Challenges and R&D Opportunities for the Future e+e- Circular Collider

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On behalf of the FCC collaboration and the FCCIS design study team

EURO-LABS Annual Meeting

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28 October 2024

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.

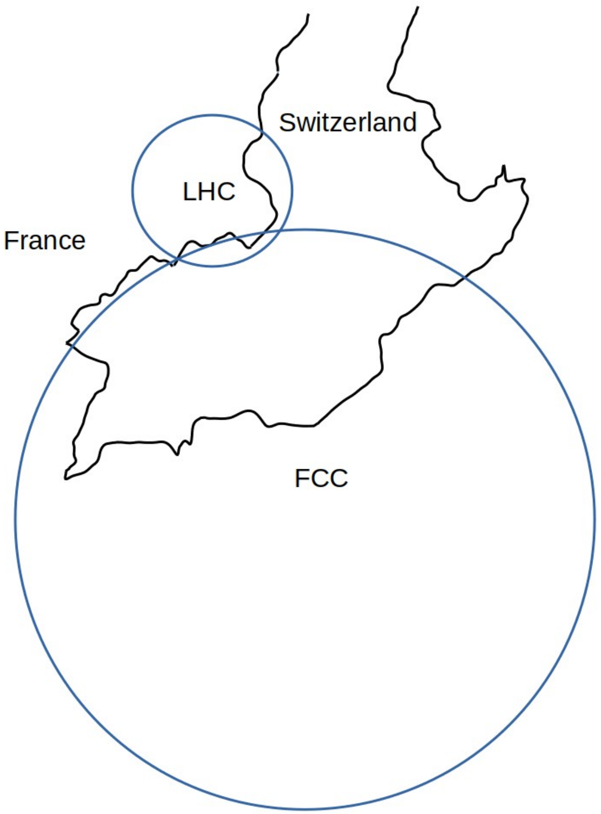
Particle Physics Future

- 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
  - Off-shore **Higgs and electroweak factory**

Future Circular Collider

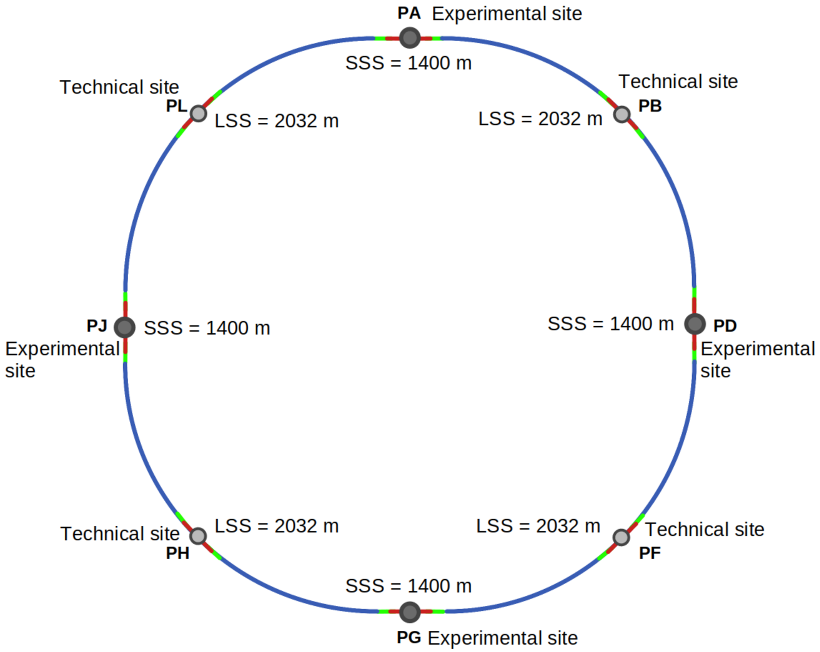
Inspired by LEP-LHC programm

Re-using CERN infrastructure



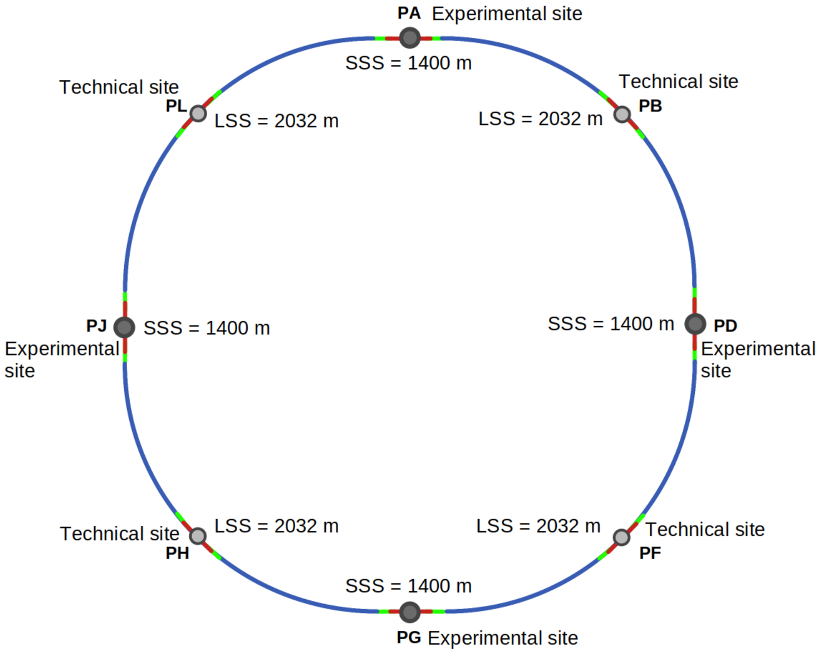
Compatible lattice designs

FCC-ee
Electron-positron collider



~ 2045 - 2060

FCC-hh
Proton-proton collider



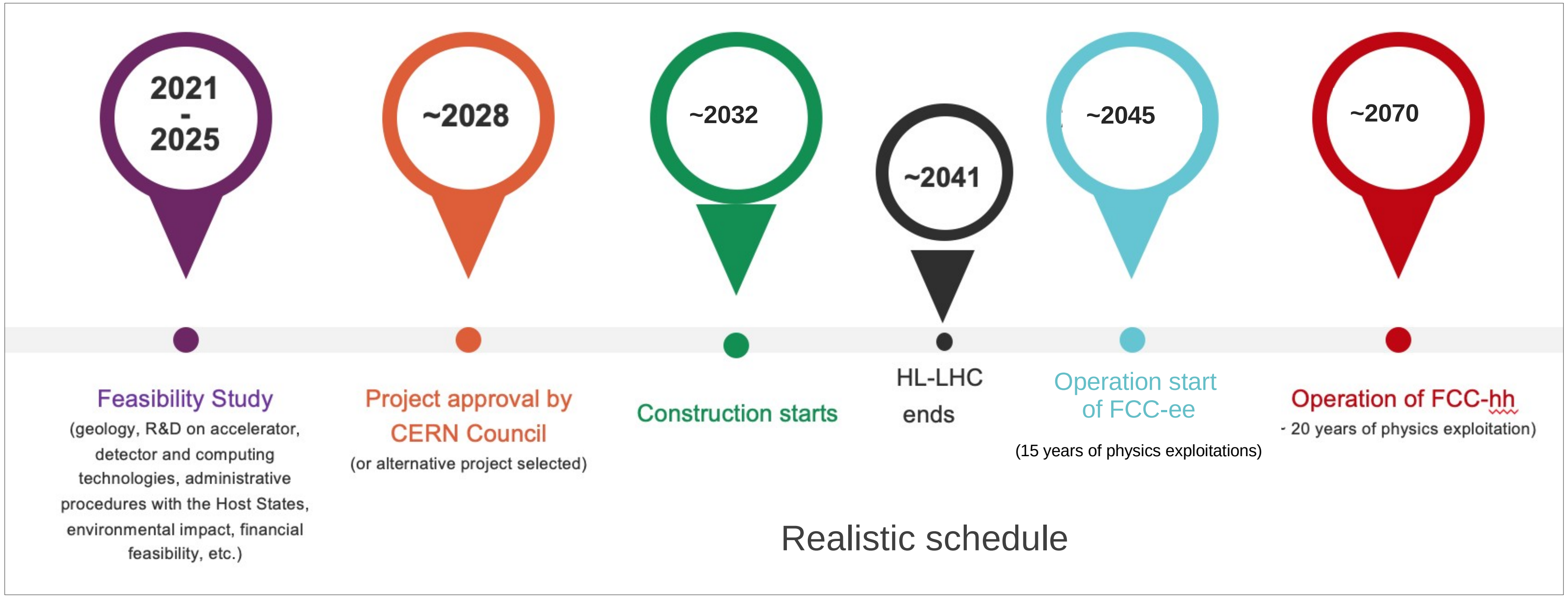
~ 2070 - 2090

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

Feasibility Study and Schedule

- **Goal:** Demonstration of the geological, technical, environmental, financial and administrative feasibility of the FCC-ee, including its optimisation
- Project preparatory phase with adequate resources immediately after Feasibility Study



FS High Level Objectives

- Demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- Pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- Optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- Elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- Development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- Identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- Consolidation of the physics case and detector concepts for both colliders.

Mid-Term Report

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

Future Circular Collider
Midterm Report

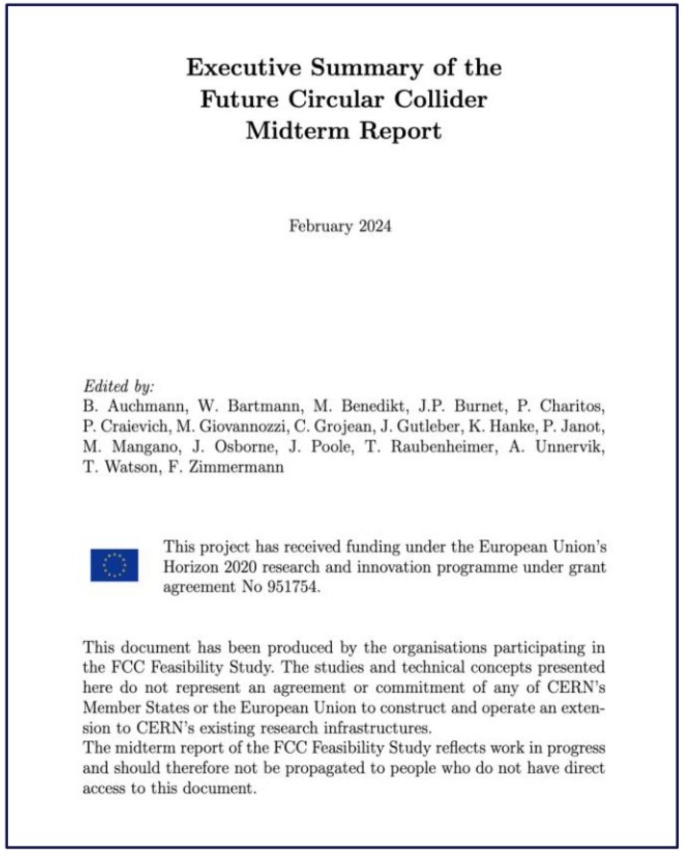
February 2024

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

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8 Chapters
~ 45 pages
~ 16 editors

Courtesy: F. Gianotti

FCC Physics Potential

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

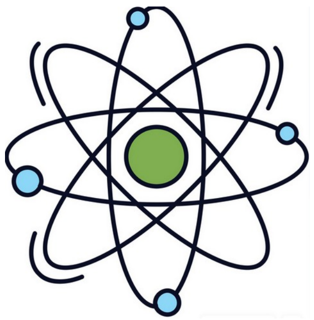
	√s	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	182 x 10^{34} 19.4 7.3 1.33	22 2.3 0.9 0.16	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5-30 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 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

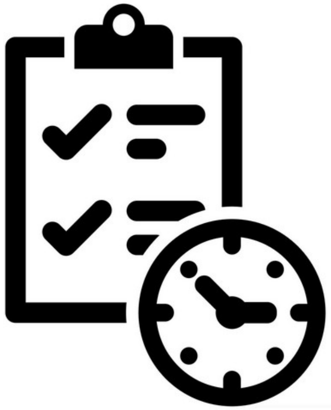
Why FCC?

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

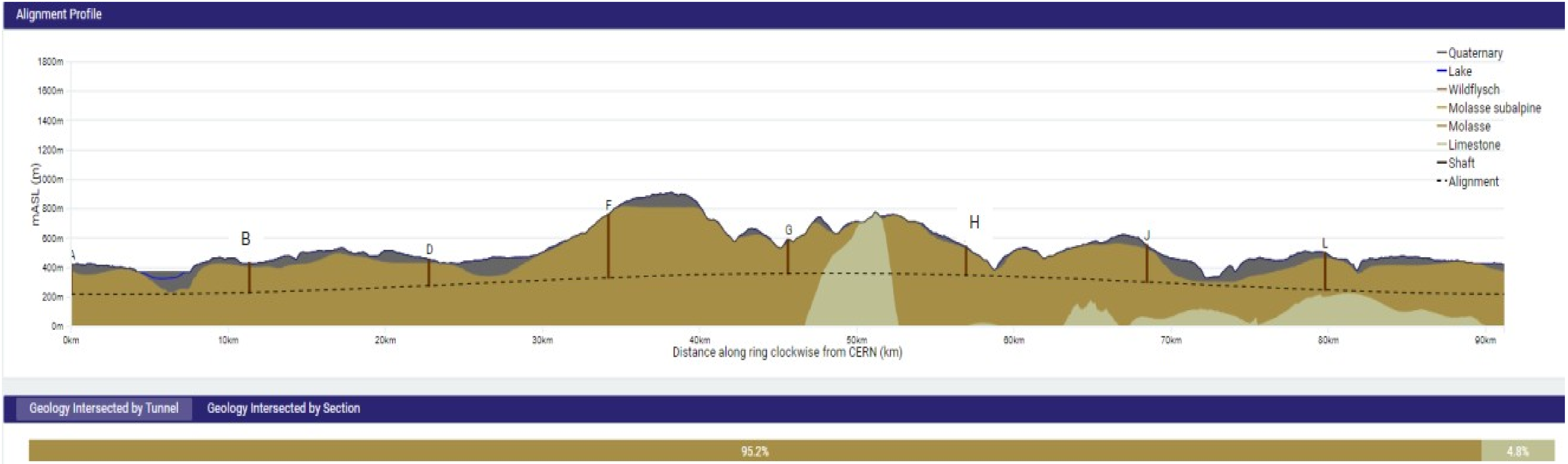


- FCC-ee technology is mature; collisions could start few years after HL-LHC
- Integrated FCC project allows for ~20 more years magnet R&D
- Optimized overall investment

Community

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

Placement Studies

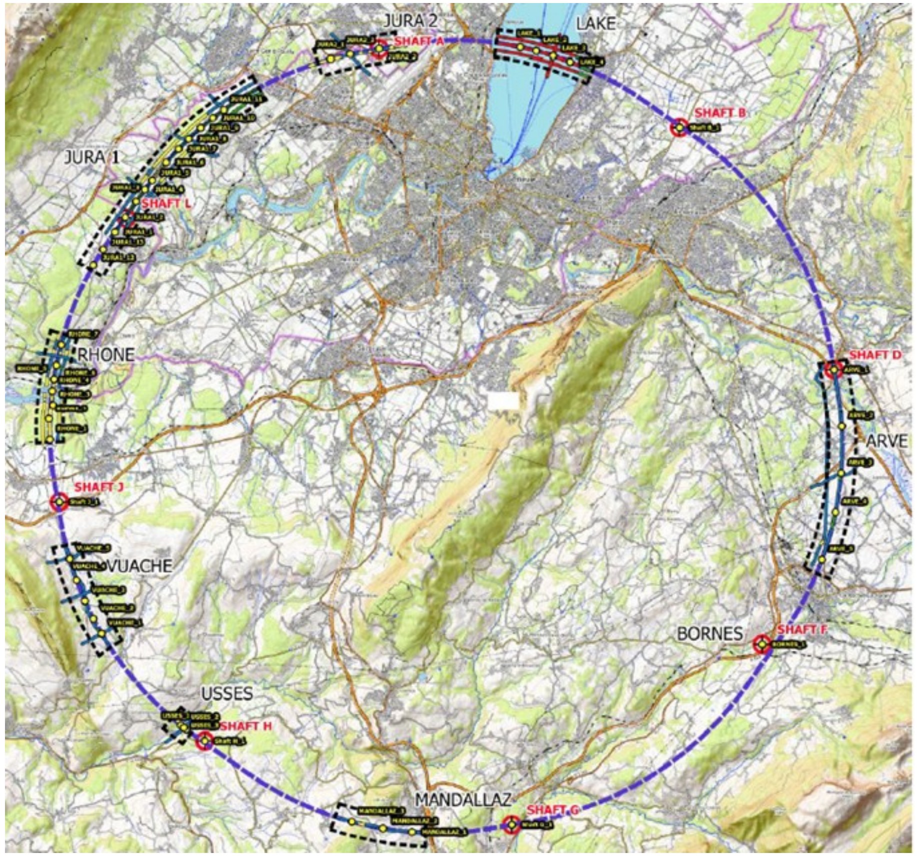


- 91 km circumference
- 95 % in molasse for minimizing tunnel construction risks
- Site investigations ongoing until end of 2025

Site Investigations

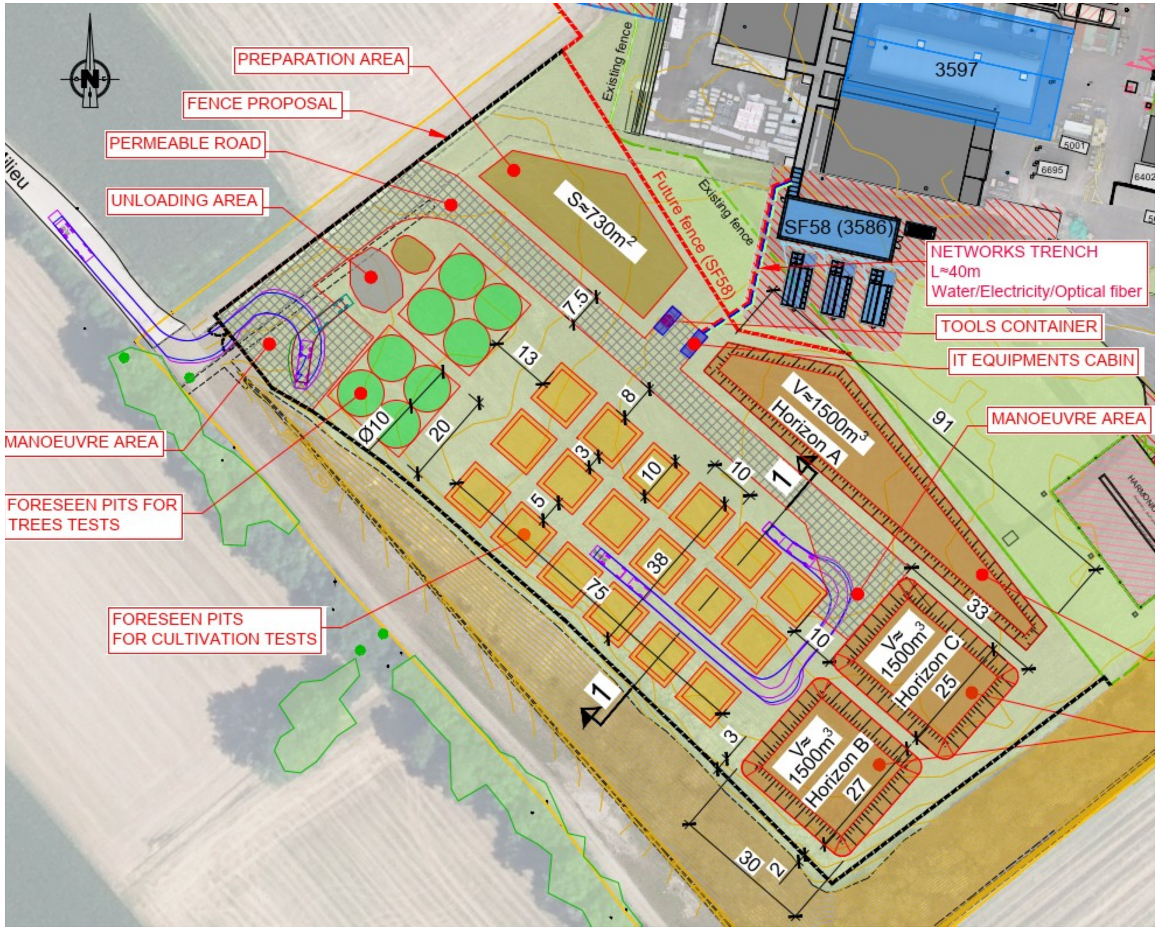
- Goal: to identify exact location of geological interfaces
- About 30 drillings foreseen

Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)



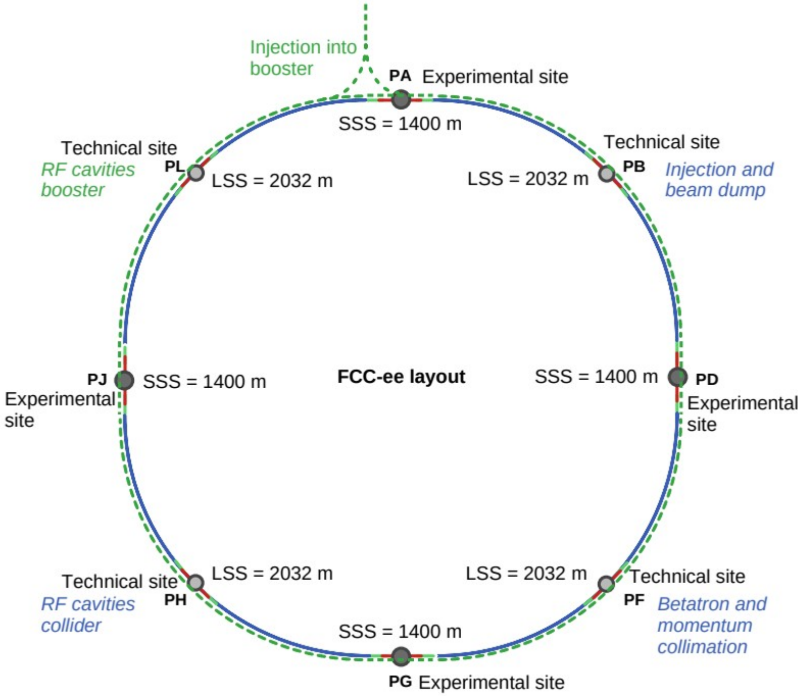
Excavation Material Management

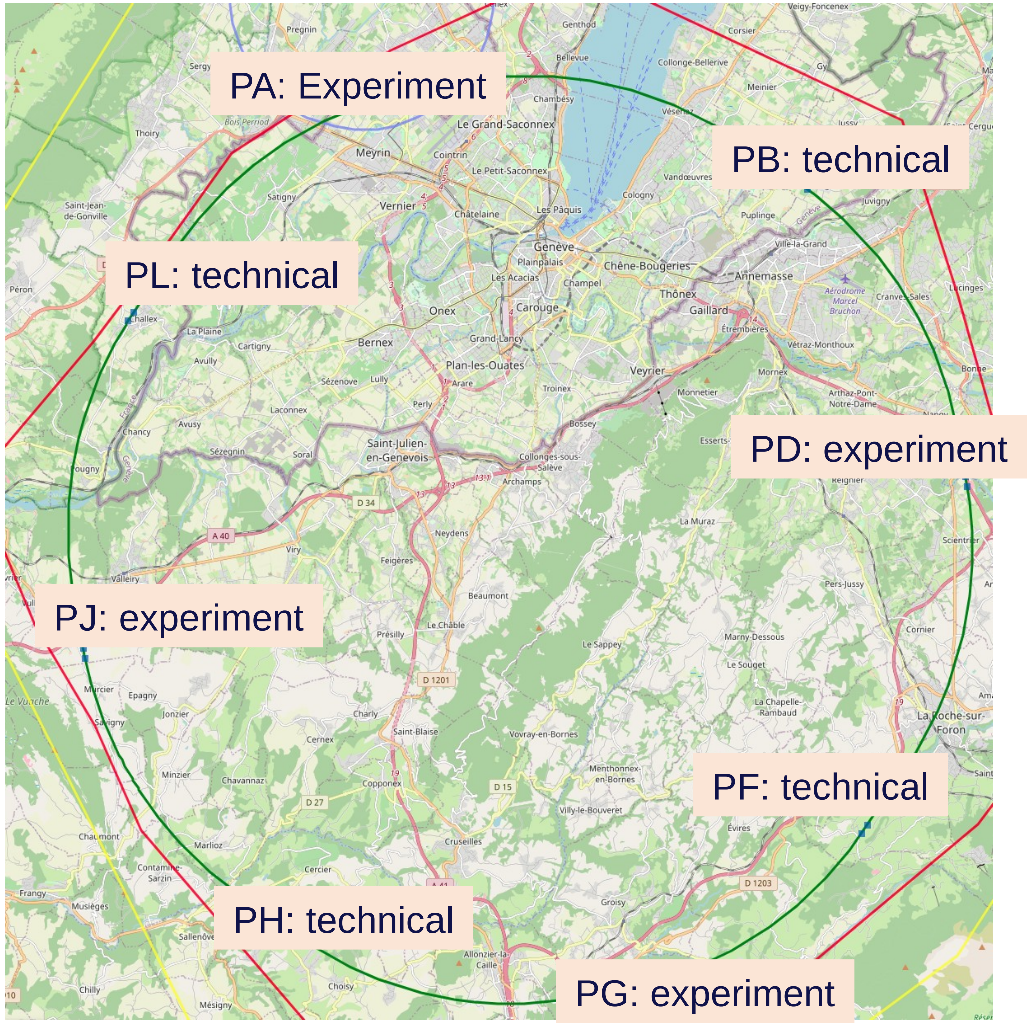
- Excavated material from FCC subsurface infrastructure:
  - 6.5 Mm^3 in situ
  - 8.4 Mm^3 excavated
- **OpenSkyLab Goal:** Develop quality assured processes for transforming molasse materials that can be accredited in both host states for re-use applications; examples include, but are not limited to amendments for agricultural and forestry use, renaturalisation of wastelands, management of rural paths, refurbishment of polluted soil
- Project launched in January 2024
- 10000 m^2 near LHC P5 in Cessy, France



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



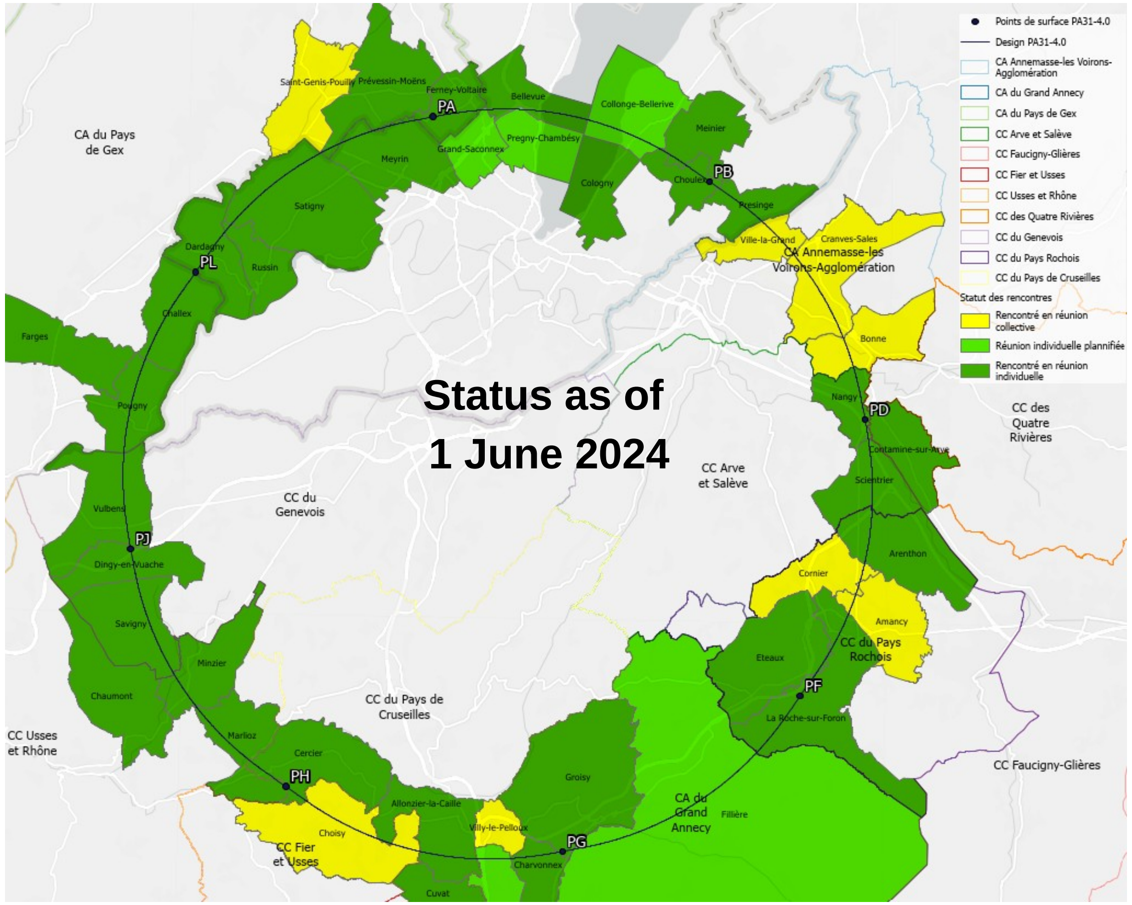


Courtesy: J. Gutleber

Progress with Baseline

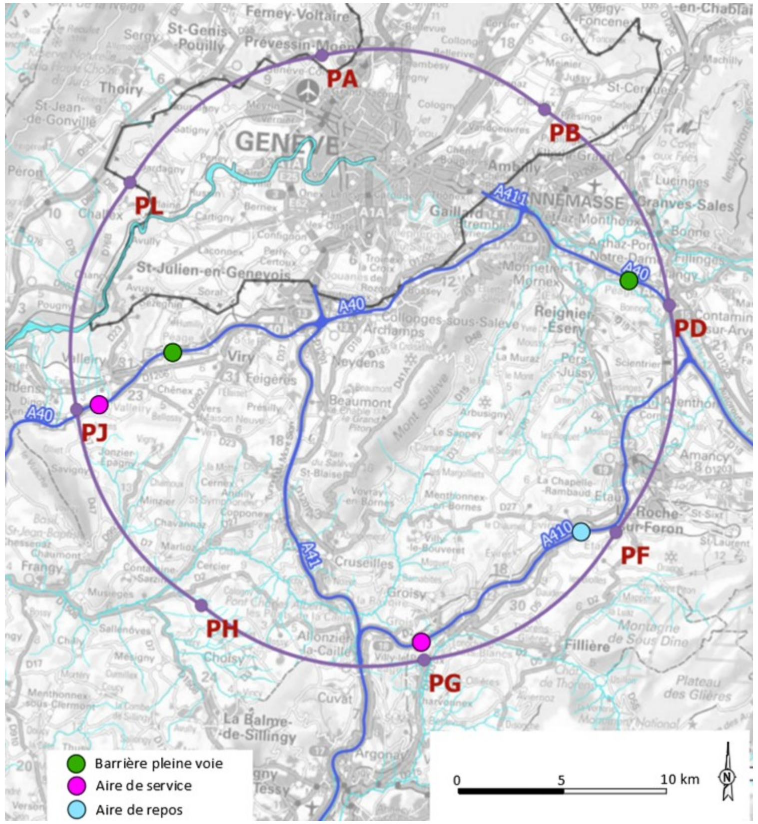
Meetings with municipalities concerned:

- 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

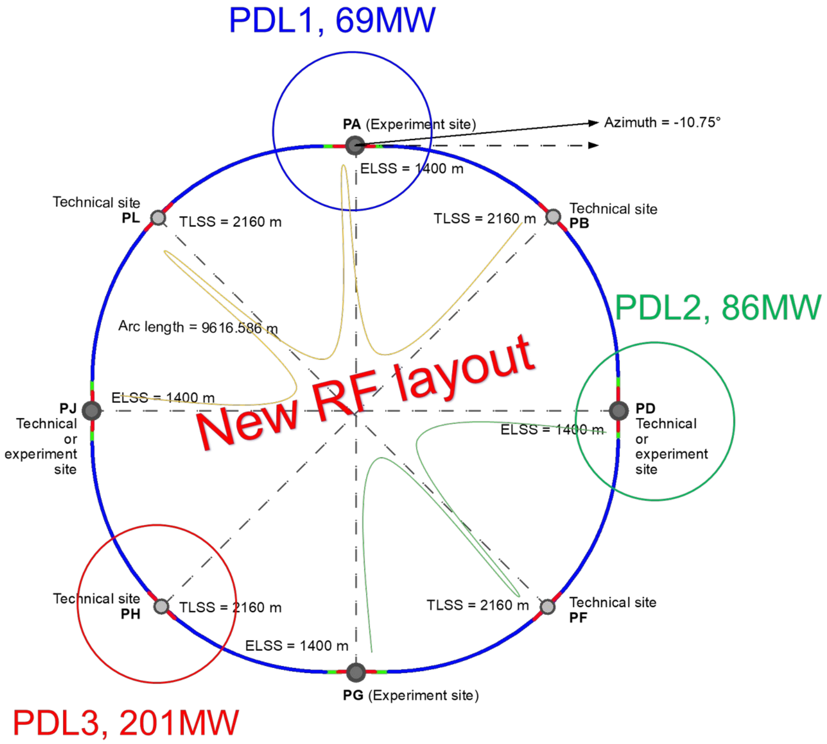


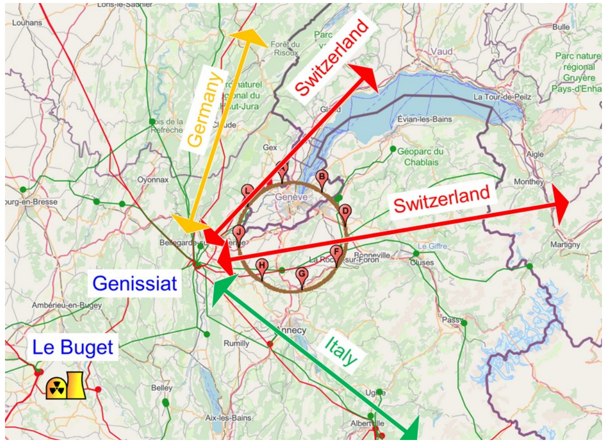
The support of the host states is greatly appreciated and essential for the study progress!

Regional Infrastructure Connection



- Electrical connection concept studied by RTE (French electrical grid operator)
- Requested loads have no significant impact on grid





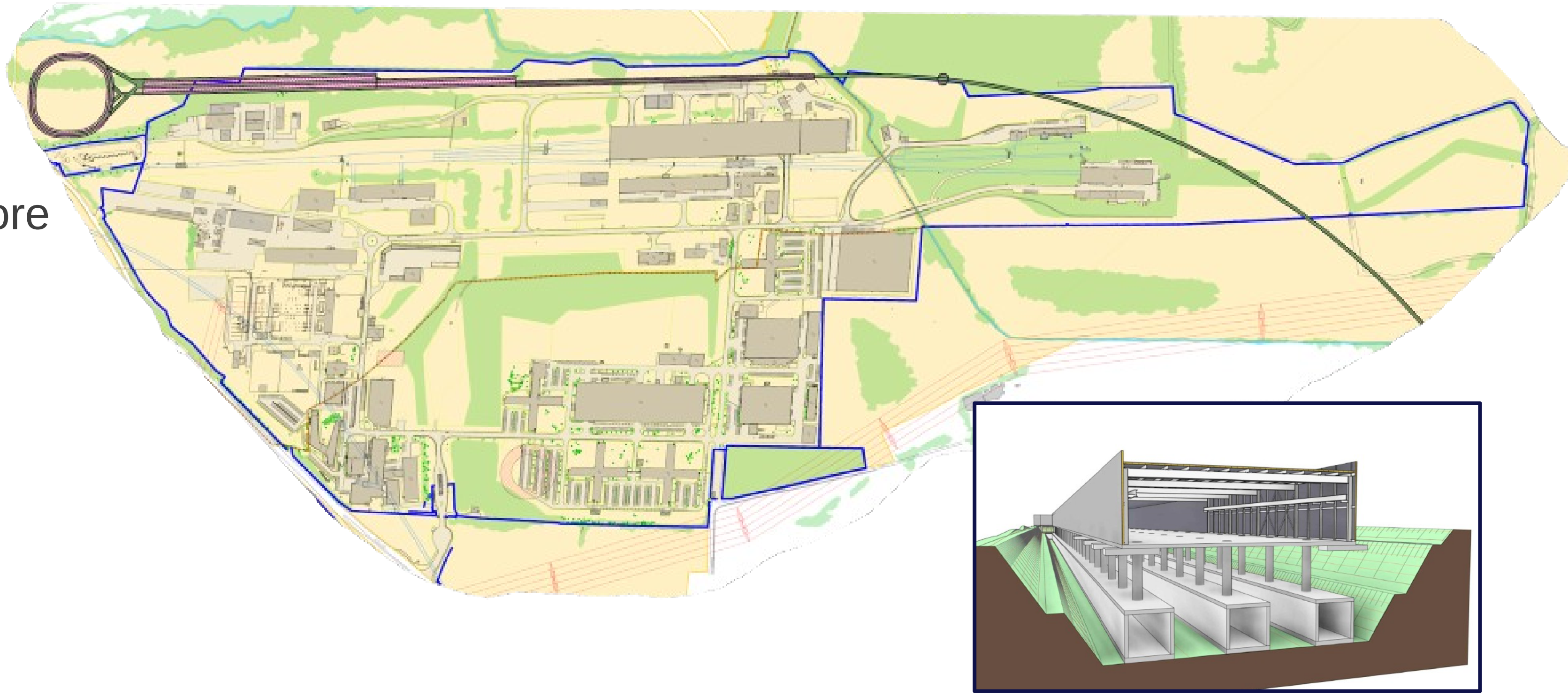
- **Road access** developed for all 8 surface sites
- ~3 km road access creation or enlargement required

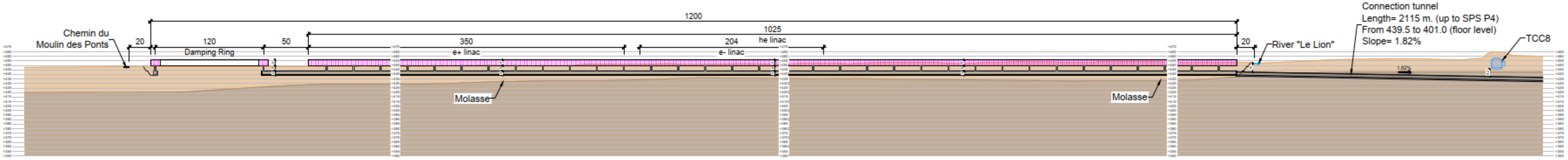
R&D efforts aiming at further reduction of the energy consumption for FCC-ee and FCC-hh.

Optimized Injector Layout

Courtesy: W. Bartmann, P. Craievich

- Good integration with CERN site
- With respect to MTR power consumption of linacs reduced by more than factor 3 thanks to
  - New accelerating structure with higher shunt impedance
  - Lower gradient (22.5/20.5 MV/m)
  - Lower repetition rate (100 Hz)

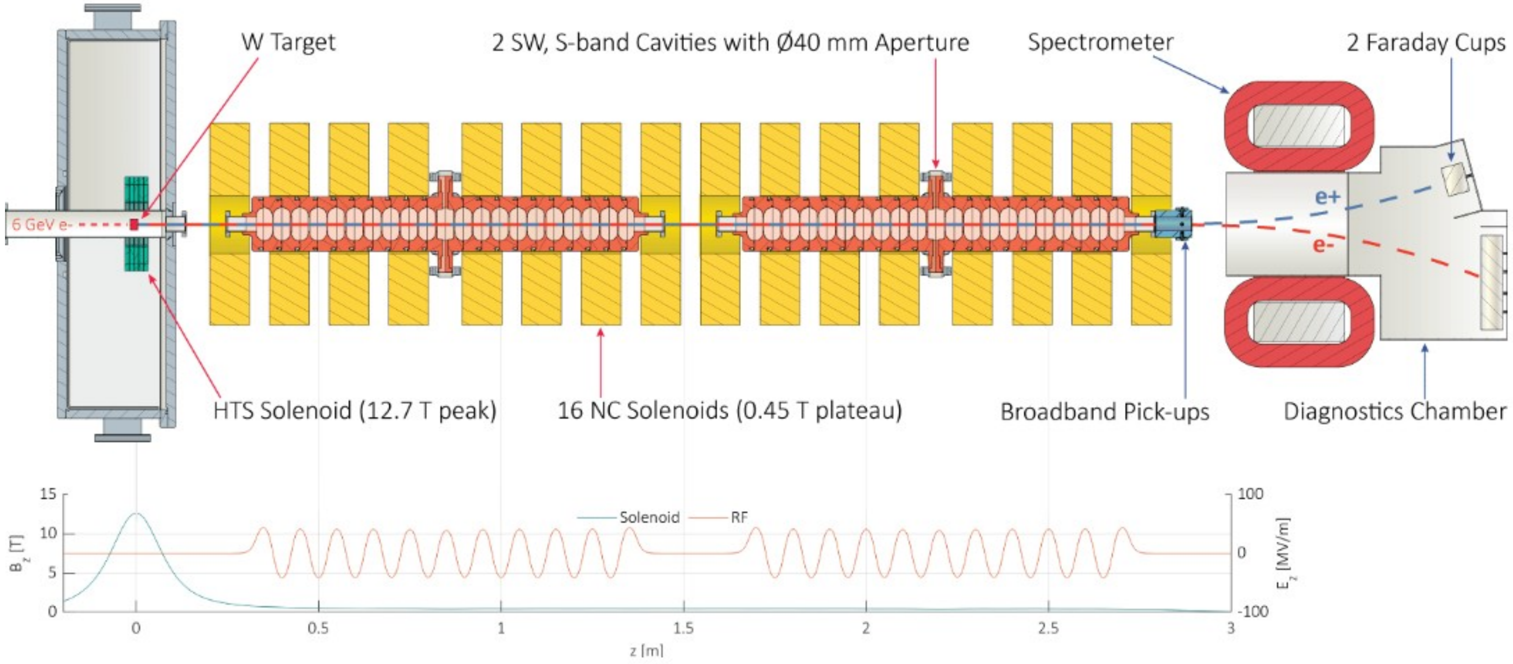




LONGITUDINAL PROFILE

Positron Production

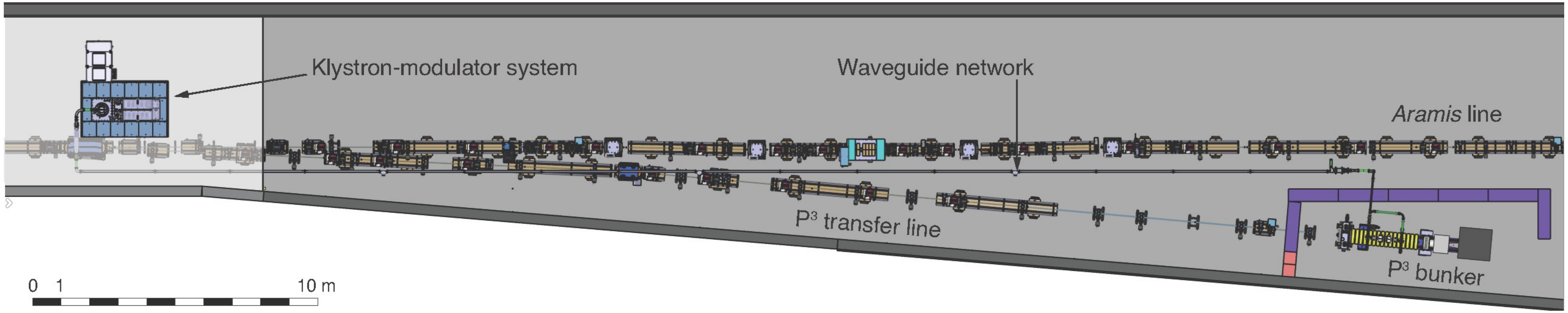
- Positrons generated by electrons hitting high-Z-target
- Generated positrons have **large emittance and energy spread** → must be reduced
- Novel capture techniques tested at **P³** (PSI Positron Production), relevant for future colliders



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

PSI Positron Production (P^3)

- Installation works at SwissFEL progressing smoothly
  - Parts of dedicated extraction line and HV klystron-modulator system accommodated in the tunnel
  - **Procurement and assembly of most accelerator and diagnostics components on schedule**
  - Operation of HTS solenoid up to 18 T successfully demonstrated
  - Radiation tests under discussion.
- **Start of operation with e^+ expected in 2026.**



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/
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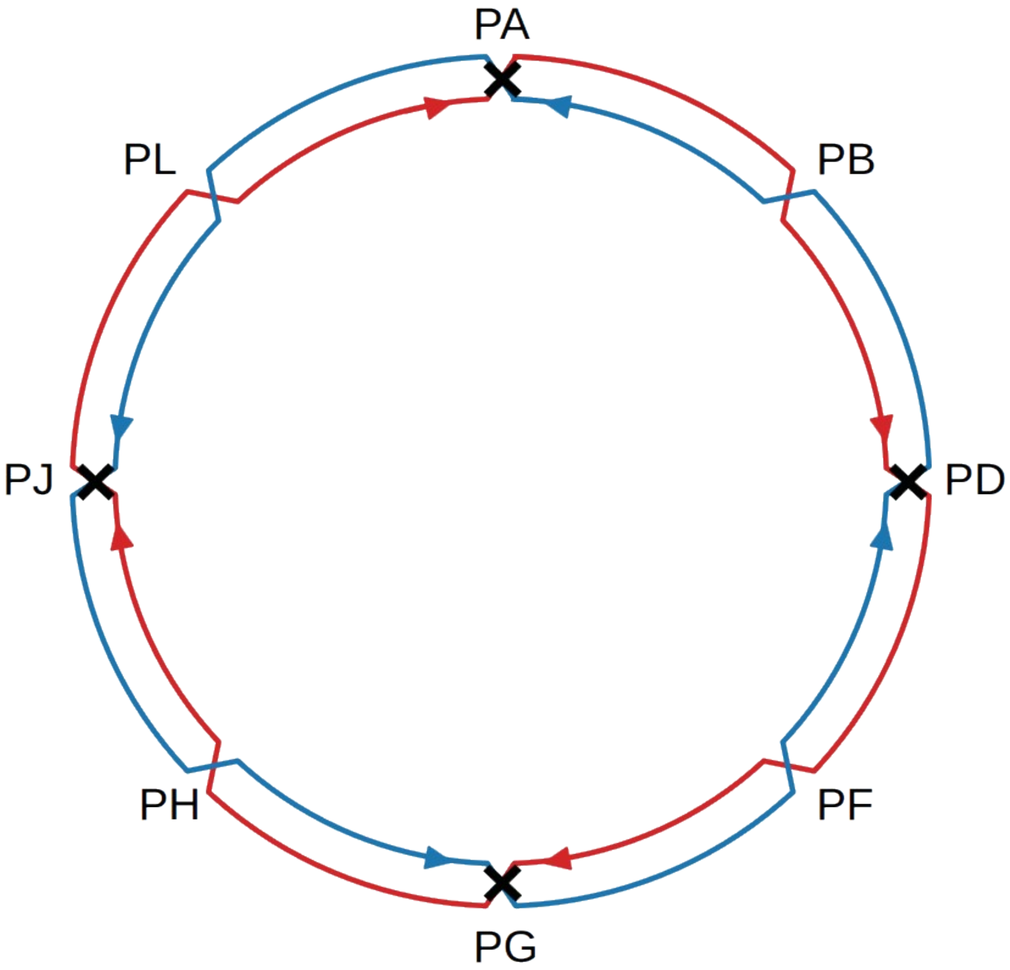


FCC-ee Parameters

	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

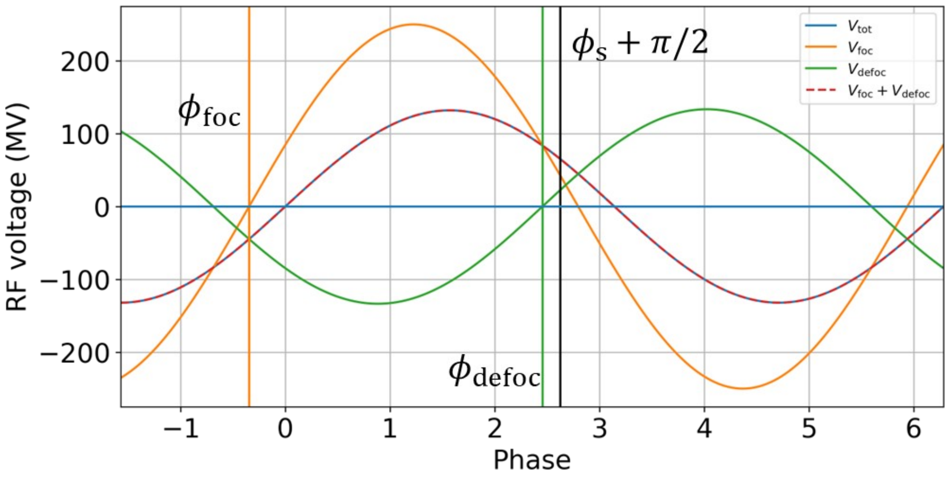
	Z	WW	ZH	ttbar
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 ttbar pairs

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

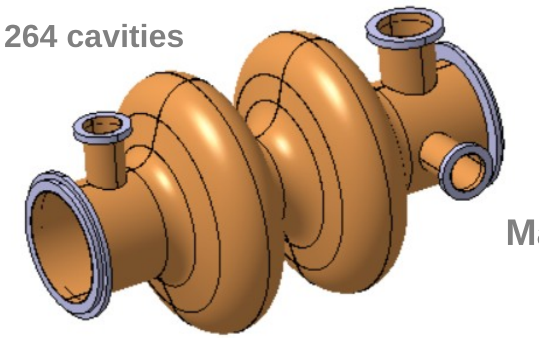
Defines
→ RF system
→ Beam parameters

400 MHz SRF Progress

- **Same two-cell RF cavities for Z, WW and ZH operation** with constant cavity coupling thanks to **<u>reverse phase operation</u>**
  - (1) experimentally verified w high beam loading at KEKB
  - (2) Baseline solution US EIC
- No longer any 1-cell 400 MHz cavities
- Reduced installation time
- Reduced commissioning effort
- Fast switching between Z, WW and ZH operation

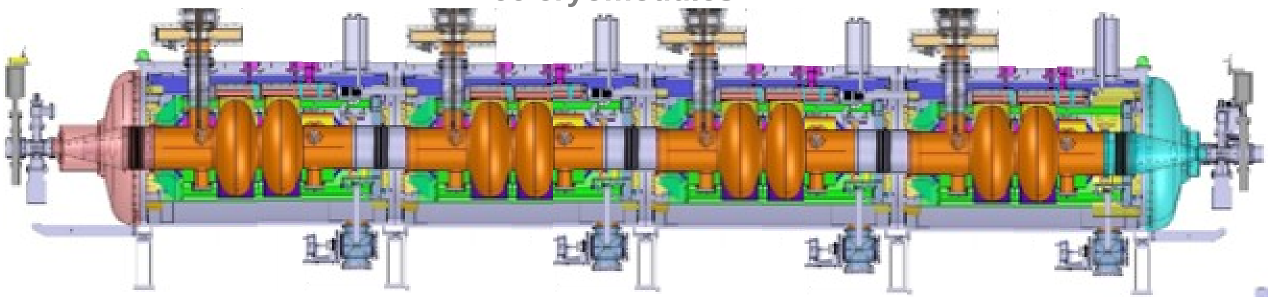


264 cavities



400 MHz 2-cell cavity
Niobium thin film on Copper,
Operation at 4.5 Kelvin
Max. accel. gradient E_{acc} = 13 MV/m
Quality factor Q_0 = 3.3 x 10^9

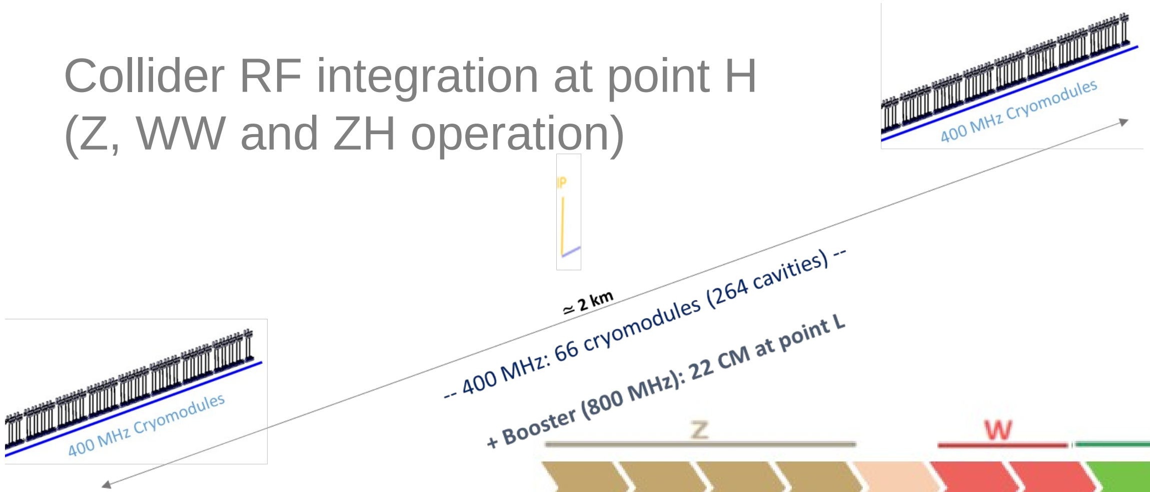
66 cryomodules



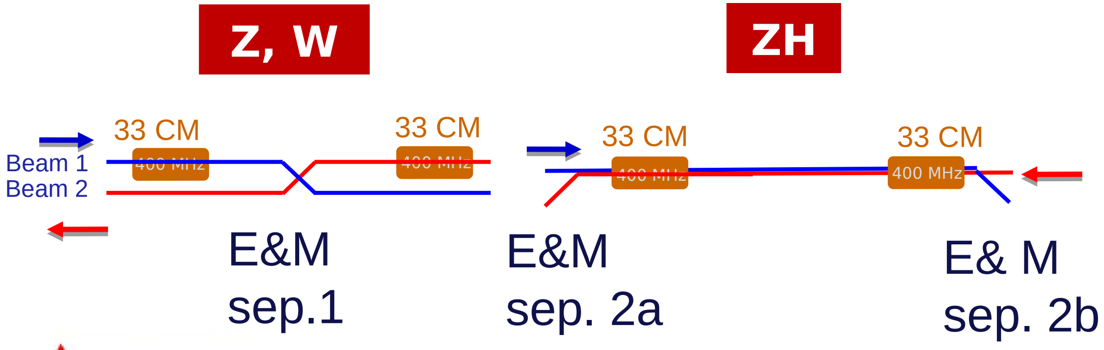
SRF Integration

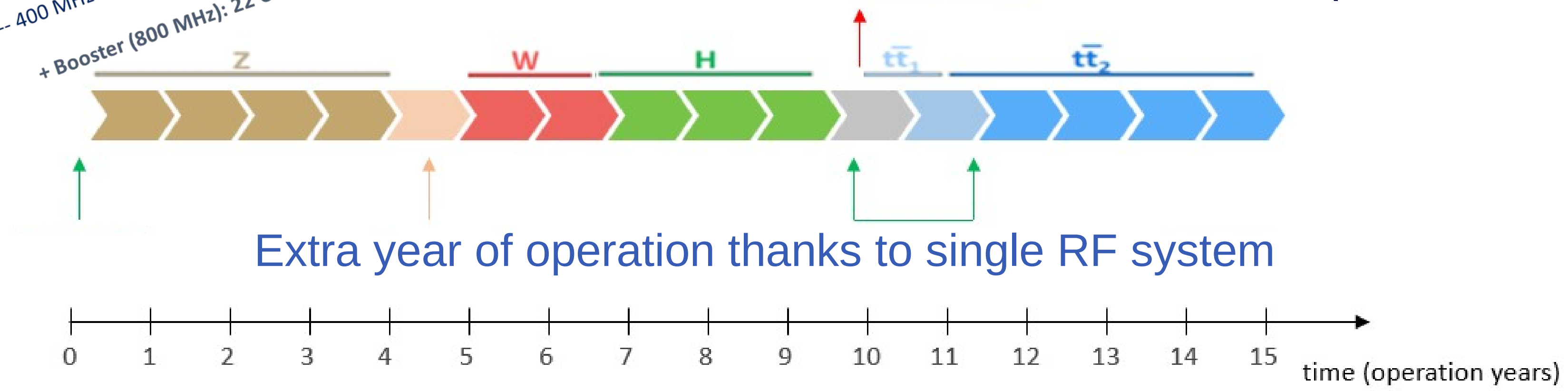
- **Beam switching between (Z, W) and ZH operation**
  - RF section: Electrostatic separators and magnetic field to not emit SR towards RF cavities
  - Allows quasi “instantaneous” switching between Z, W, ZH

Collider RF integration at point H
(Z, WW and ZH operation)



Beam crossing and combination at RF section in point H



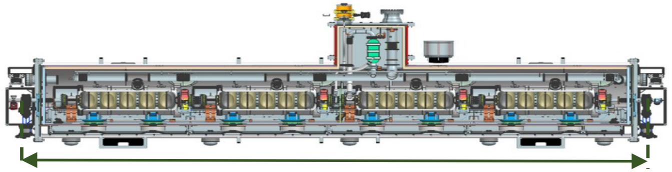


Extra year of operation thanks to single RF system

RF R&D Activities

- RF system is key technology for increasing energy efficiency for the FCC-ee
- Nb on Cu 400 MHz cavities, seamless cavity production and coating techniques
- Bulk Nb 800 MHz cavities, surface treatment techniques, cryomodule design
- RF power source R&D in synergy with HL-LHC

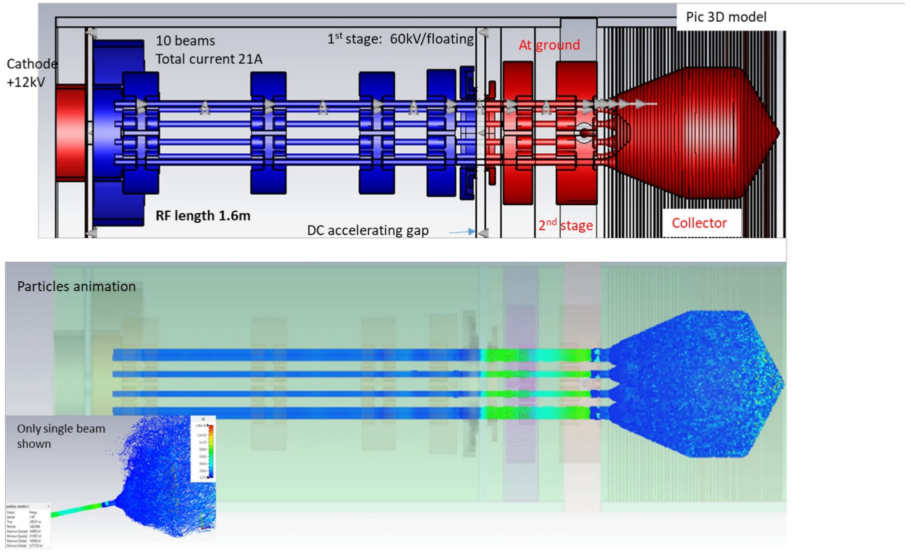
800 MHz cavity and CM design
collaborations with **JLAB** and **FNAL**



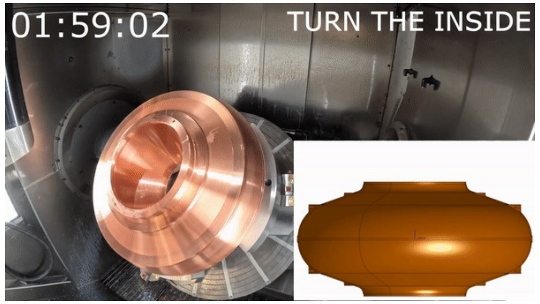
~7m

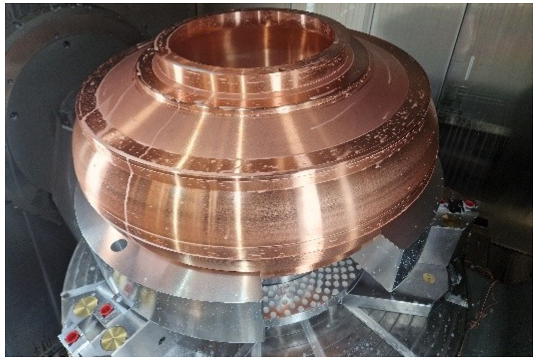
High-efficiency klystron R&D
in collaborations with **THALES & CANON**

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



400 MHz cavity production
in collaboration with **KEK**



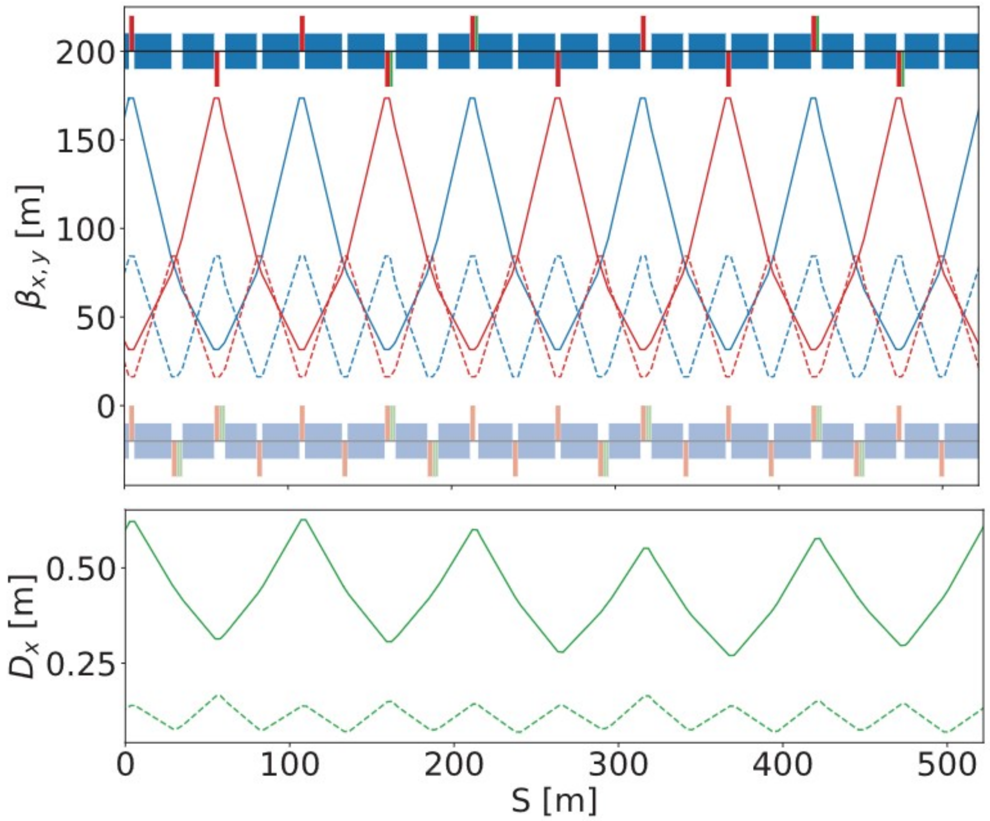


FCC-ee Arc Designs

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

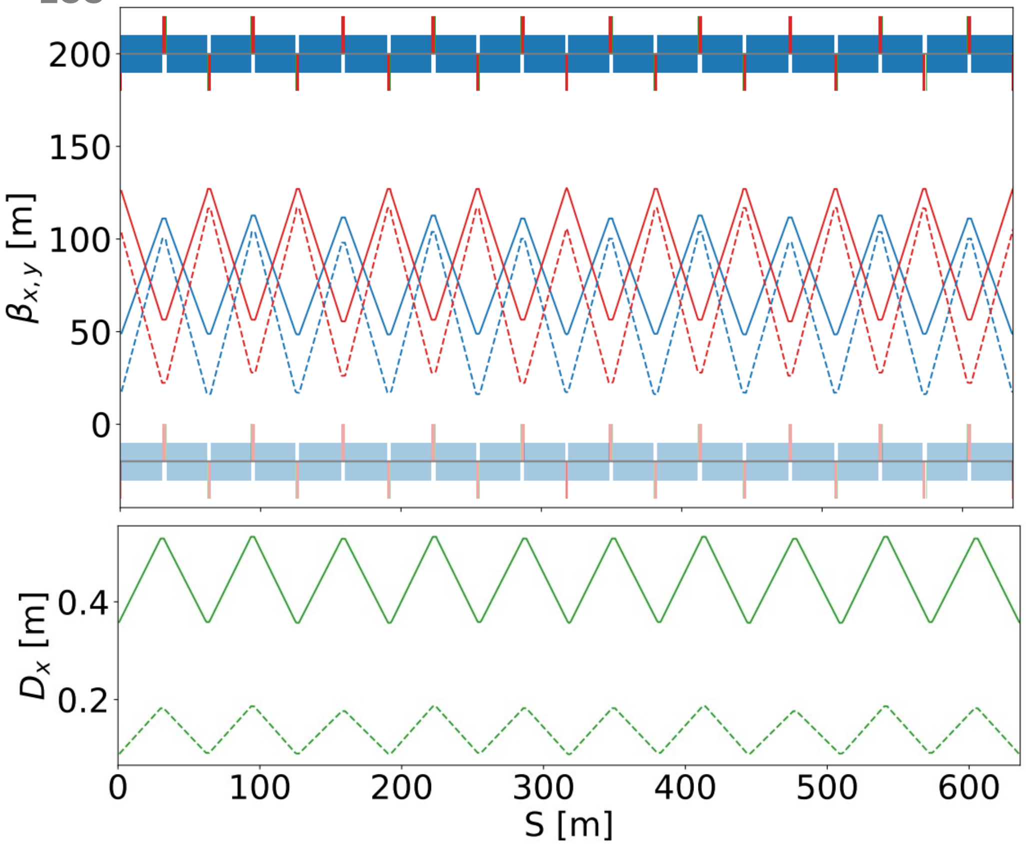
- 300 m Hybrid FODO cell
- Same number of sextupoles for all energies

GHC



Blue: dipoles
Red: quadrupoles
Green: sextupoles

LCC

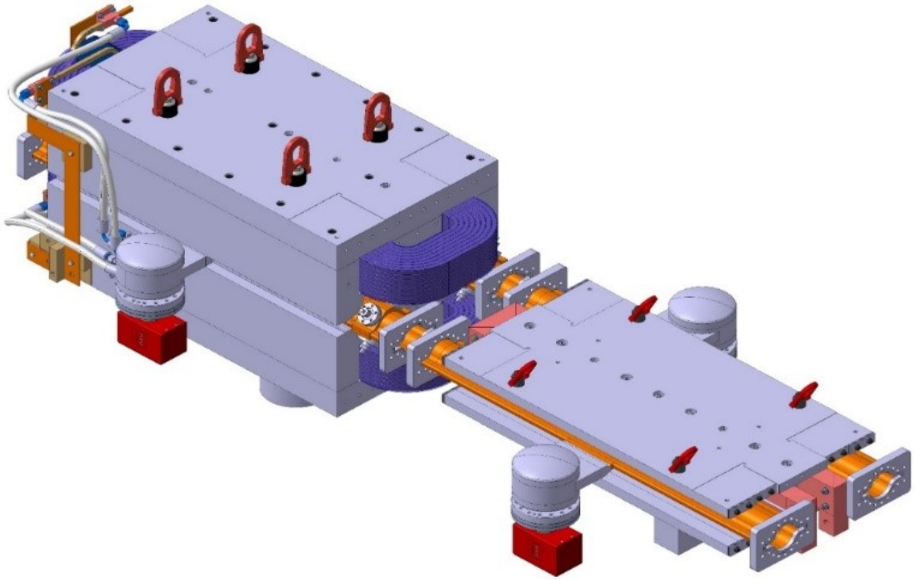


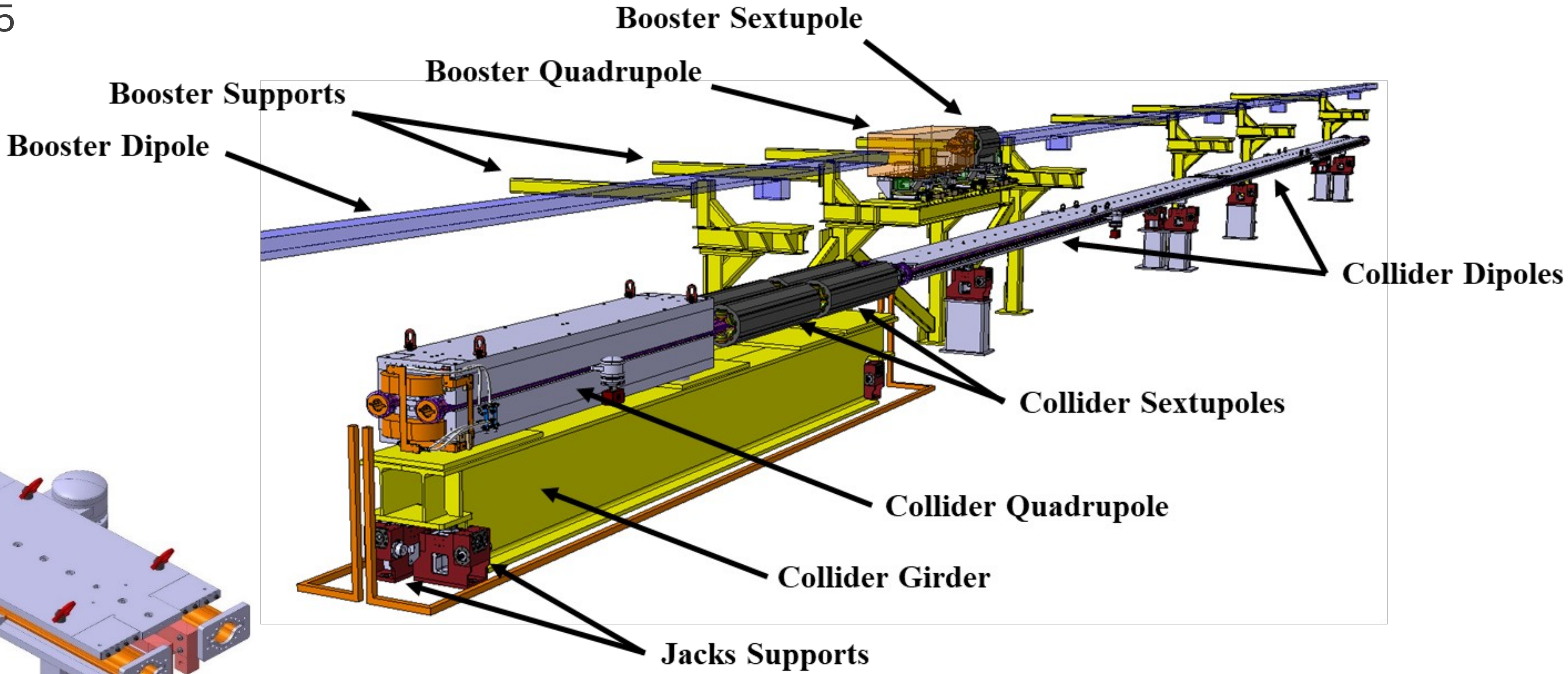
Solid: Z; Dashed: ttbar

Courtesy: F. Carra, A. Piccini, et al.

Arc Integration Optimization

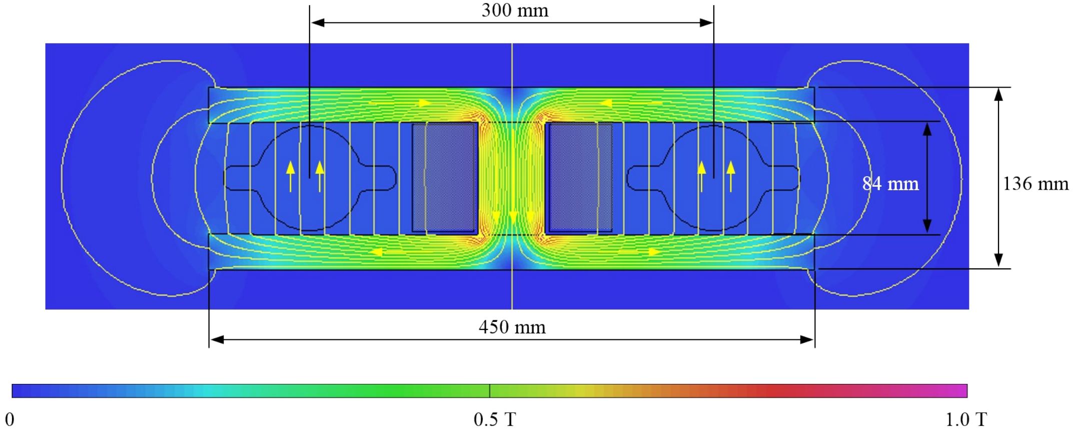
- Arc half-cell mock-up to test aspects related to installation, transport, cost, assembly, maintenance, etc.
- Including support, girder, alignment, shielding, vacuum system, BPMs, cabling, cooling, etc.
- Begin installation in 2025

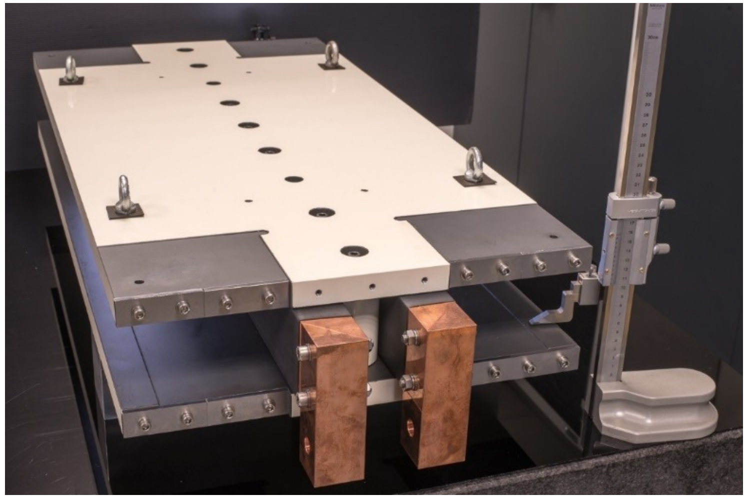




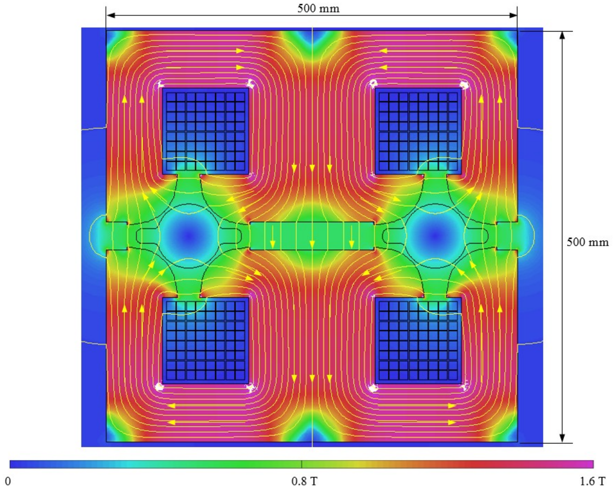
Low Power Arc Magnets

- Twin-dipole design and prototype

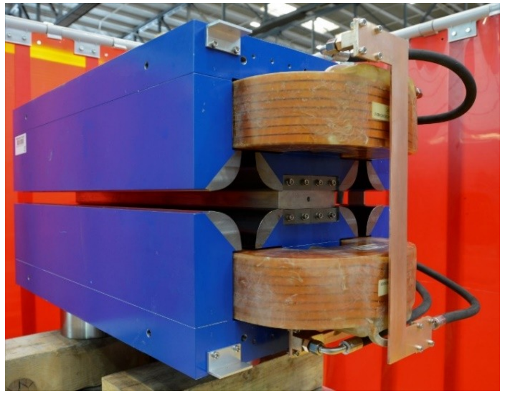




- Twin-dipole arc quadrupole design



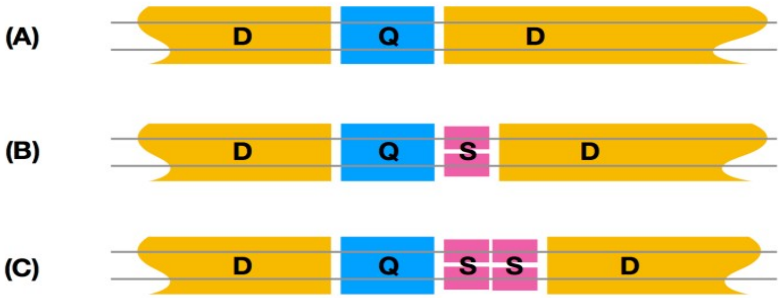
CDR:
- 5800-8700 dipoles
- 2900 quads
- 4700 sextupoles
For collider arcs



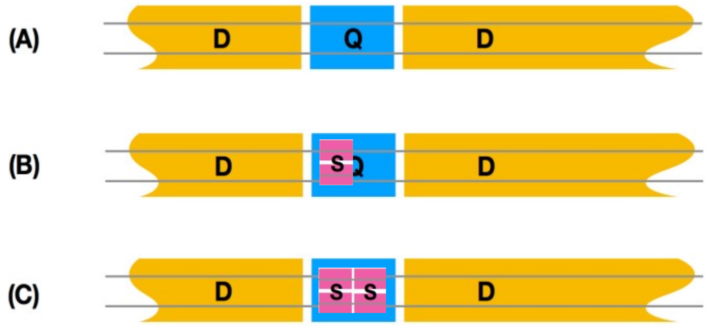
Courtesy: M. Koratzinos, B. Auchmann

HTS Optics for FCC-ee Arcs

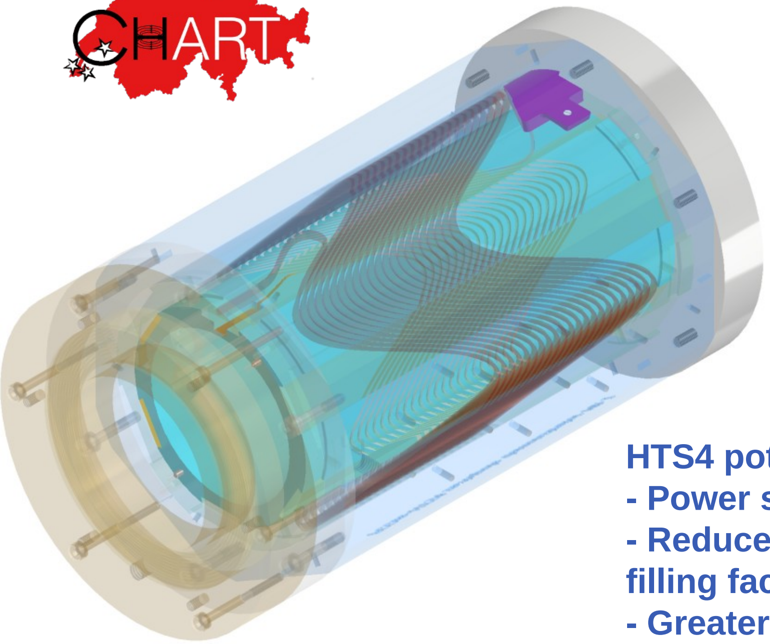
- Baseline design: normal conducting arc quadrupoles and sextupoles

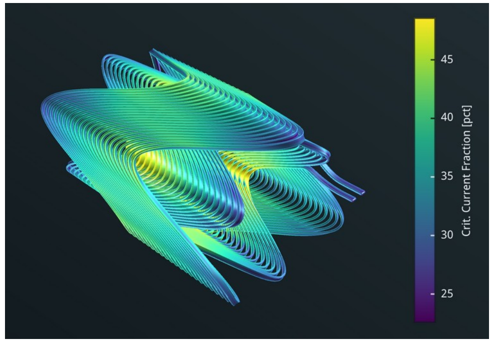


- HTS: High Temperature Superconducting magnets



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





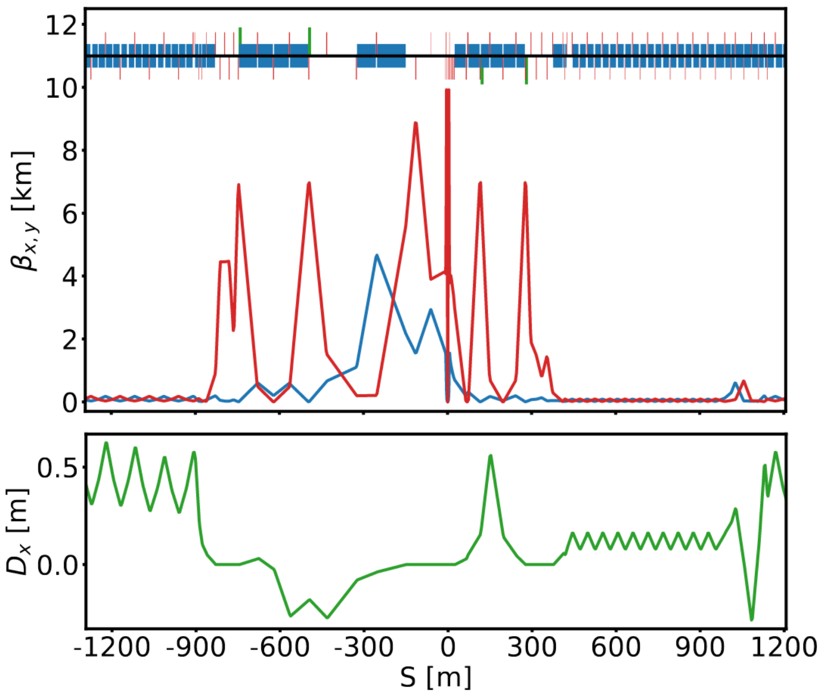
HTS4 potential:
- Power saving
- Reduced length and increased dipole filling factor
- Greater optics flexibility

Experimental IR

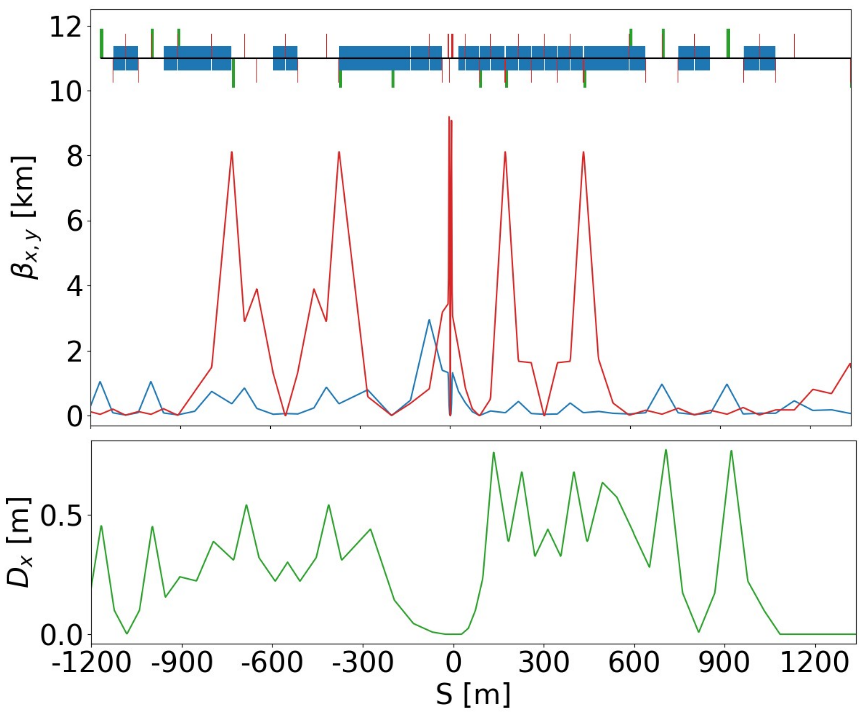
- Local vertical chromaticity correction
- Global horizontal chromaticity correction
- Virtual crab-waist scheme

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

GHC

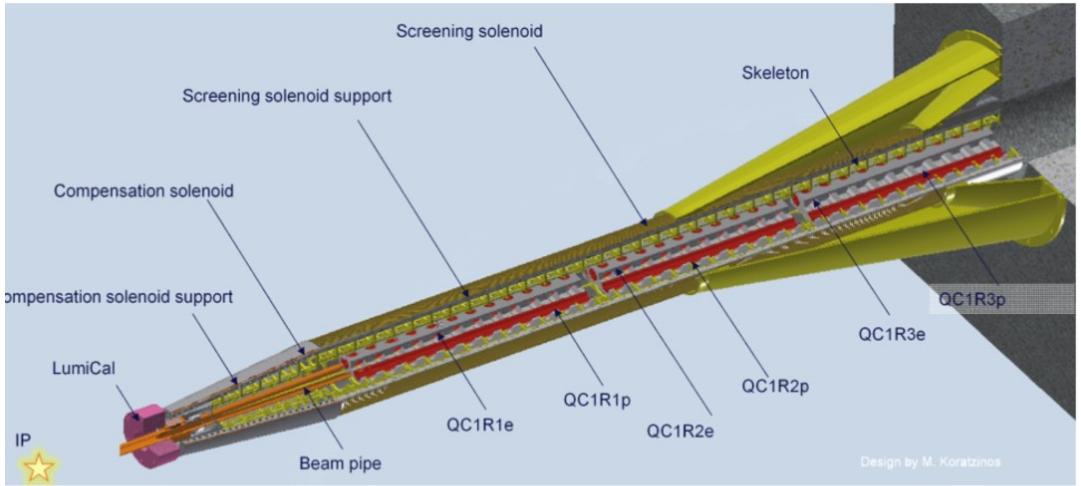


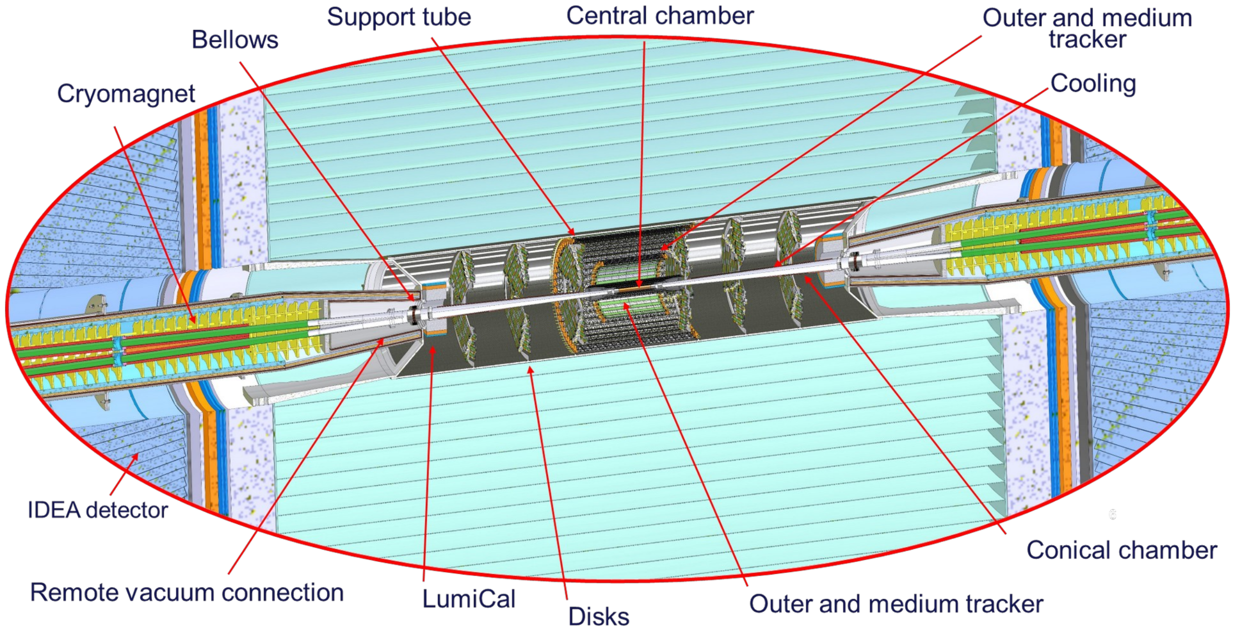
LCC



Machine Detector Interface

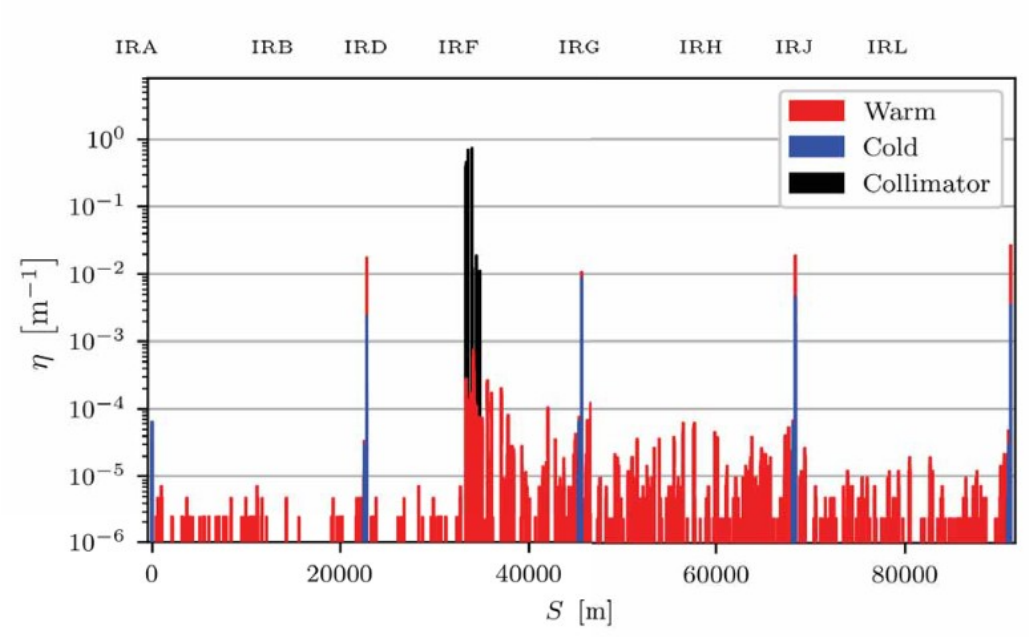
- Key topics:
  - Superconducting IR magnet system and cryostat design
  - 3D integration
  - IR mock-up at INFN-LNF



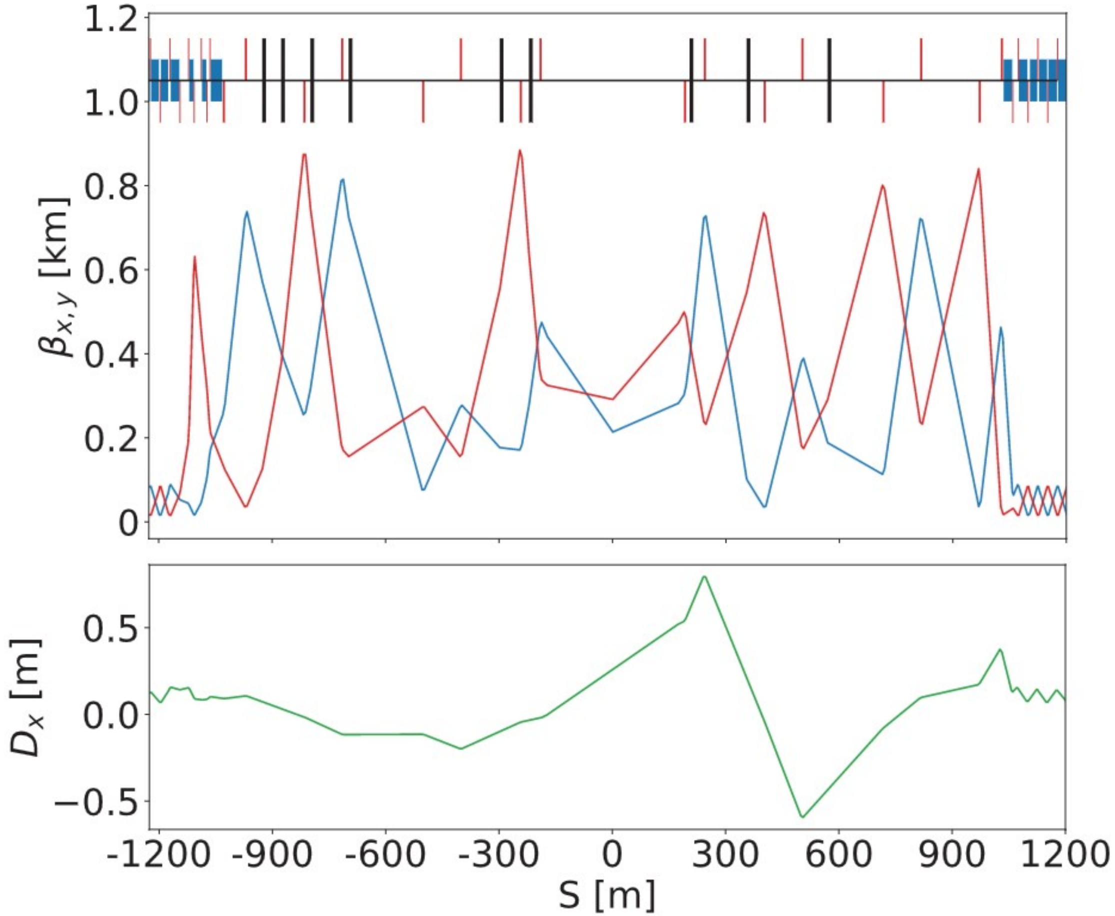


Collimation FCC-ee

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

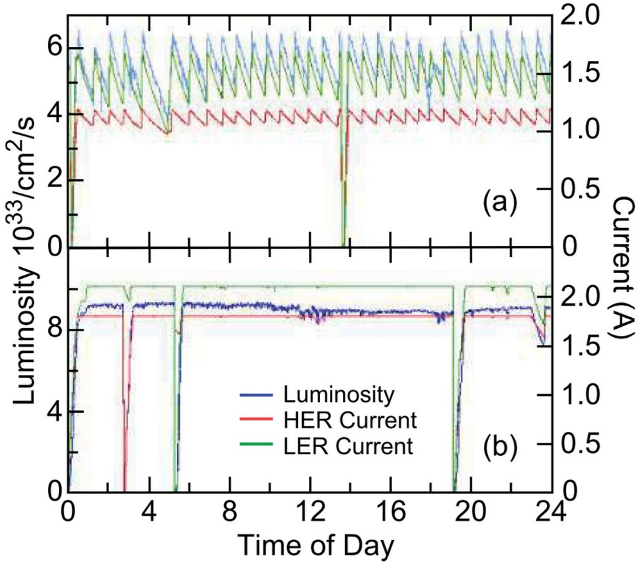


Loss studies at 182.5 GeV; Courtesy: A. Abramov

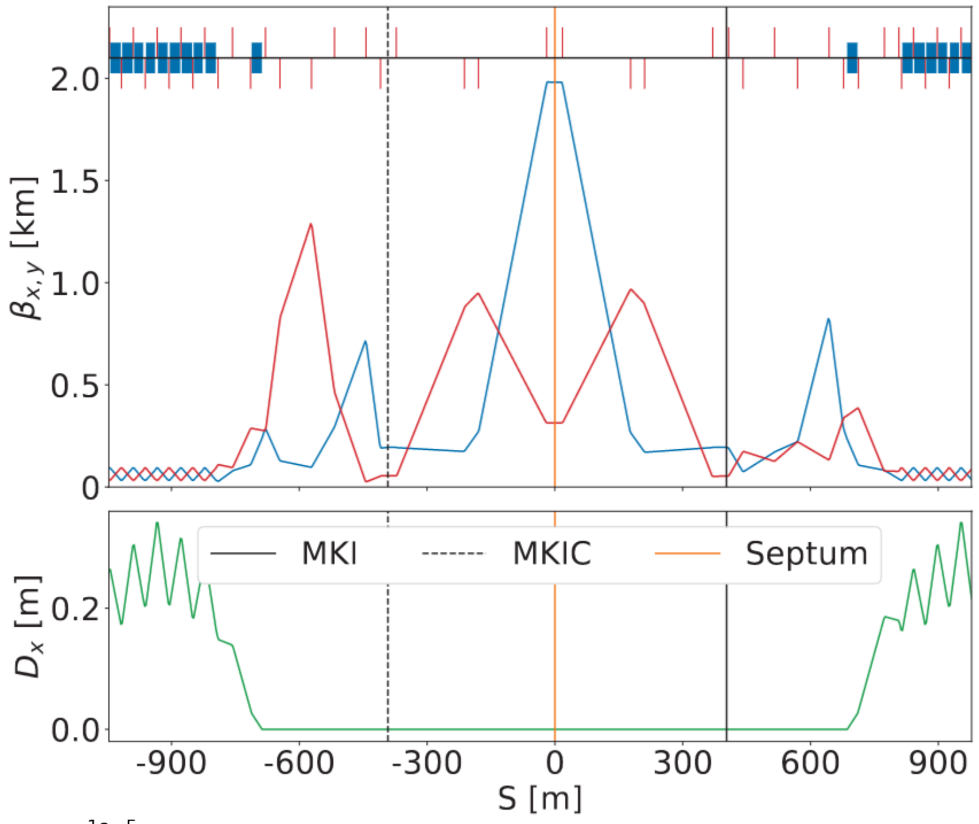


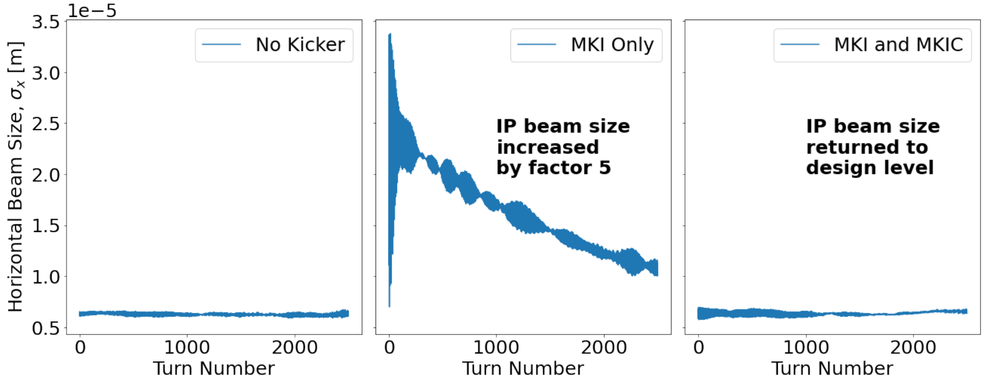
Top-Up Injection

- Combined injection and extraction insertion designed
- **Injection at collision energy** into collider rings
- Continous injection to keep **constant beam current**
- SR intercepted by last mask



Top-up injection at KEKB (predecessor of SuperKEKB)





Tuning and Lattice Comparisons

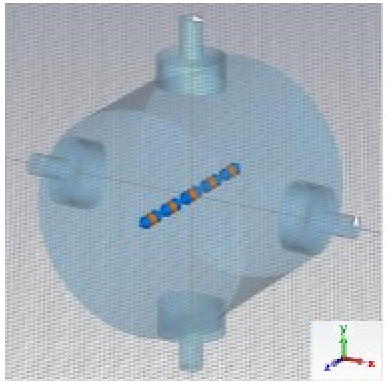
- Great effort to compare and tune lattice optics
  - Magnetic field and misalingment sensitivity
  - Specification of beam diagnostic requirements
  - Dynamic aperture and optimisation
  - …

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

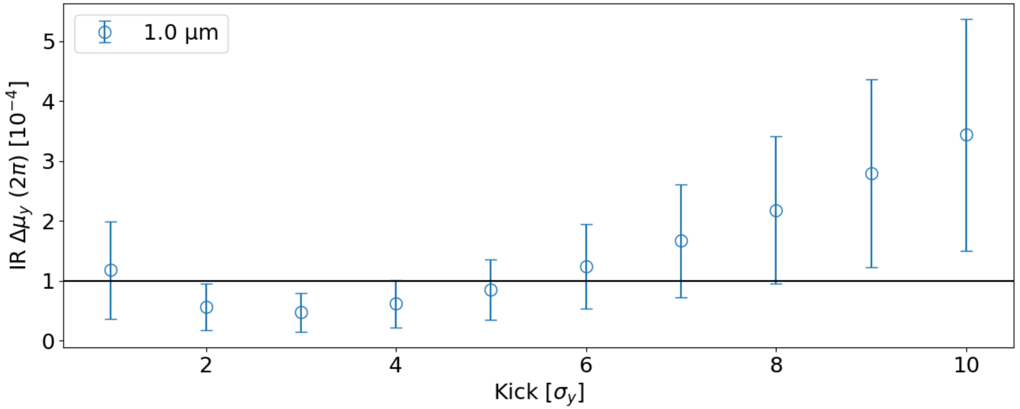
			orbit		$\Delta\beta/\beta$		$\Delta\eta$	
	E_0	#	H	V	H	V	H	V
criteria			100 µm	100 µm	1 %	1 %	1 mm	1 mm
			arc quadrupoles sensitivity [µm]					
V22 (.26 .38	Z	1420	1.9	1.9	2.9	0.7	0.1	0.1
LCCO89 (.20 .30)	Z	2168	1.7	1.4	5.3	0.4	0.2	0.24
LCCO89 (.26 .38)	Z	2168	2.0	1.6	6.1	0.5	0.9	0.26
V22	$t\bar{t}$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

BPM Parameter	Requirement	Comments
Orbit resolution	0.1 µm	Smaller pipe diameter helps (reduced from 7 to 6 mm)
TxT resolution	< 10 µm	
IP BPM accuracy	**1 µm** (from [2])	Challenging! Could measure BPM offsets by BBA to this level, but not possible for accuracy over large range of beam positions. What is really required?
Arc BPM accuracy	20 µm	No BPMs on sextupoles yet
Min bunch spacing	**25 ns**	Signal processing time needed.



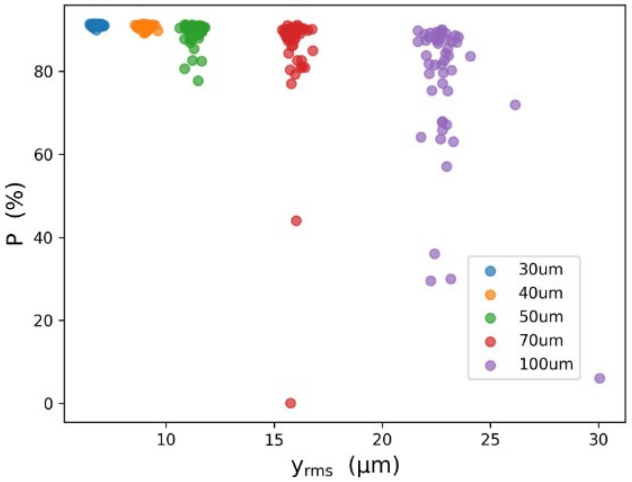
Courtesy: E. Howling



Energy Calibration and Polarization

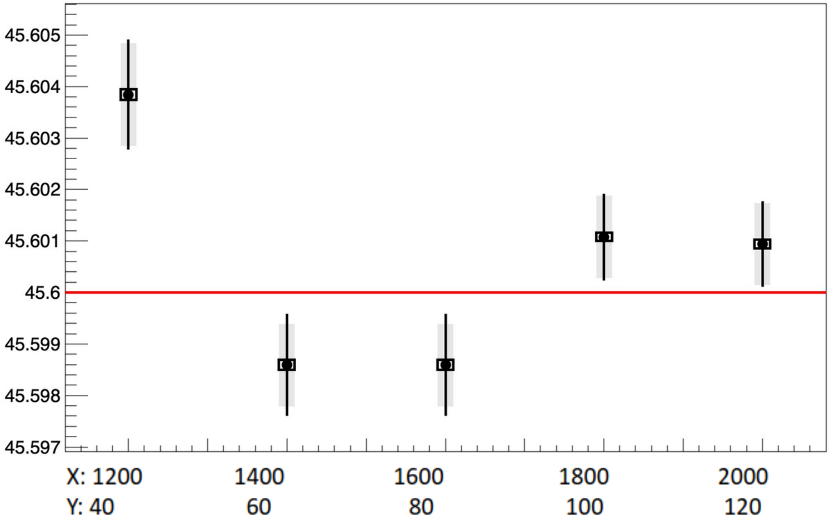
- Great effort to increase polarization level in presence of errors
- Huge progress on polarimeter design moving towards technical design
- Experimental tests at KARA (Karlsruhe Research Accelerator)

Achievable polarization level with misalignment errors



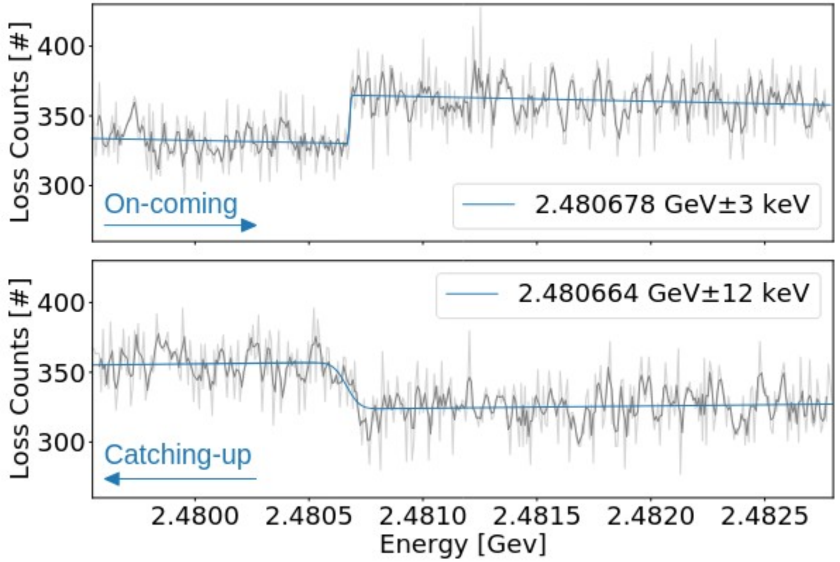
Courtesy: Y. Wu

Simulations to determine required pixel size for polarimeter electron detector



Courtesy: A. Martens

Measurements of the beam energy at KARA



FCC Main Goals for Coming Years

- **Completion of the FCC Feasibility Study by March 2025**

- **By 2027-2028, possible FCC project approval, start of CE design contract:**
  - Specifications to enable CE tender design by 2028
  - Refined input for environmental evaluation and project authorisation process
  - Requires overall integration study and designs based on technical pre-design of accelerators, technical infrastructure and detectors

- **By 2031-32, possible start of CE construction:**
  - CE groundbreaking
  - TDR to enable prototyping, industrialization towards component production

- **Strong international collaboration is essential for success!**

FCC-ee Accelerator R&D Focus

- **Key items, cost drivers and engery efficiency**
  - SRF system – SC cavities, cryomodules, power source
  - Arc magnets for collider & booster
  - Arc vacuum chamber with photon stops, shielding, NEG…
  - Support structures, survey & alignment systems
  - Arc beam diagnostics – beam loss & beam position monitors
  - ..
- **Special and challenging components**
  - IR elements, SC IR magnets system, IR supporting structures
  - Special diagnostics: polarimetry, beamstrahlung monitors, collimators
  - ...

FCC-Week 2025

Future Circular Collider (FCC) Week 2025
at the
Hofburg Palace, Vienna, Austria
from
Monday 19 May to Friday 23 May 2025

We look forward to welcoming you in Vienna for what promises to be an exciting and informative event!

Thank you!

Jacqueline Keintzel (CERN)

On behalf of the FCC collaboration and the FCCIS design study team

EURO-LABS Annual Meeting

CERN, Geneva, Switzerland

28 October 2024

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