FCC Feasibility Study Status

HFM annual meeting 2023

CERN, 30 October 2023

Michael Benedikt, Frank Zimmermann, CERN

on behalf of FCC collaboration & FCCIS DS team

photo: J. Wenninger

FCC hh ee he | EuroCirCol A key to New Physics | EASITrain | iFAST | FUTURE CIRCULAR COLLIDER Innovation Study | E-JADE | EAJADE | CHART Swiss Accelerator Research and Technology | http://cern.ch/fcc | CERN

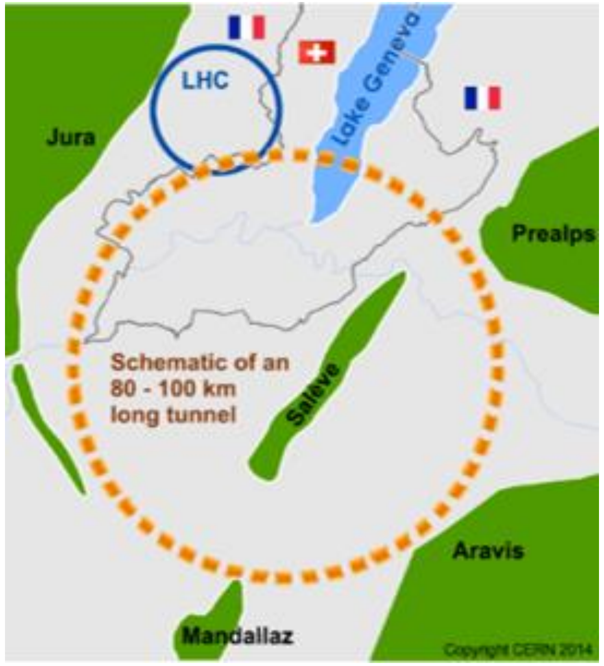
*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **iFAST**, grant agreement 101004730, **FCCIS**, grant agreement 951754; **E-JADE,** contract no. 645479; **EAJADE**, contract number 101086276; and by the Swiss **CHART** program*

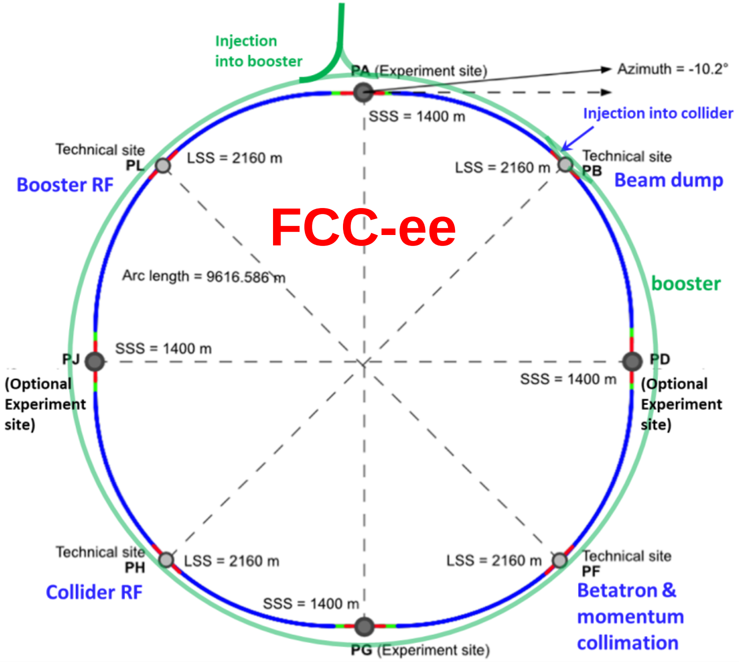
European Commission | Horizon 2020 European Union funding for Research & Innovation

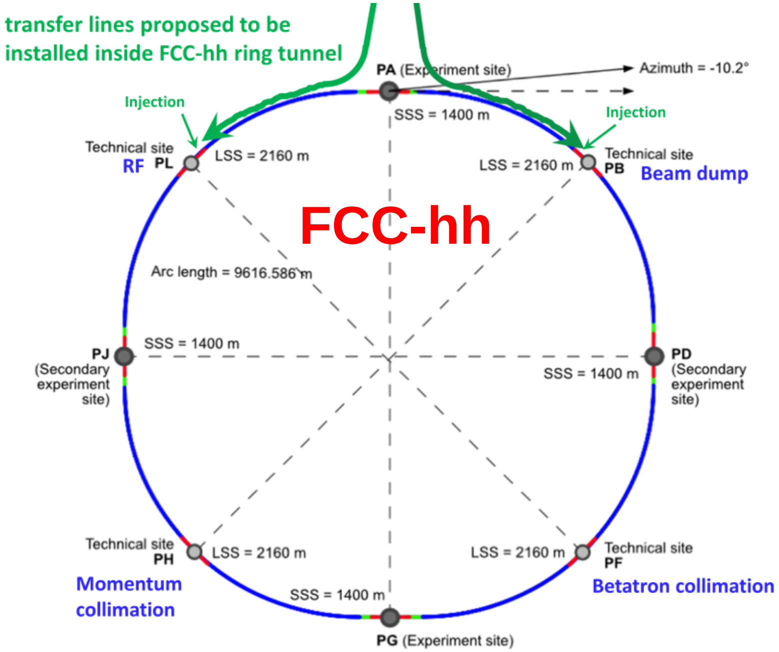
FCC integrated program

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as “energy upgrade” of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC

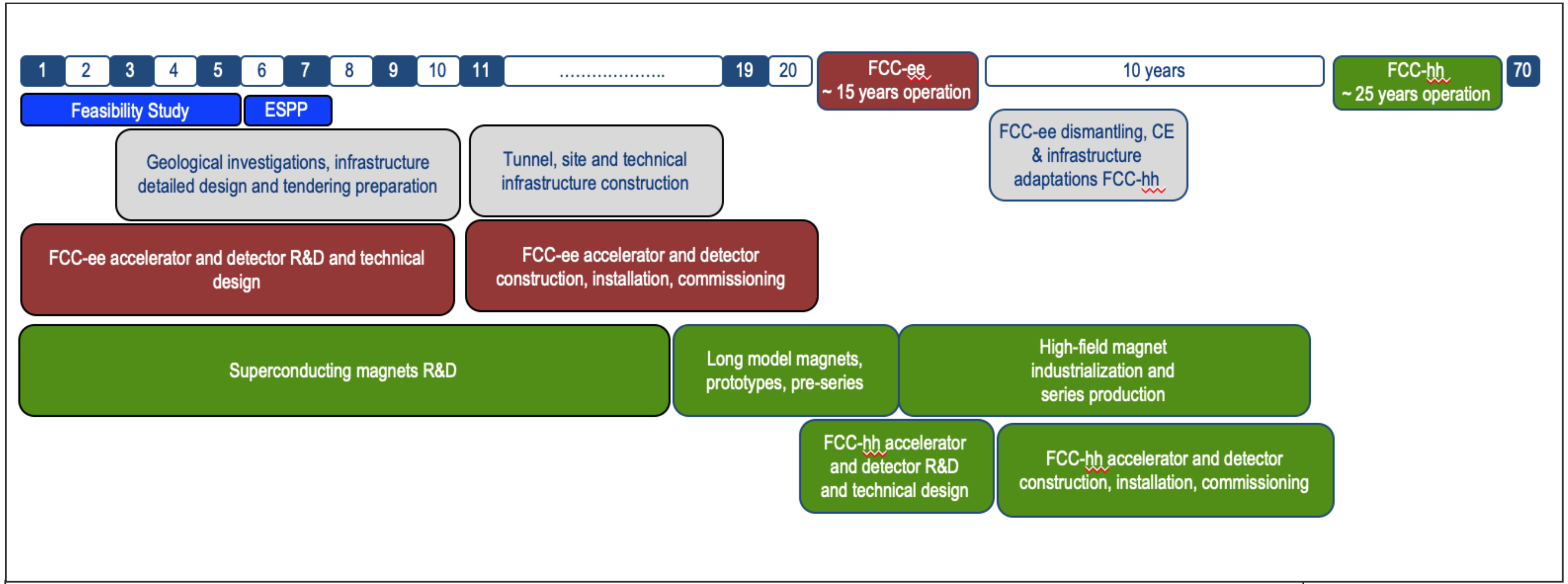




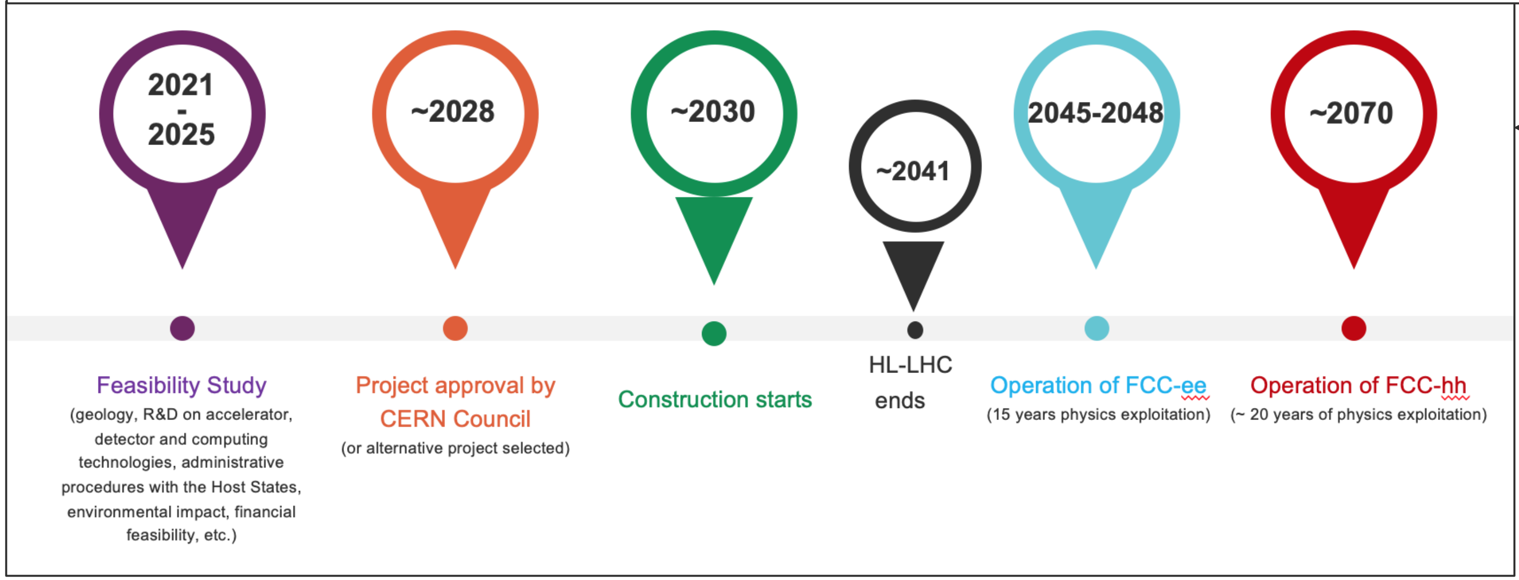


2020 - 2040 | **2045 - 2063** | **2070 - 2095**

FCC timeline



Technical schedule:
FCC integrated project



Schedule takes into account:

- ❑ CERN Council approval timeline
- ❑ past experience in building colliders at CERN
- ❑ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)

F. Gianotti

European Strategy for Particle Physics

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."

→ FCC Conceptual Design Reports (2018/19)

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

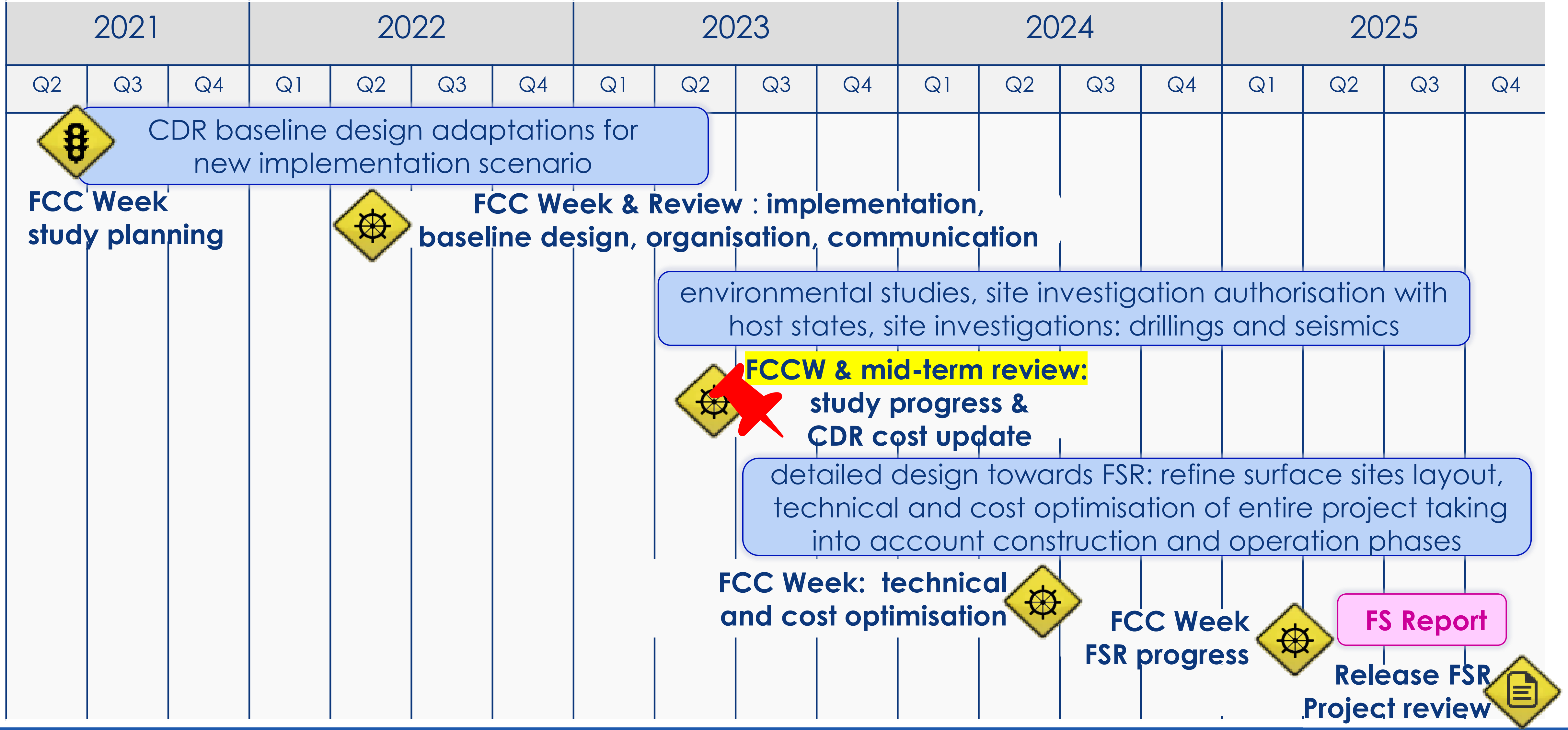
CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

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."

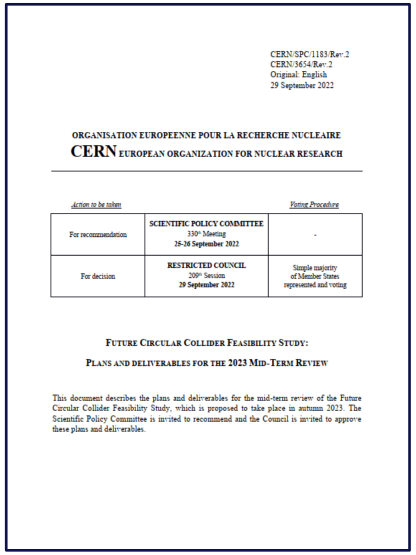
Feasibility Study timeline and main activities/milestones



FCC FS mid-term review

Mid-term review setup and deliverables are defined in CERN/SPC/1183/Rev.2:

- *the scientific and technical results be reviewed by the FCC FS Scientific Advisory Committee, augmented by additional experts as needed;*
- *the cost and financial feasibility, which will focus on the first-stage project (tunnel, technical infrastructure, FCC-ee machine and injectors), be reviewed by a committee including external experts, as proposed in CERN/3588;*


CERN/SPC/1183/Rev.2
CERN/3654/Rev.2
Original: English
29 September 2022

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

Action to be taken		Voting Procedure
For recommendation	**SCIENTIFIC POLICY COMMITTEE** 330th Meeting **25-26 September 2022**	-
For decision	**RESTRICTED COUNCIL** 209th Session **29 September 2022**	Simple majority of Member States represented and voting

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:

PLANS AND DELIVERABLES FOR THE 2023 MID-TERM REVIEW

This document describes the plans and deliverables for the mid-term review of the Future Circular Collider Feasibility Study, which is proposed to take place in autumn 2023. The Scientific Policy Committee is invited to recommend and the Council is invited to approve these plans and deliverables.

SAC: review of deliverables 1, 2, 3, 4, 5, 6, 8

- D1: Definition of the baseline scenario
- D2: Civil engineering
- D3: Processes and implementation studies with the Host States
- D 4: Technical infrastructure
- D5: FCC-ee accelerator
- D6: FCC-hh accelerator
- D7: Project cost and financial feasibility
- D8: Physics, experiments and detectors

Cost Review Panel Mandate

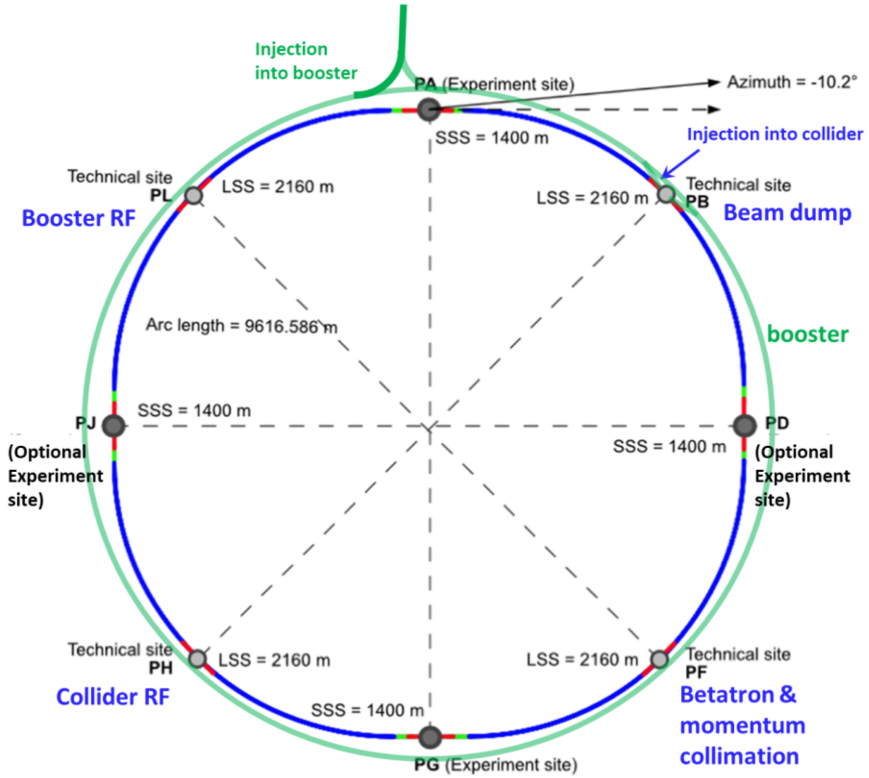
- Review the methodology and assumptions used in producing the cost estimates
- Identify inaccurate or missing cost information
- Check the consistency of the cost estimates with respect to applicable reference work, e.g., recent large-scale infrastructure and accelerator projects
- Review the uncertainty estimates
- Identify potential areas of savings and cost mitigation for future work
- Advise the FCC study team on matters of cost estimation in view of preparation of the final Feasibility Study Report for end 2025

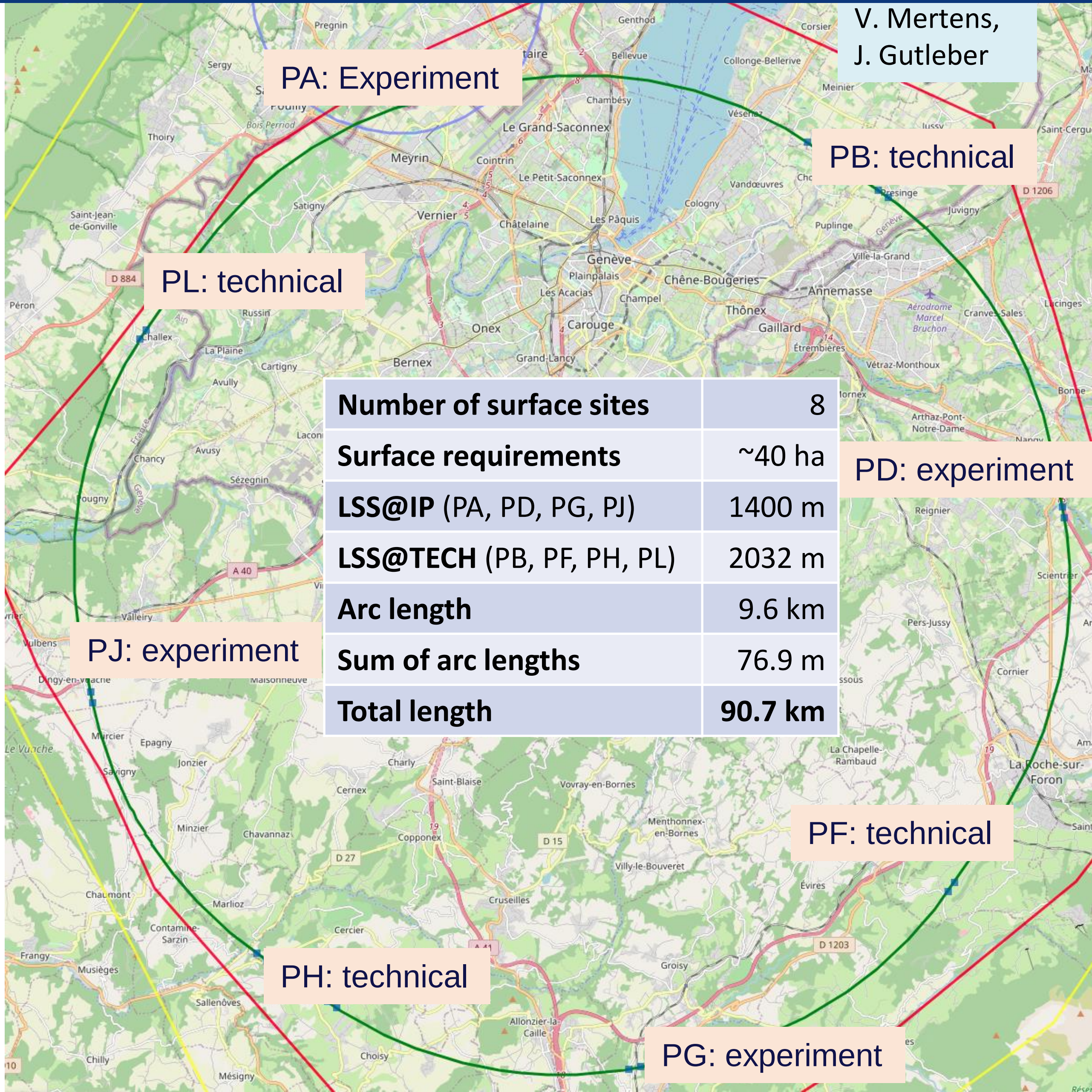
Optimized placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce -compensate” principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement





Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

progress with implementation baseline PA31 90.7 km

Meetings with municipalities concerned in France (31) and Switzerland (10)

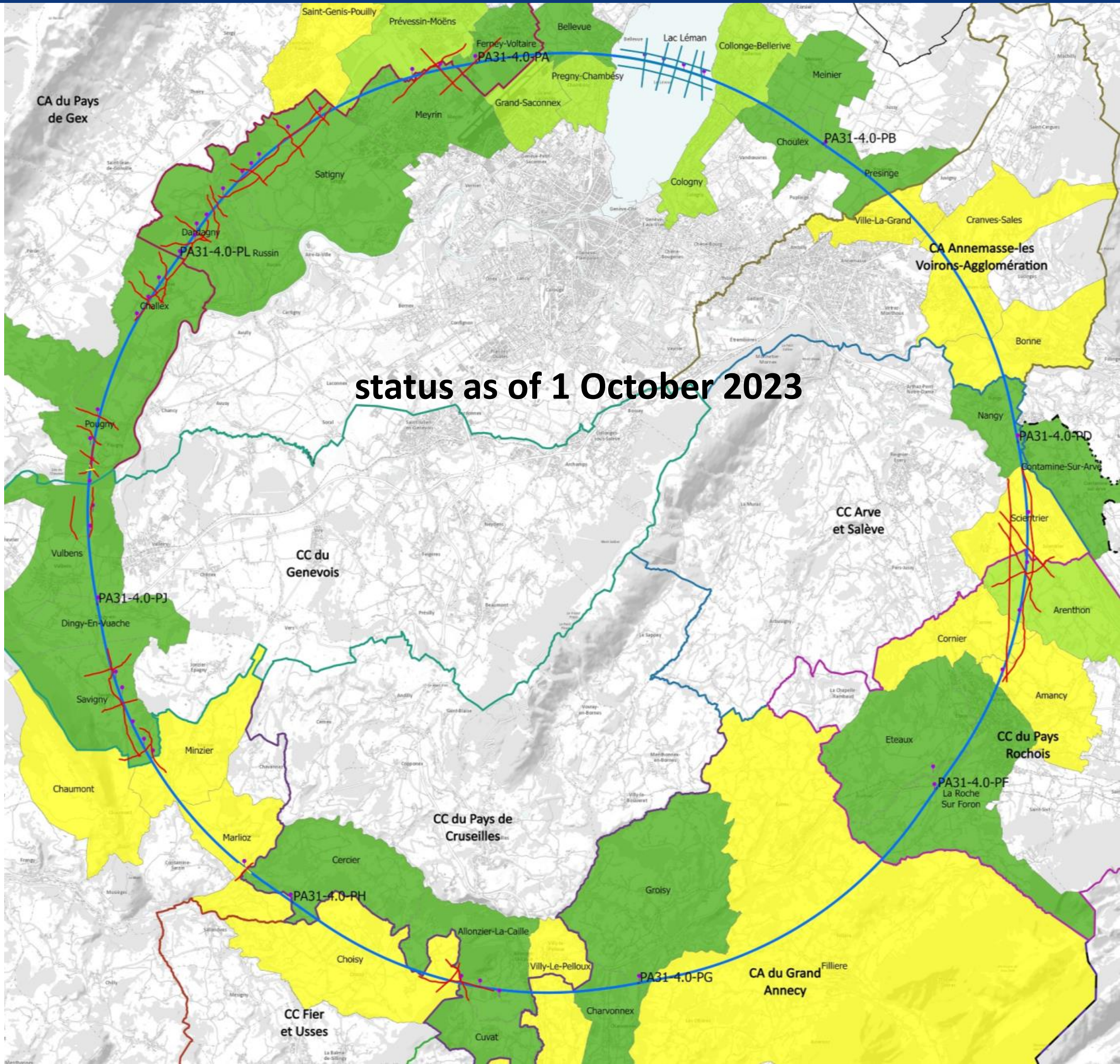
- **PA – Ferney Voltaire** (FR) – site experimental
- **PB – Présinge/Choulex** (CH) – site technique
- **PD – Nangy (FR)** – site experimental
- **PF – Roche sur Foron/Etaux** (FR) – site technique
- **PG – Charvonnex/Groisy** (FR) – site experimental
- **PH – Cercier** (FR) – site technique
- **PJ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

Individual meeting

Individual meeting planned

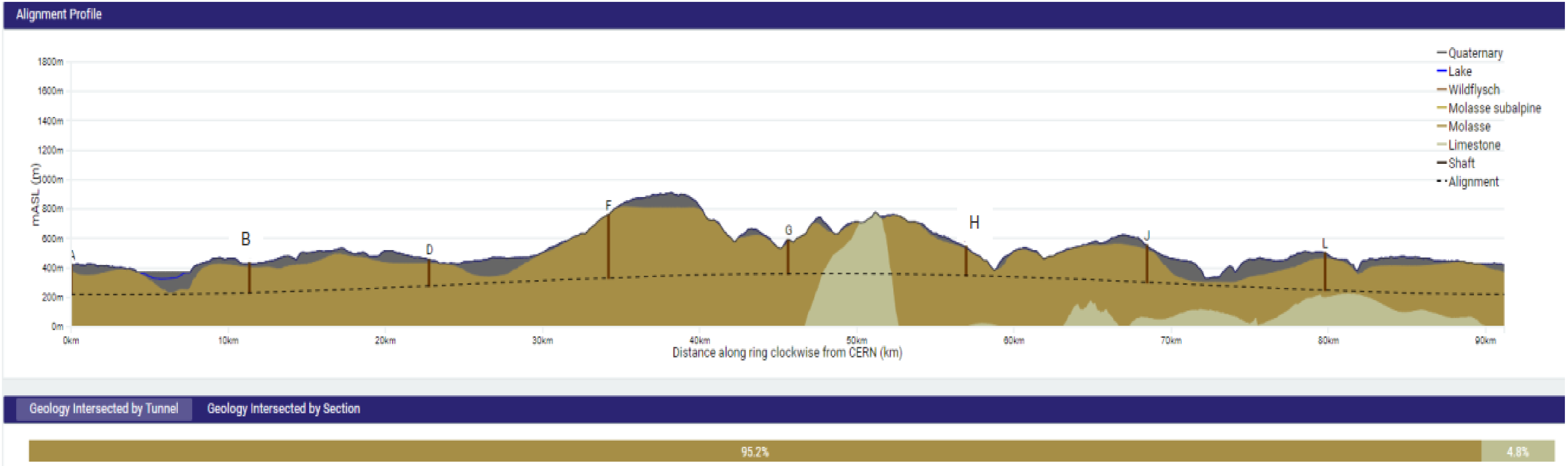
Collective meeting

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



FCC tunnel implementation

FUTURE CIRCULAR COLLIDER

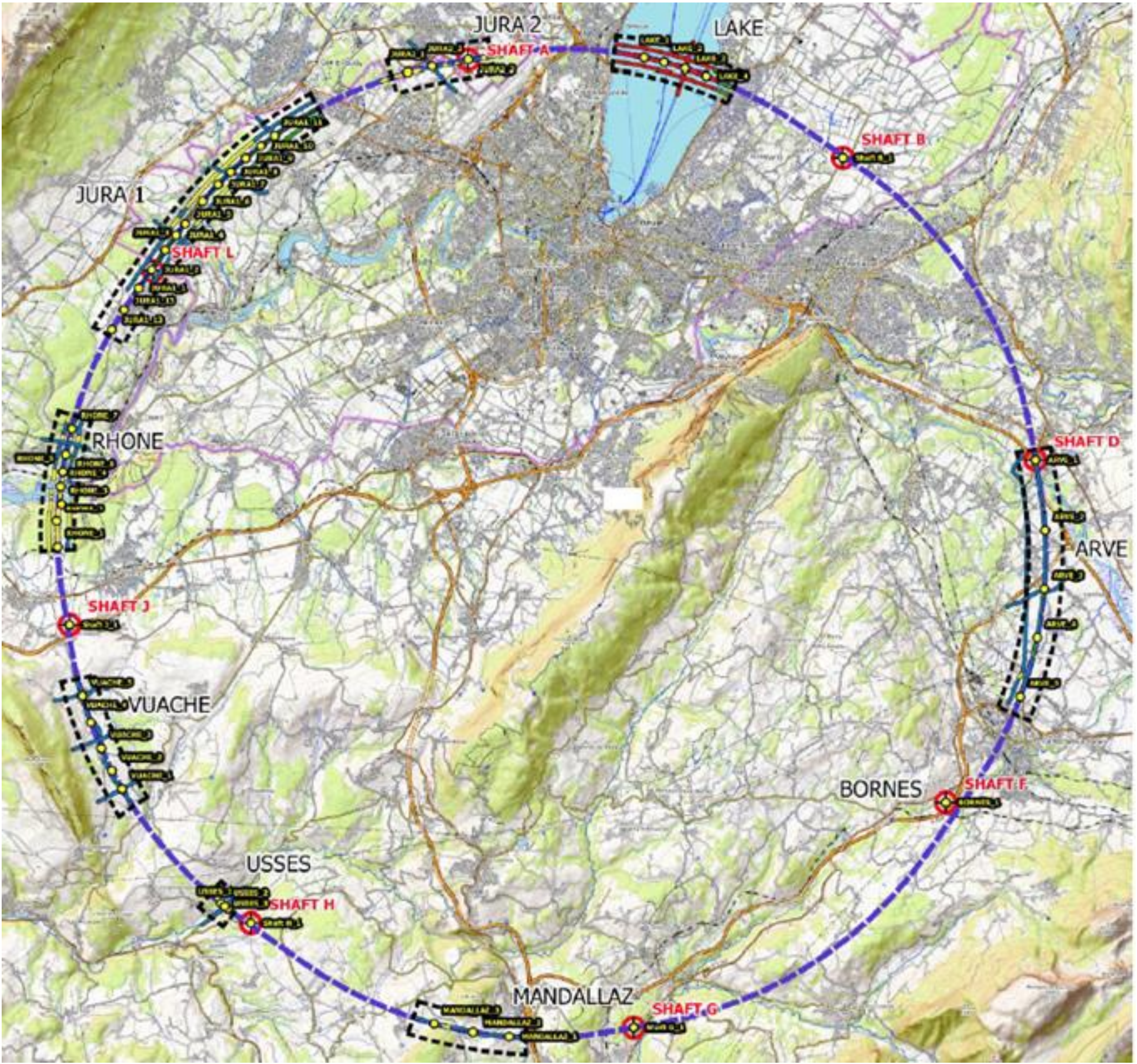


Tunnel implementation summary

- 91 km circumference
- 95% in molasse geology for minimising tunnel construction risks
- 8 surface sites with ~5 ha area each.

FUTURE CIRCULAR COLLIDER

Status site investigations



- **Site investigations in areas with less well known geological conditions:**
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022.
  - **Alignment with FR and CH on the process for obtaining autorisation procedures. Ongoing for start of drillings in 03/2024.**

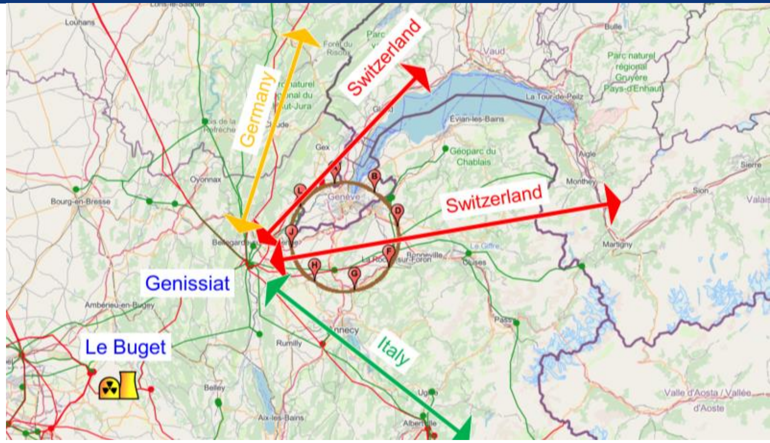
- **Contracts Status:**
  - Contract for engineering services and role of Engineer during works, active since July 2022
  - Site investigations tendering ongoing towards contract placement in December 2023 and mobilization from January 2024.

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

Drilling works on the lake

Connections to electrical grid infrastructure

Updated FCC-ee energy consumption	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. power during beam operation (MW)	**222**	**247**	**273**	**357**
Average power / year (MW)	122	138	152	202
Total yearly consumption (TWh)	**1.07**	**1.21**	**1.33**	**1.77**

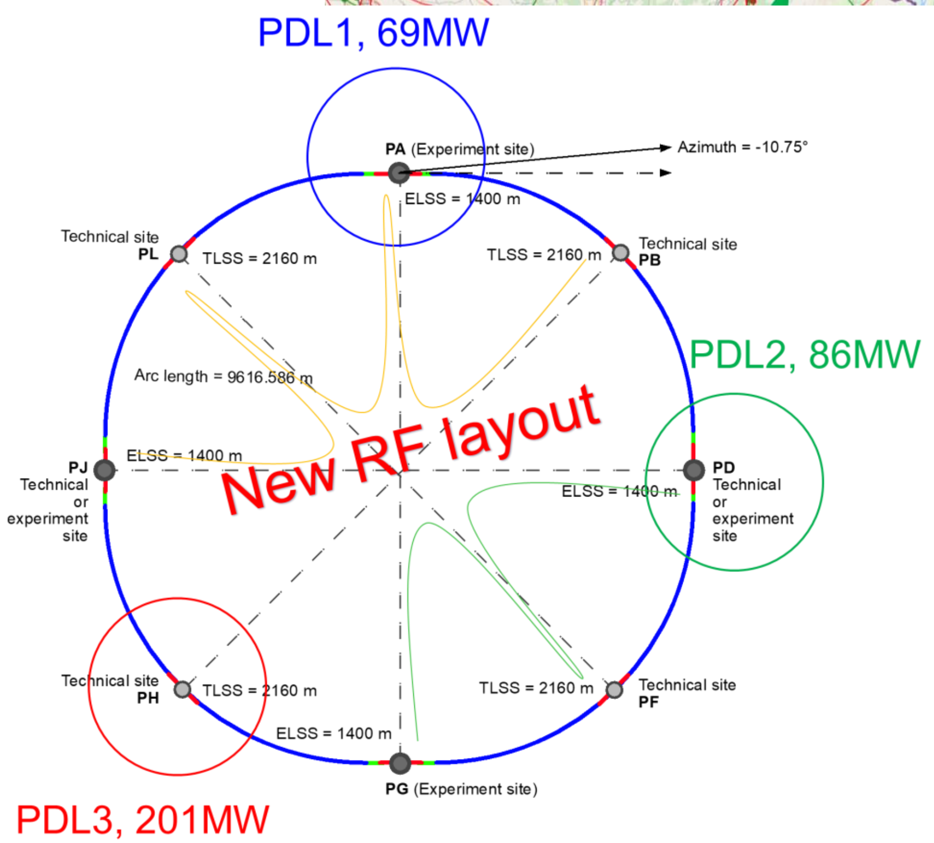


Powering concept and max power load by sub-stations:

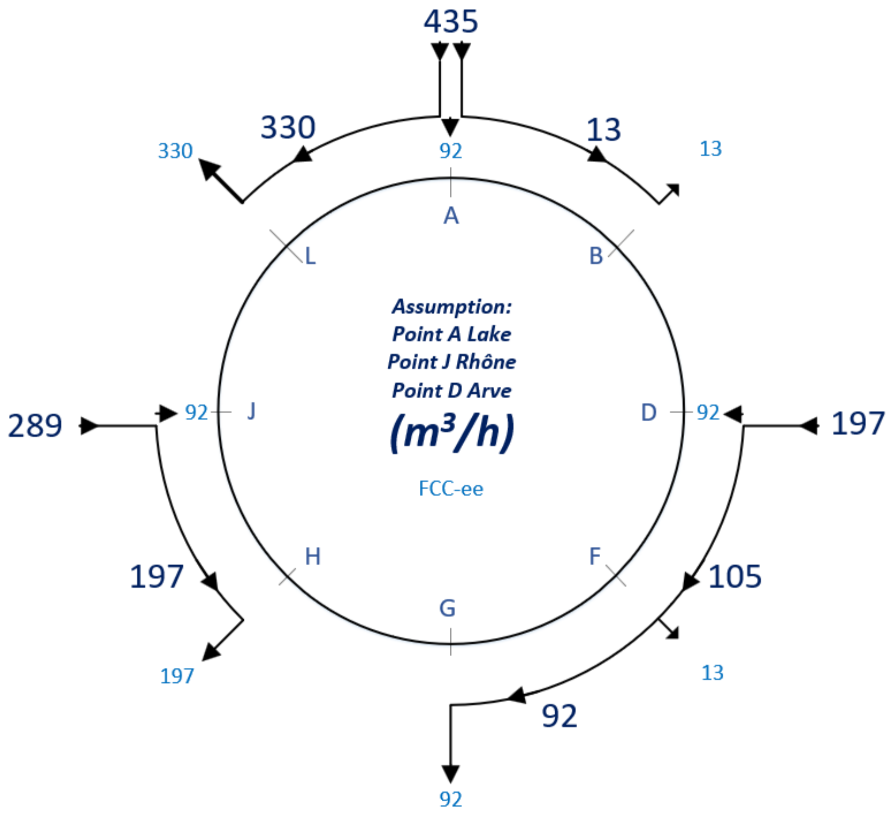
The loads could be charged on three sub-stations (optimally connected to existing regional HV grid):

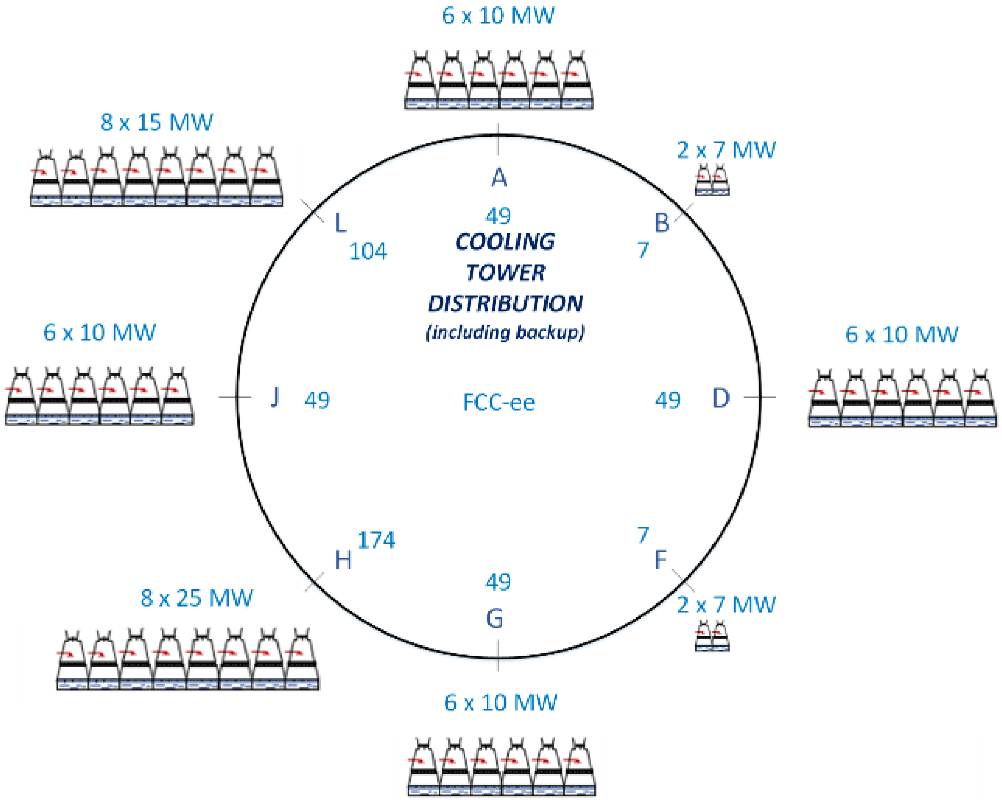
- **Point D with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- **Point A with existing CERN station** covering PB – PL – PJ

- **Connection concept was studied and confirmed by RTE (French electrical grid operator)**
- **Requested loads have no significant impact on grid**
- **Powering concept and power rating of the three sub-stations compatible with FCC-hh**



Cooling Water

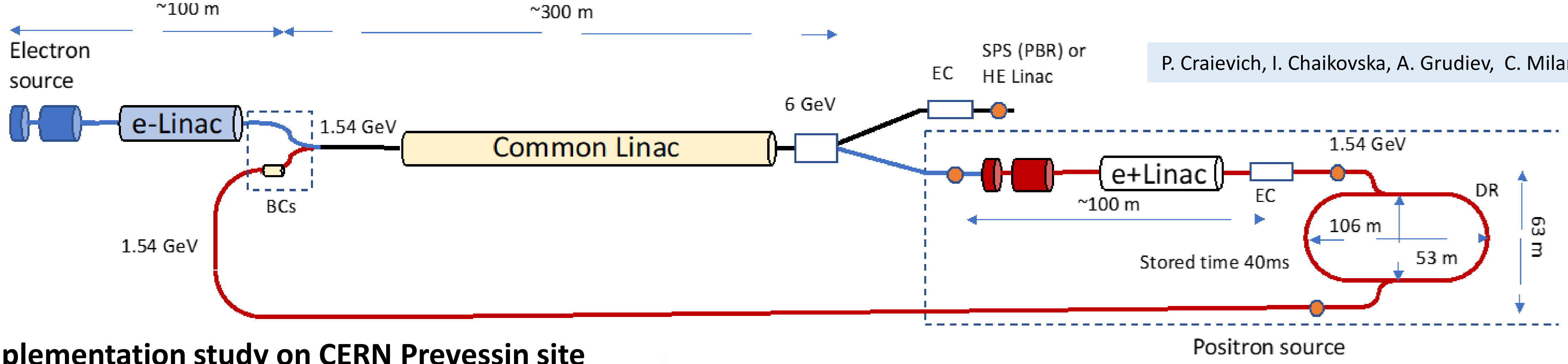




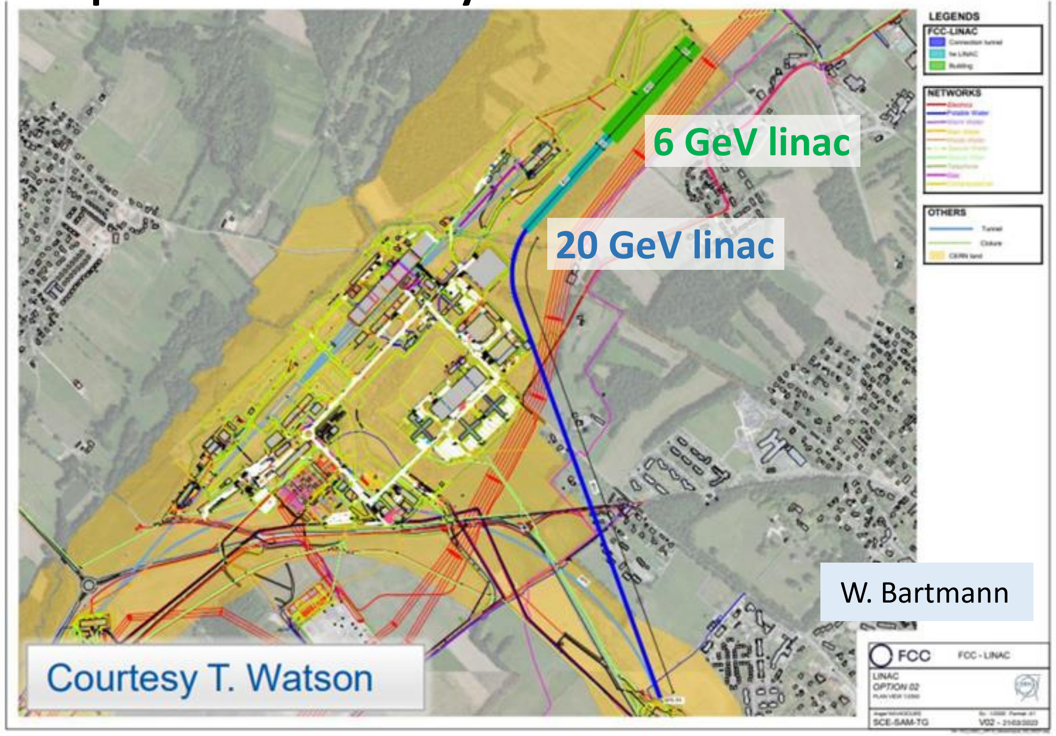
- **Potential sources of cooling water Geneva lake (PA), Rhone (PJ) and Arve (PD).**
- **Existing line with lake water provided by SIG to CERN LHC P8 (LHCb) sufficient for FCC-ee.**
- **Pipework in the tunnel will connect the remaining points to points PA, PD and PJ.**
- **Main cooling towers placed at experiment points, and RF points (PL, PH).**

FCC-ee injector layout & implementation

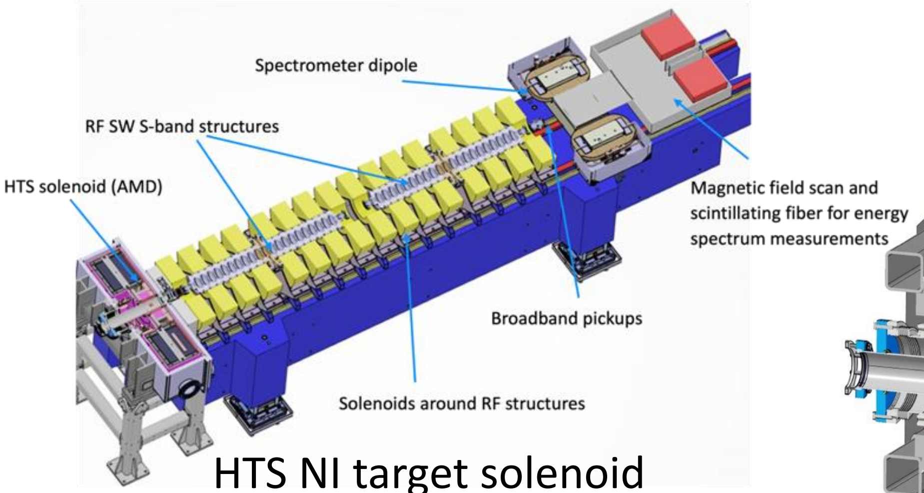
P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

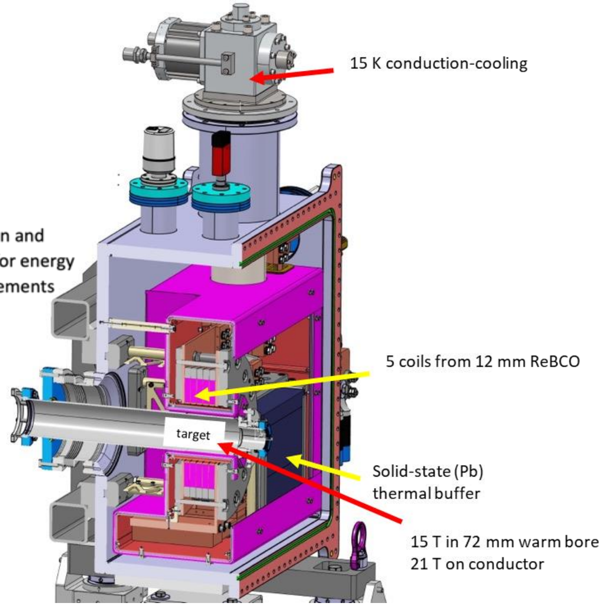


implementation study on CERN Prevessin site



"Positron production experiment" at PSI's SwissFEL, beam tests from 2025/26





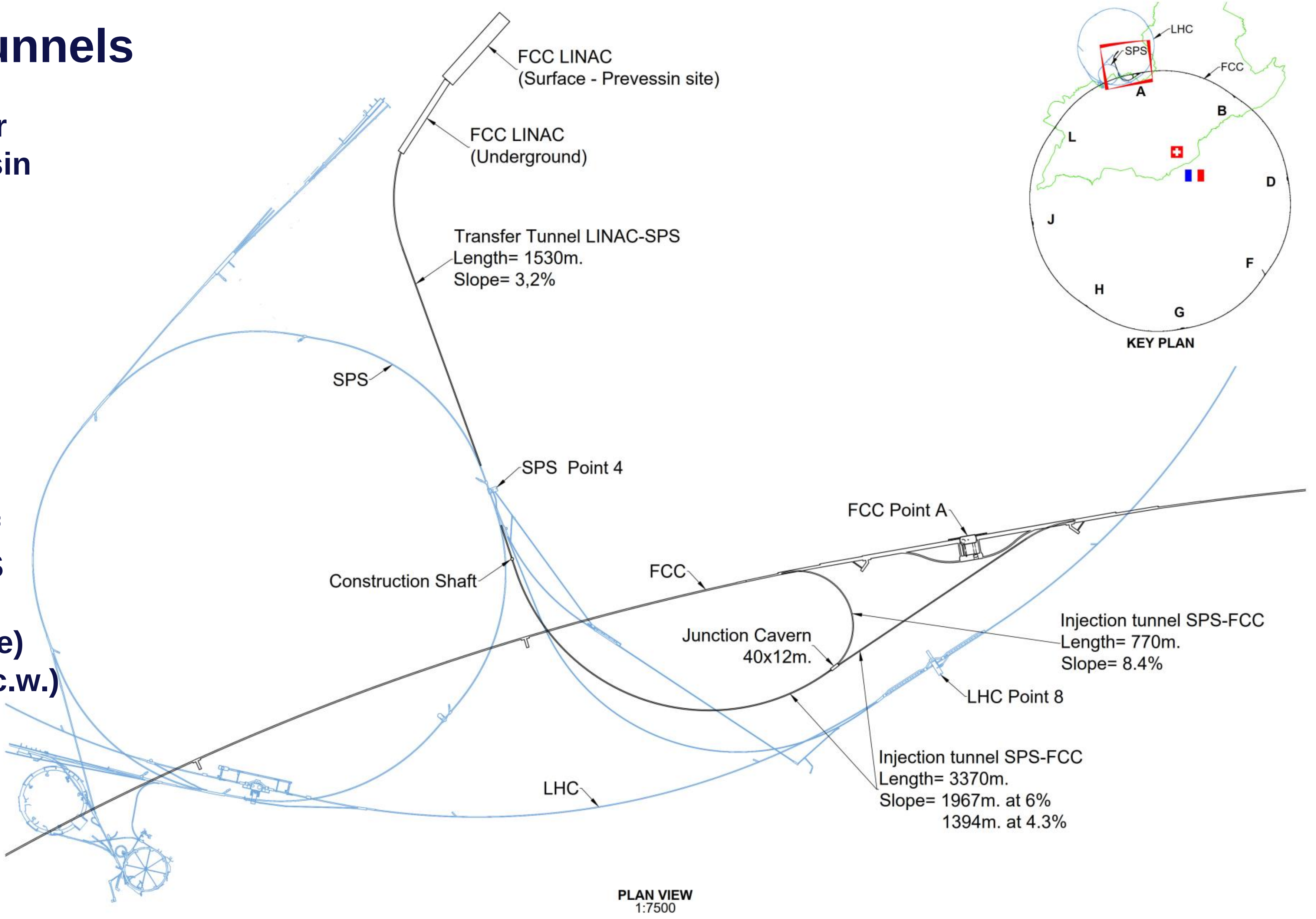
HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues

Transfer line FCC-ee (option with SPS for FCC-hh)

LINAC and Injection Tunnels

- **Designed to enable injection either from the HE Linac sited at Prevessin of from the SPS as pre-booster**
- **Single tunnel with spur to enable anti-clockwise injection**
- **Design allows re-use for FCC-hh if injector in the SPS tunnel (SC-SPS option)**
  - **SPS Point 4 to FCC (clockwise)**
  - **SPS Point 6 to FCC (counter-c.w.)**



FUTURE CIRCULAR COLLIDER

FCC-ee: main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	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 tt pairs

technical feasibility of changing operation sequences was assessed (e.g. starting at ZH energy)

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

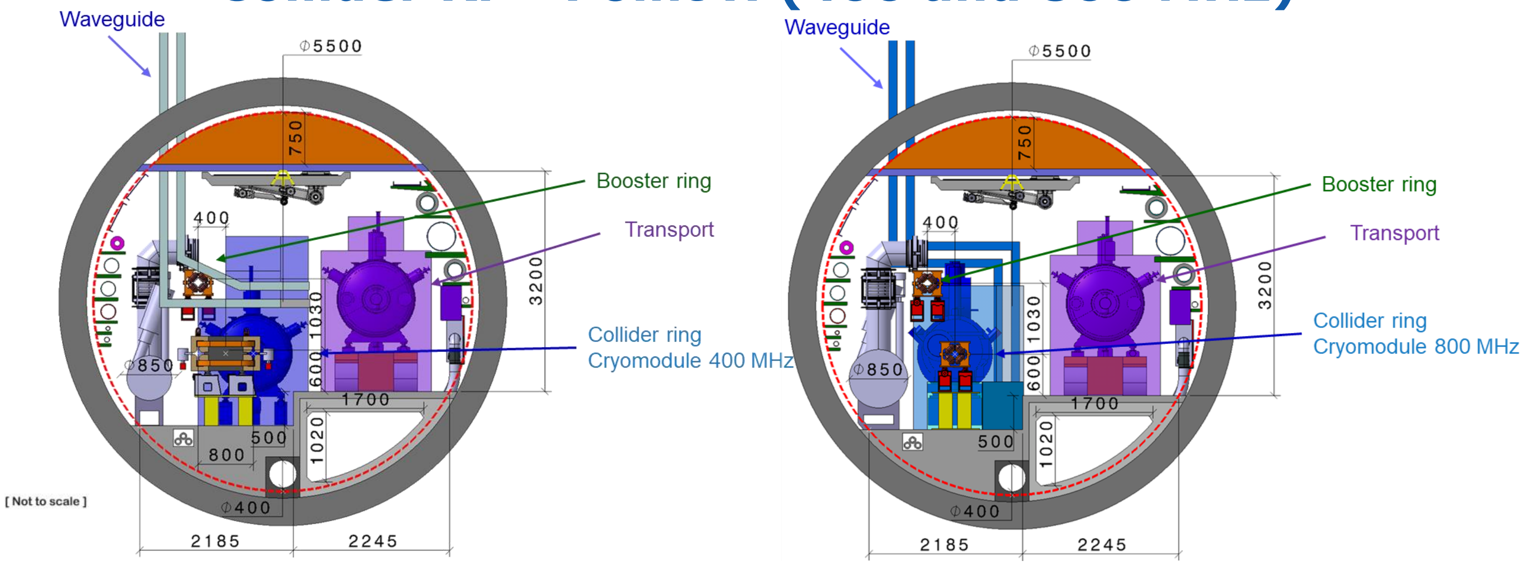
Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

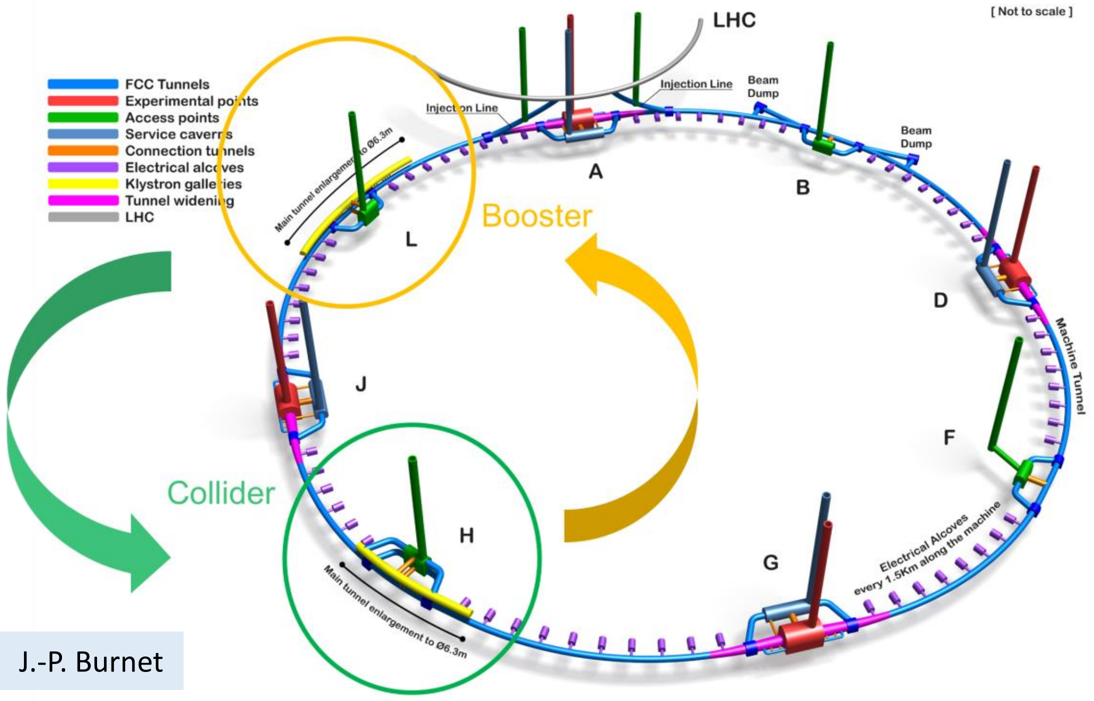
F. Gianotti

FCC-ee RF layout

- RF for collider and booster in separate straight sections H and L.
- fully separated technical infrastructure systems (cryogenics)
- collider RF (highest power demand) in point H with optimum connection to existing 400 kV grid line and better suited surface site

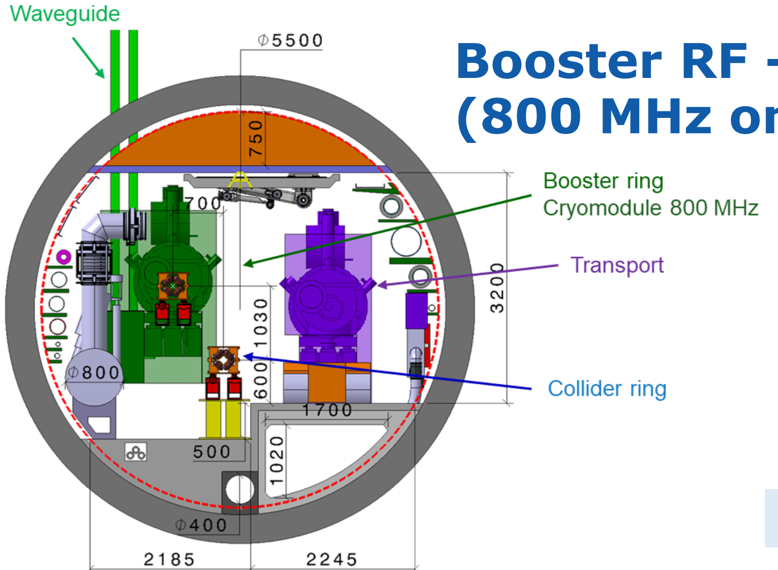
Collider RF - Point H (400 and 800 MHz)





J.-P. Burnet

Booster RF - Point L (800 MHz only)



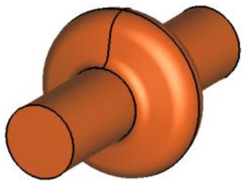
F. Valchkova, F. Peauger

FCC-ee SRF Technology

Broad R&D collaborations on SRF

Z

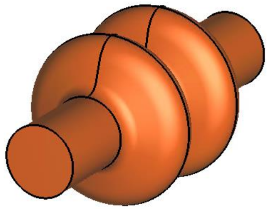
1-cell 400 MHz, Nb/Cu



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H

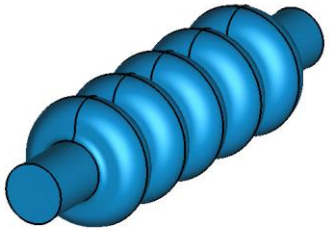
2-cell 400 MHz, Nb/Cu



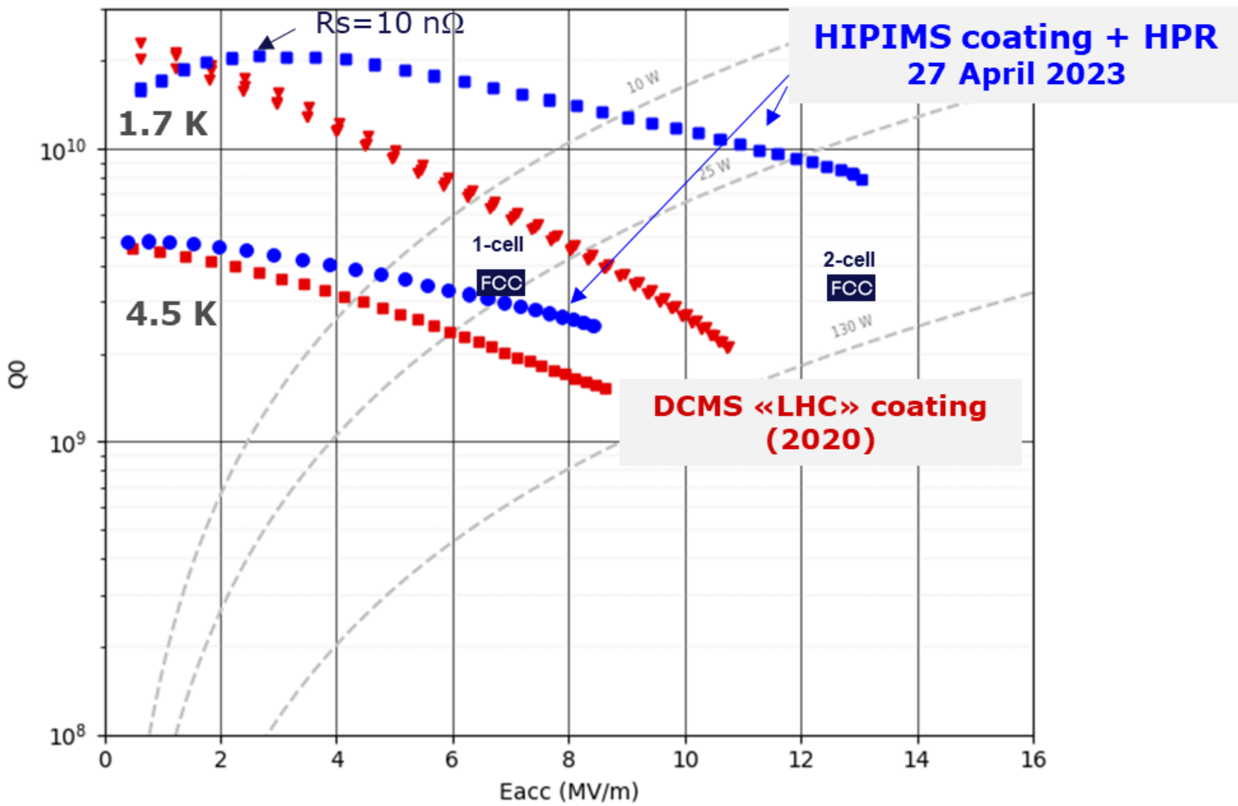
moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

ttbar, booster

5-cell 800 MHz, bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity



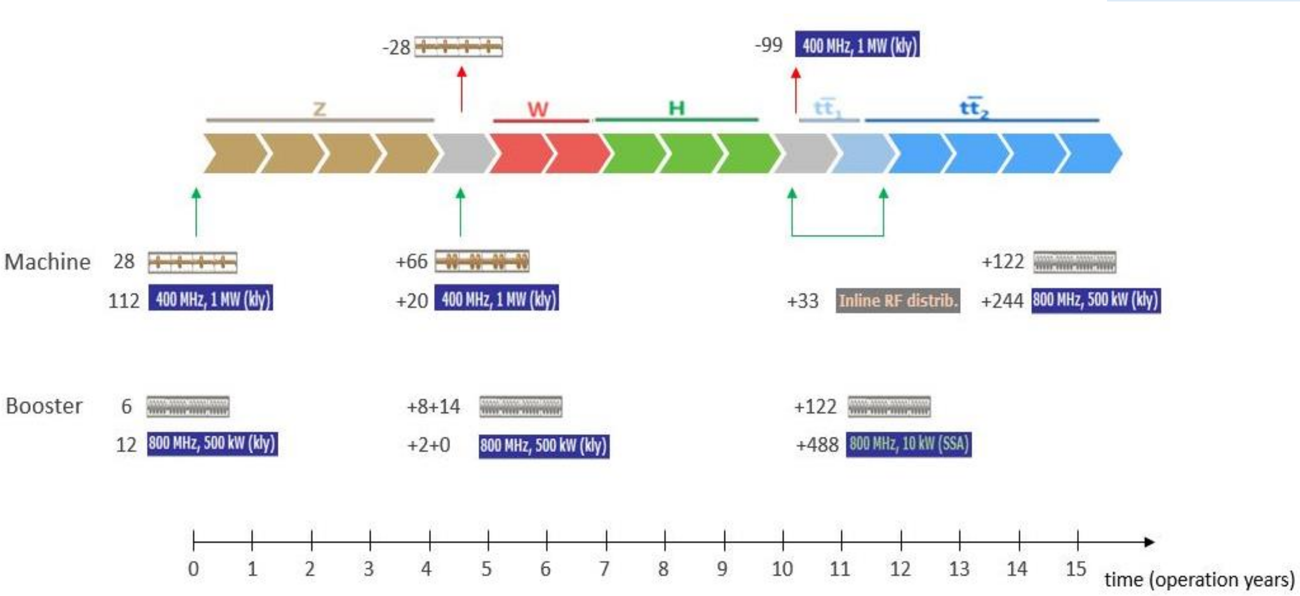
First attempt of HiPIMS* niobium coating on a 400 MHz Cu cavity

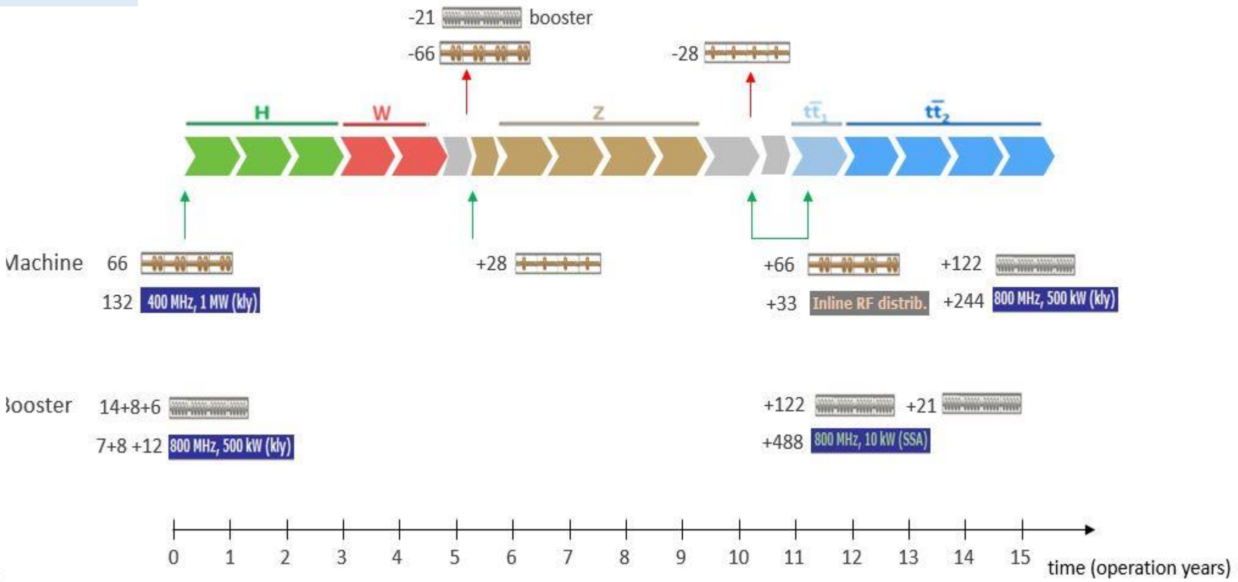
*High-power impulse magnetron sputtering

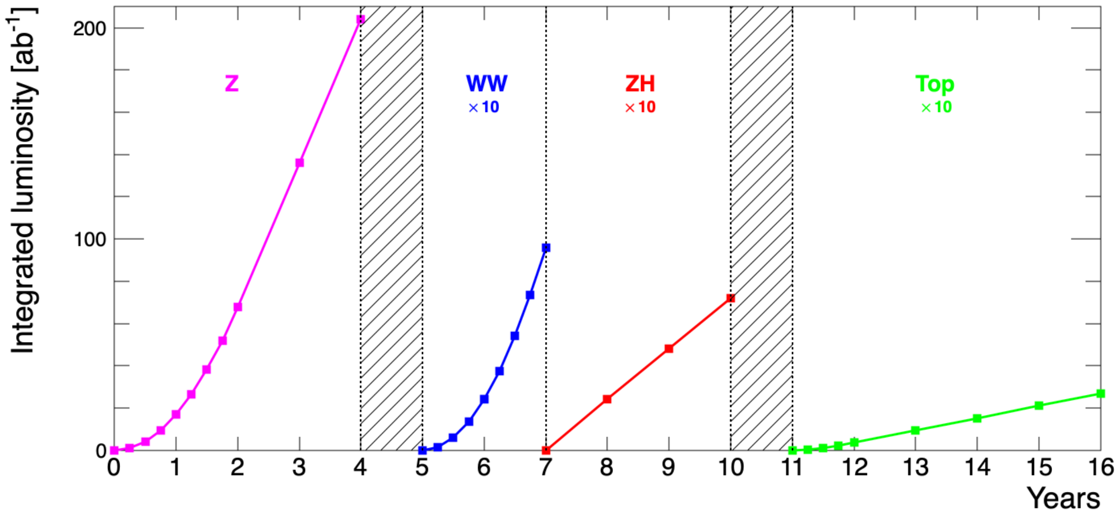
F. Peauger, O. Brunner

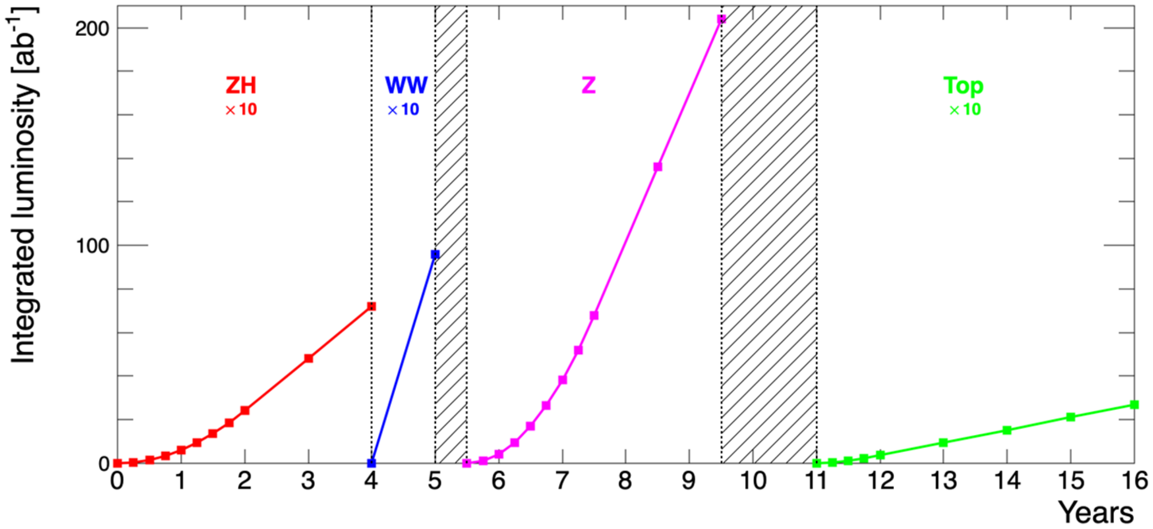
Operation sequences for FCC-ee

O. Brunner, F. Peauger









FCC-hh parameters

FUTURE CIRCULAR COLLIDER

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

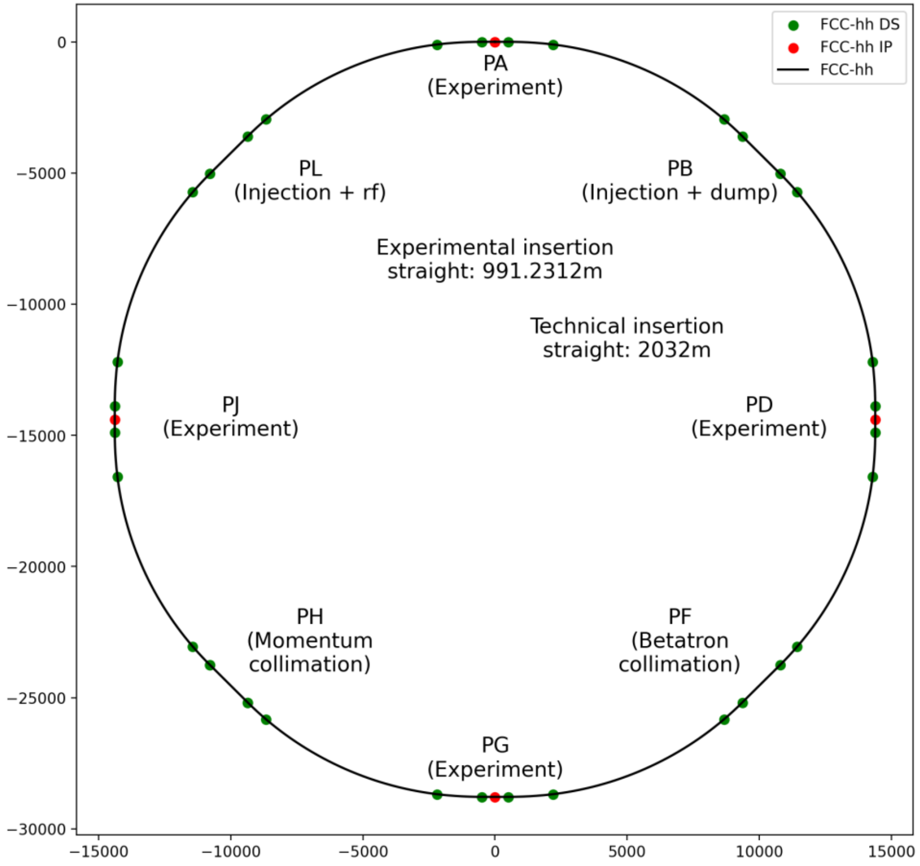
- high-field superconducting magnets: 14 - 20 T
- power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- stored beam energy: ~ 9 GJ → machine protection
- pile-up in the detectors: ~1000 events/xing
- energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

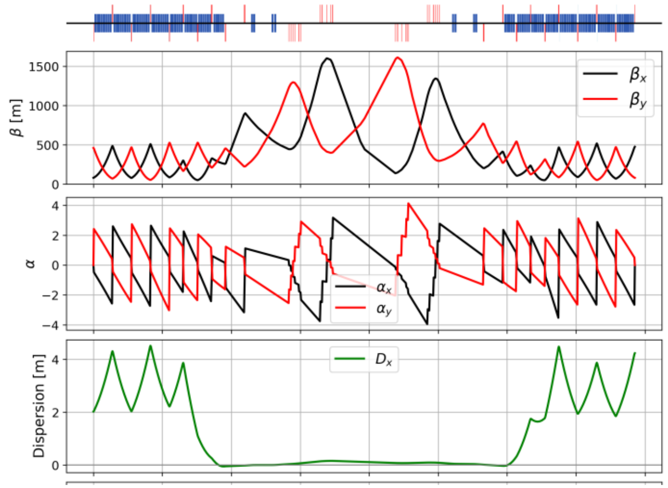
- Direct discovery potential up to ~ 40 TeV
- Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)
- Final word about WIMP dark matter

F. Gianotti

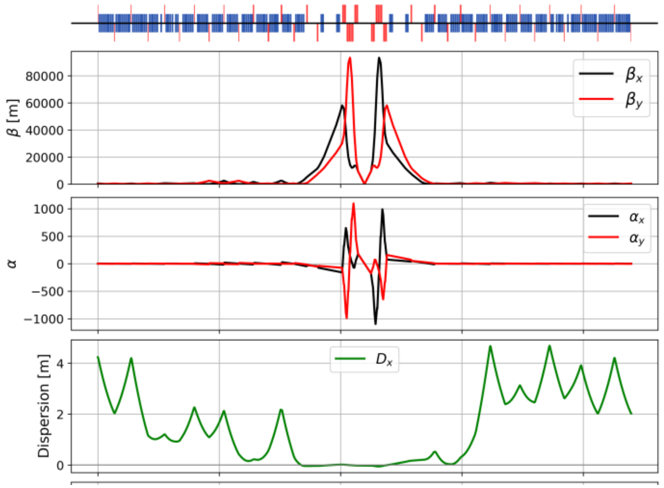
FCC-hh layout, optics work, geom. integration



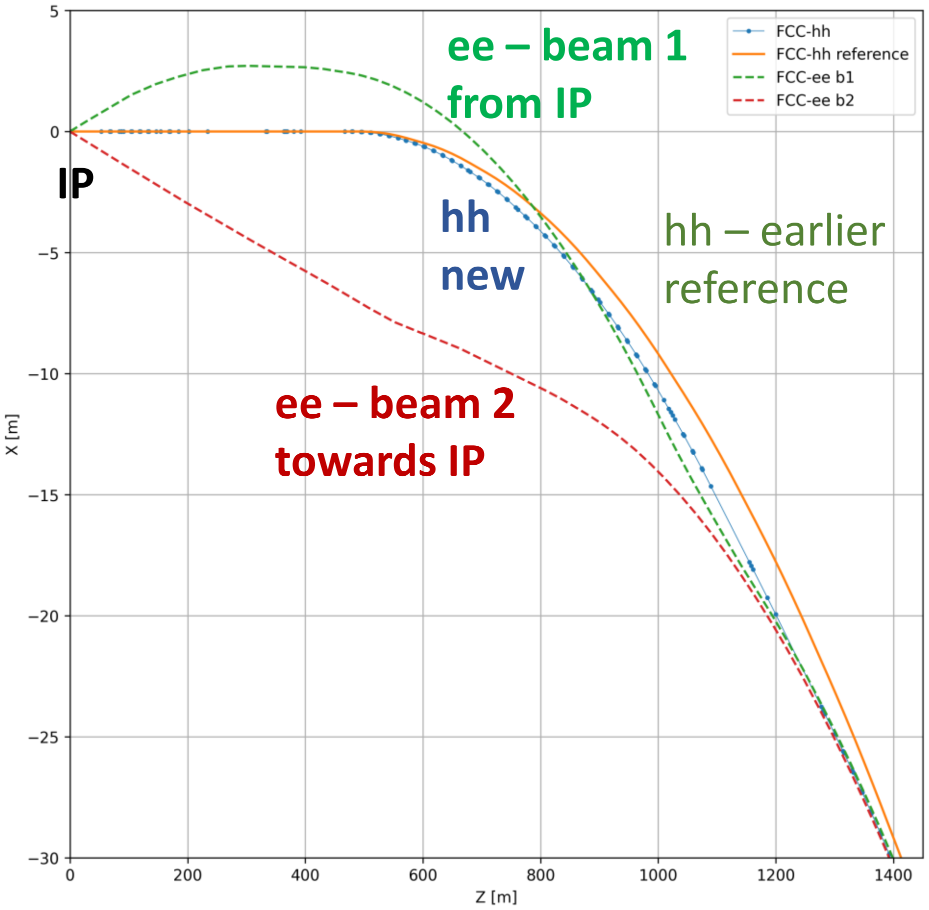
betatron collimation straight



experimental straight



3 - beam footprint at interaction point



- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)
- move hh IPs on top of ee IP to optimise tunnel and cavern widths.

M. Giovannozzi, T. Risselada, G. Perez Segurana, M. Hofer, K. Oide

High-field magnets for FCC-hh

- A power-saving, cost-effective High-Field Magnet technology with minimum cryogen inventory is the ambitious goal for FCC-hh HFM R&D.
- FCC-hh magnet R&D requires a sustained and globally coordinated efforts by international magnet R&D programs (HFM Programme, US-MDP, nat'l programs, etc.).
- Good coordination and communication among the FCC integrated program and magnet R&D programs is indispensable.
- Many technologies and target parameters compete for optimum value:
  - LTS today is seen as a cost-effective, rel. low risk, and potentially fast-tracked option.
  - HTS as path towards FCC-hh aspirational goals (c.o.m energy, societal impact, etc., while remaining affordable).
  - Technical readiness of HTS lags behind that of LTS by many years.
- Need to exploit synergies with other fields and applications to help to sustain the long-term effort.

Status of FCC global collaboration

FUTURE CIRCULAR COLLIDER

increasing international collaboration as a prerequisite for success

150 Institutes

32 Companies

34 Countries

EC H2020

Conclusions

The first half of the FCC FS will soon be completed with the mid-term review

- End October 2023: Review committee reports available to Scientific Policy Committee and Finance Committee
- 20 – 22 November 2023: SPC and FC review meetings on mid-term review
- 2 February 2024: CERN Council meeting on mid-term review

Focus so far: identifying best placement & layout and adapting entire project to new placement

Focus until end 2025: performance-risk-cost optimization considering project/operation phases and preparations for project preparatory phase

- Performance-risk-cost optimization considering construction & operation phases at system and global level
- Site investigation, surface site implementation with host states, environmental initial state, administrative processes
- Setting up for project preparatory phase: structure and resources, agreements with host states
- Setting up and strengthening R&D collaborations to advance towards technical design