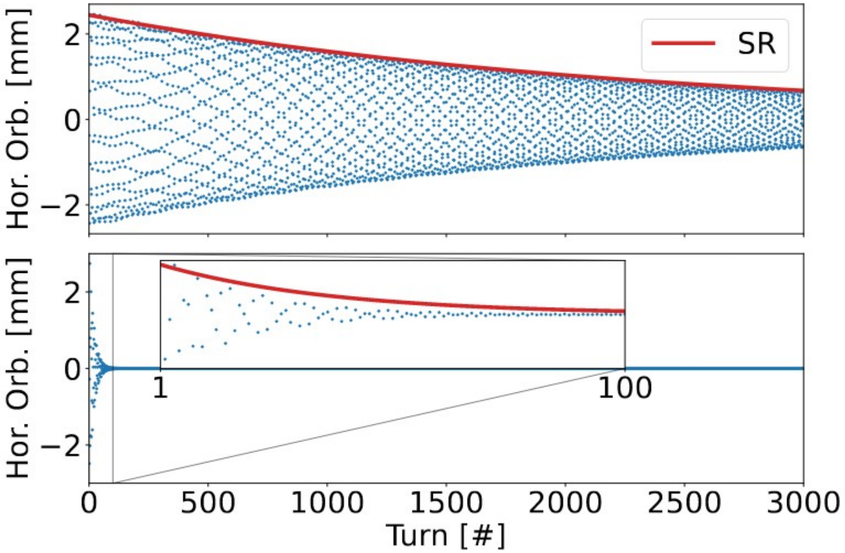
Orbit response matrix measurements



Turn-by-turn measurements

And bunch-by-bunch measurements

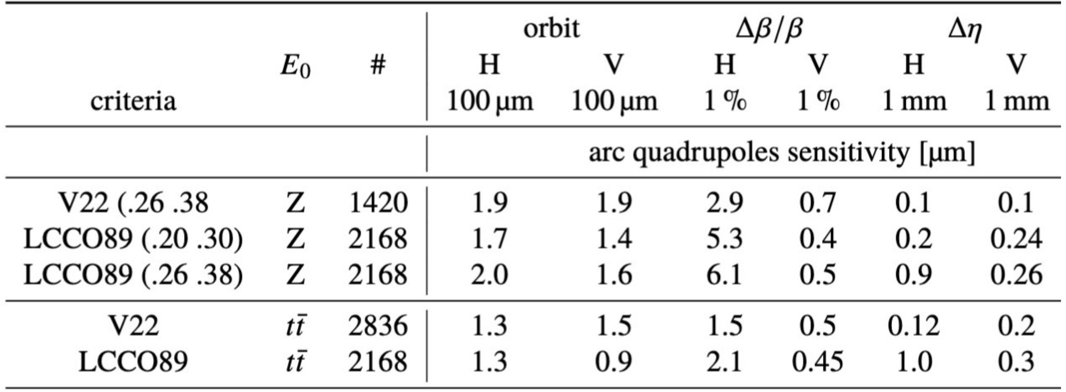
Measurement of frequency spectrum



Lattice Comparisons – FCC-ee

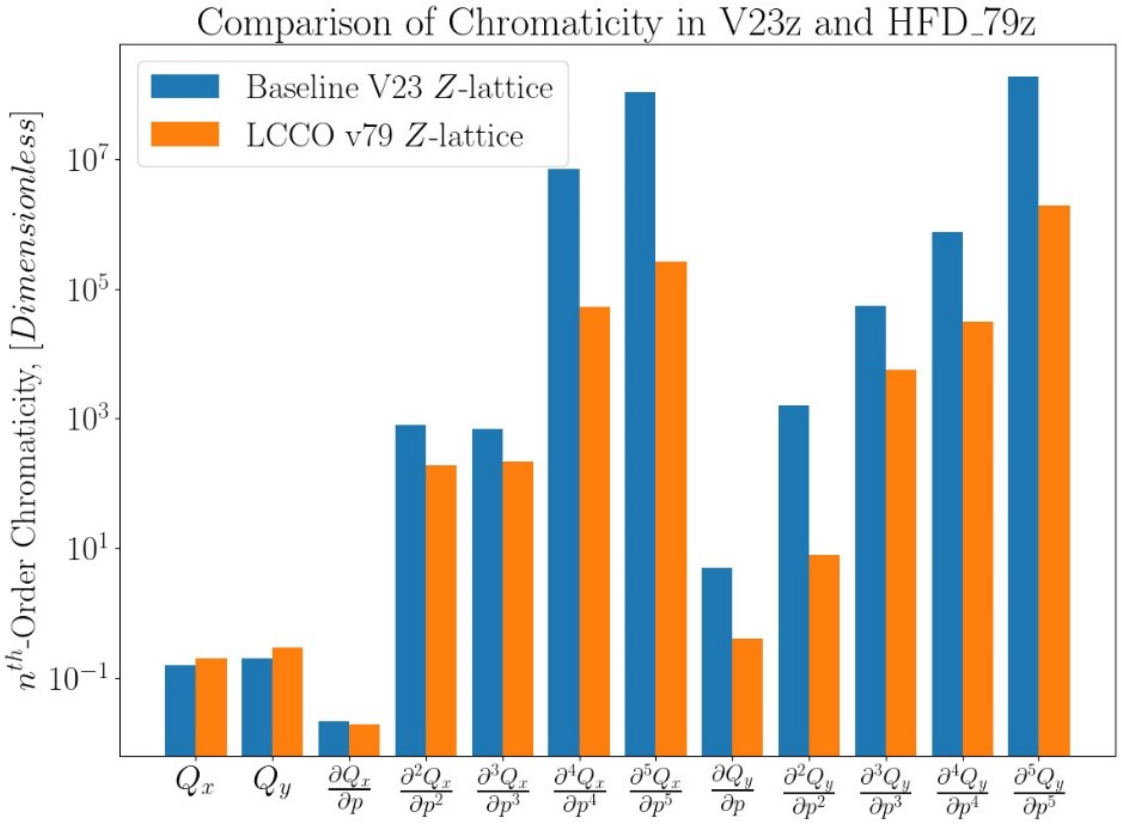
- Great effort to compare lattice optics
  - Error sensitivity
  - Magnet number and strengths
  - Generated higher-order optics abberations
  - ...

Magnitude of misalignment which generate a certain orbit, beta-function, or dispersion error



			orbit		$\Delta\beta/\beta$		$\Delta\eta$	
	E_0	#	H	V	H	V	H	V
criteria			100 µm	100 µm	1 %	1 %	1 mm	1 mm
			arc quadrupoles sensitivity [µm]					
V22 (.26 .38	Z	1420	1.9	1.9	2.9	0.7	0.1	0.1
LCCO89 (.20 .30)	Z	2168	1.7	1.4	5.3	0.4	0.2	0.24
LCCO89 (.26 .38)	Z	2168	2.0	1.6	6.1	0.5	0.9	0.26
V22	$t\bar{t}$	2836	1.3	1.5	1.5	0.5	0.12	0.2
LCCO89	$t\bar{t}$	2168	1.3	0.9	2.1	0.45	1.0	0.3

Courtesy: S. Liuzzo

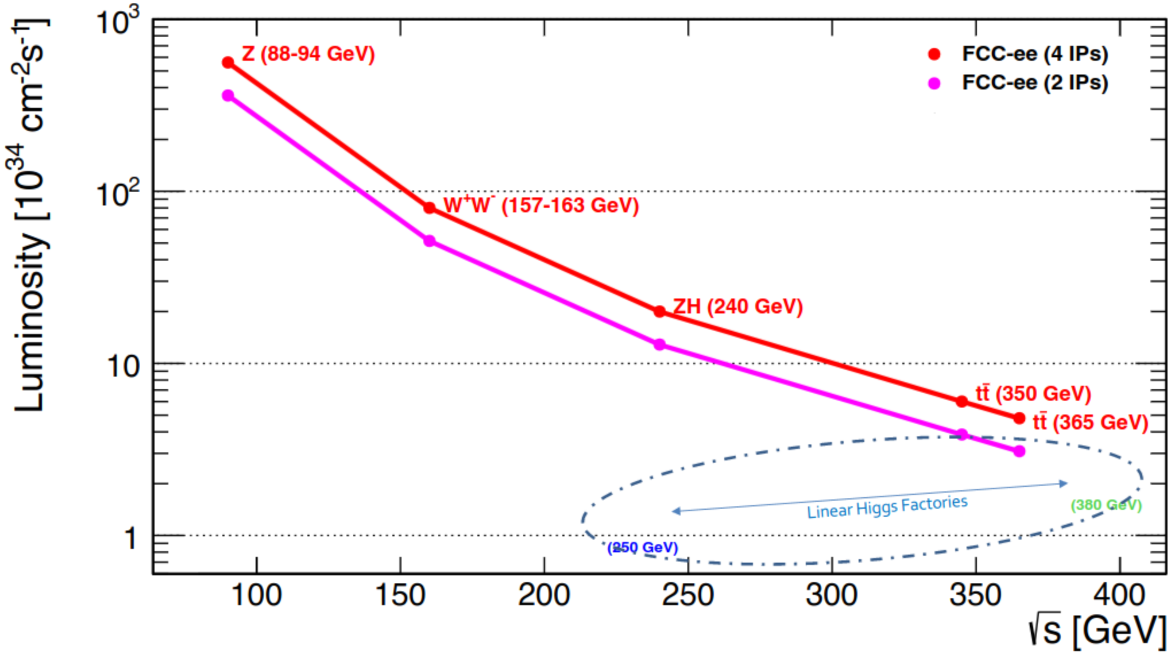


Courtesy: P. Hunchak

FCC-ee Run Plan

- In principle 4 different energy stages
  - Z-pole
  - W-pair-production
  - ZH-production
  - top-pair threshhold

Courtesy: C. Grojean

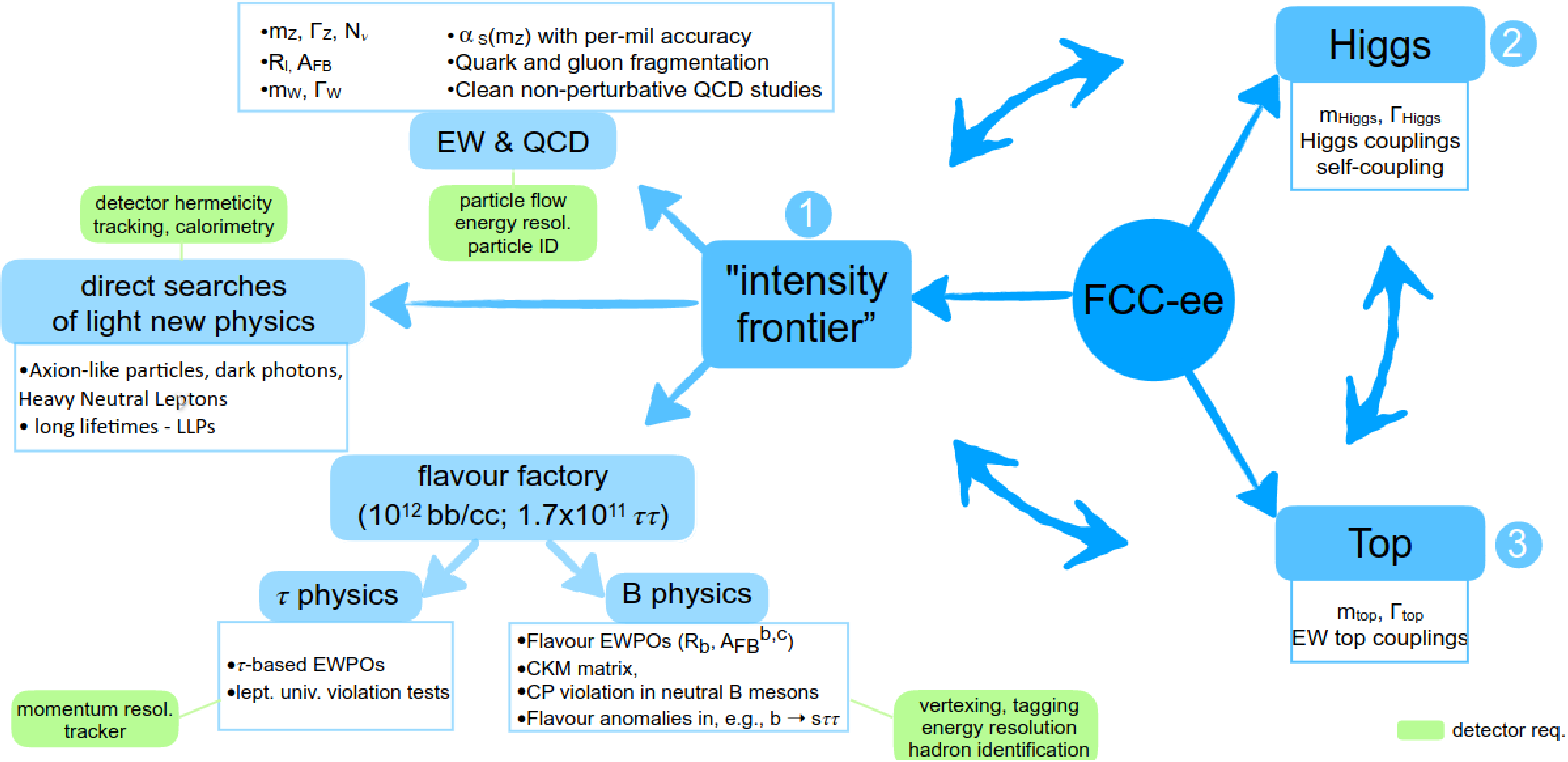


Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\ \mathrm{cm^{-2}s^{-1}}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year ($\mathrm{ab^{-1}}$)	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW → H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW → H	

Number of events are for the current baseline with 4 Interaction Points

Courtesy: C. Grojean

FCC-ee Physics Programme



•m_Z, Γ_Z, N_ν
•R_l, A_{FB}
•m_W, Γ_W

• $\alpha_S(m_Z)$ with per-mil accuracy
•Quark and gluon fragmentation
•Clean non-perturbative QCD studies

EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

direct searches
of light new physics

•Axion-like particles, dark photons,
Heavy Neutral Leptons
• long lifetimes - LLPs

"intensity
frontier"

1

FCC-ee

Higgs

2

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

flavour factory
(10^{12} bb/cc; 1.7x10^{11} $\tau\tau$)

τ physics

•τ-based EWPOs
•lept. univ. violation tests

momentum resol.
tracker

B physics

•Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
•CKM matrix,
•CP violation in neutral B mesons
•Flavour anomalies in, e.g., $b \to s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

Top

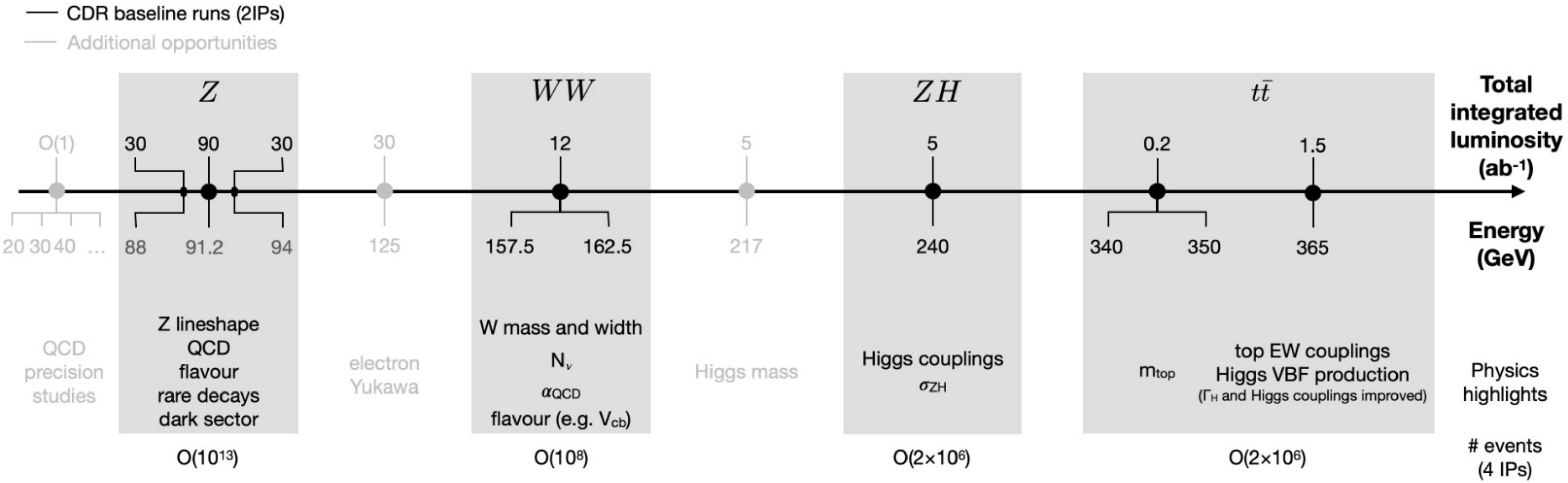
3

m_{top}, Γ_{top}
EW top couplings

🟩 detector req.

Courtesy: C. Grojean

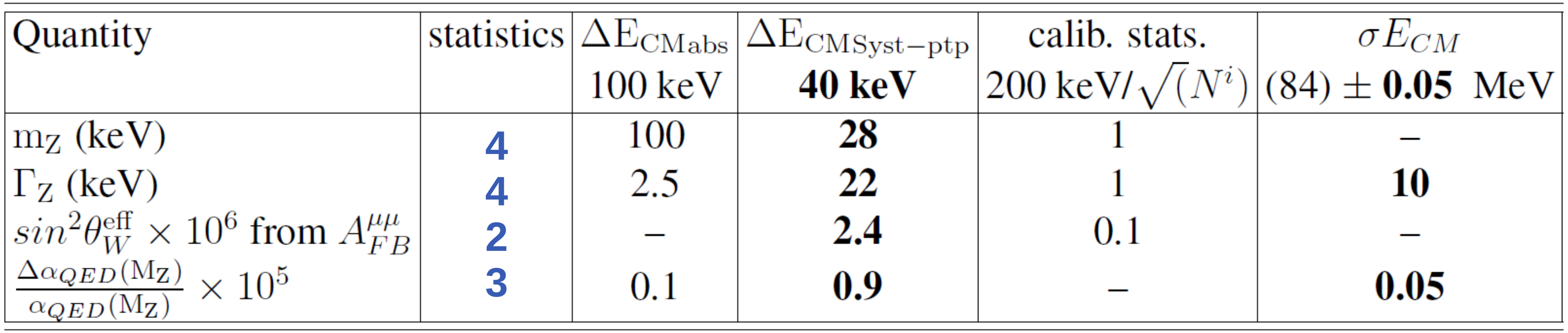
Beyond the Collider Programme



- Many opportunities beyond the baseline plan
- Complementary experiments using e.g. beam dump, re-using synchrotron radiation photons

Expected Precision

Z



Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) ± **0.05** MeV
m_Z (keV)	**4**	100	**28**	1	–
Γ_Z (keV)	**4**	2.5	**22**	1	**10**
$sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	**2**	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	**3**	0.1	**0.9**	–	**0.05**

Large expected luminosity → huge statistics → small statistical error: **4 keV per Z, ~250 keV per W**

Aim to achieve same order of magnitude for systematic errors → Scope of the **EPOL working group**

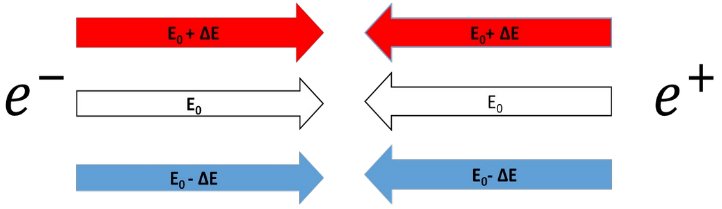
EPOL: Energy calibration, polarization and monochromatization

arXiv:1909.12245

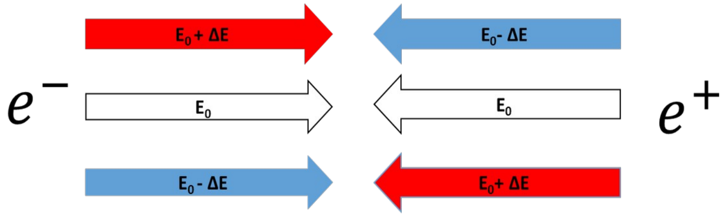
Monochromatization

- 62.5 GeV beam energy → peak of Higgs-production
- For minimization of collision energy spread –> monochromatization
- Trade-off between collision energy spread and luminosity production

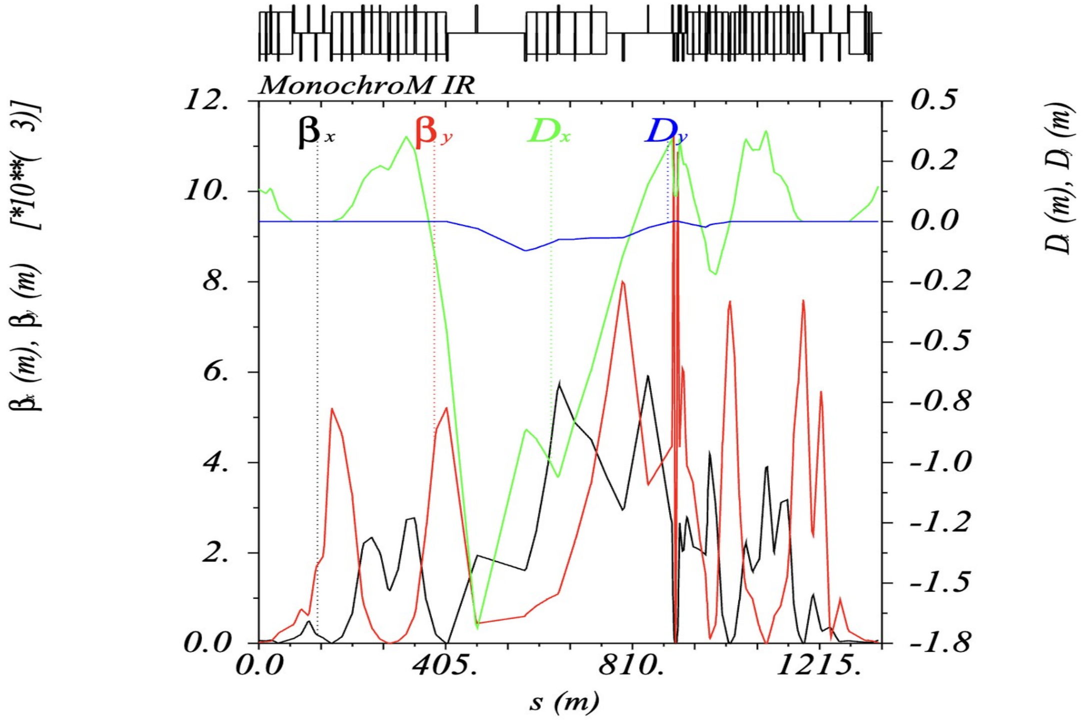
Introducing dispersion



Same sign dispersion at the interaction point leads to change of E_{CM}



Opposite sign (horizontal) dispersion helps reducing E_{CM} spread



4 MeV spread ↔ 18 x 10^{34} $cm^{-2}s^{-1}$, possible optimization