The CERN Future Circular Collider Study

CERN-KEK Committee Meeting

Mike Lamont for

Michael Benedikt and Frank Zimmermann, CERN

on behalf of FCC collaboration & FCCIS DS team

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

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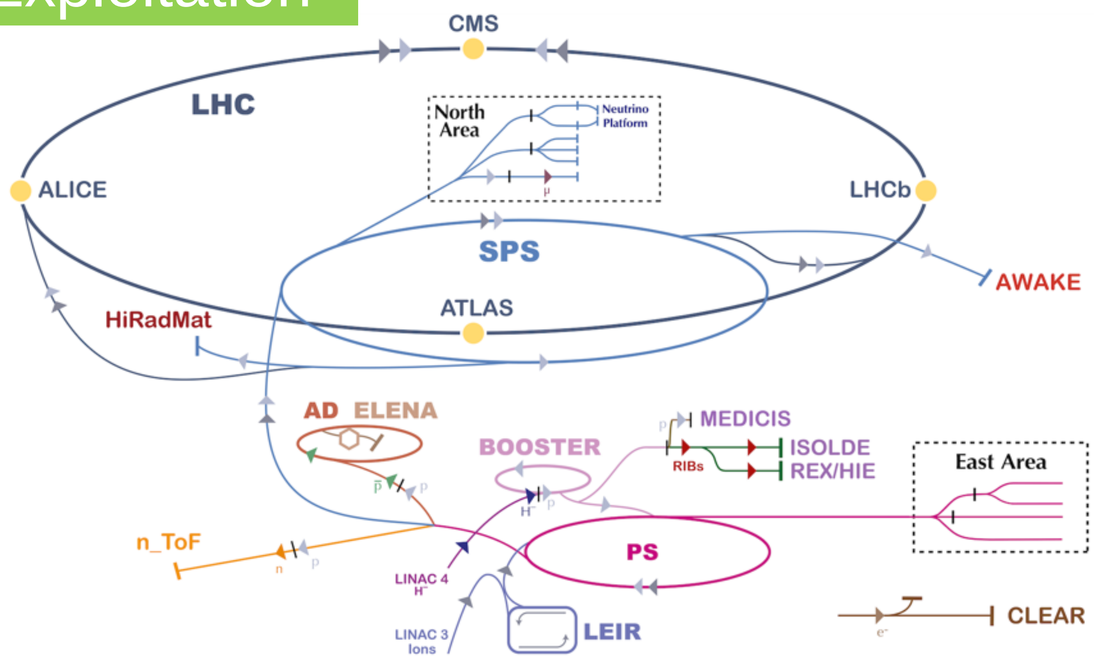
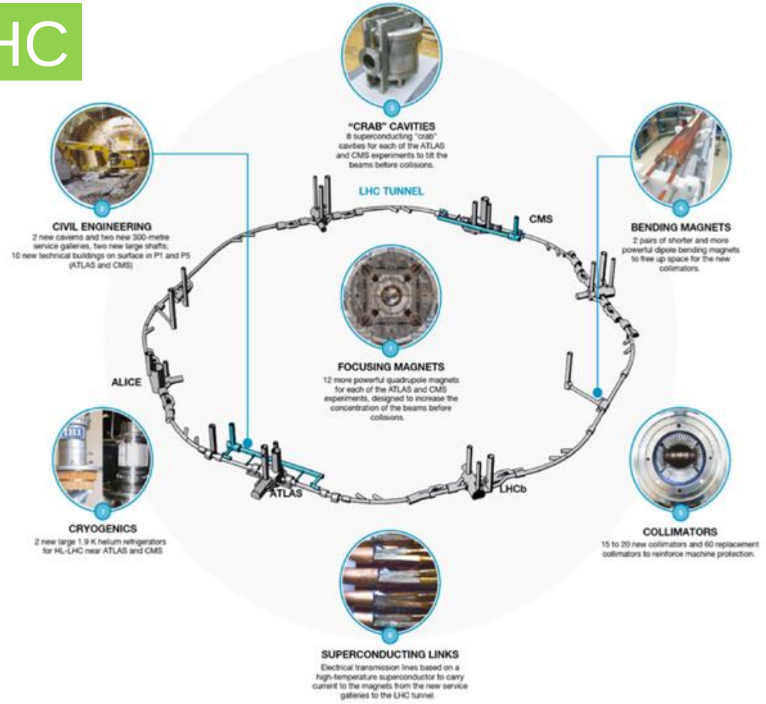
European Commission | Horizon 2020 European Union funding for Research & Innovation

photo: J. Wenninger

Exploitation

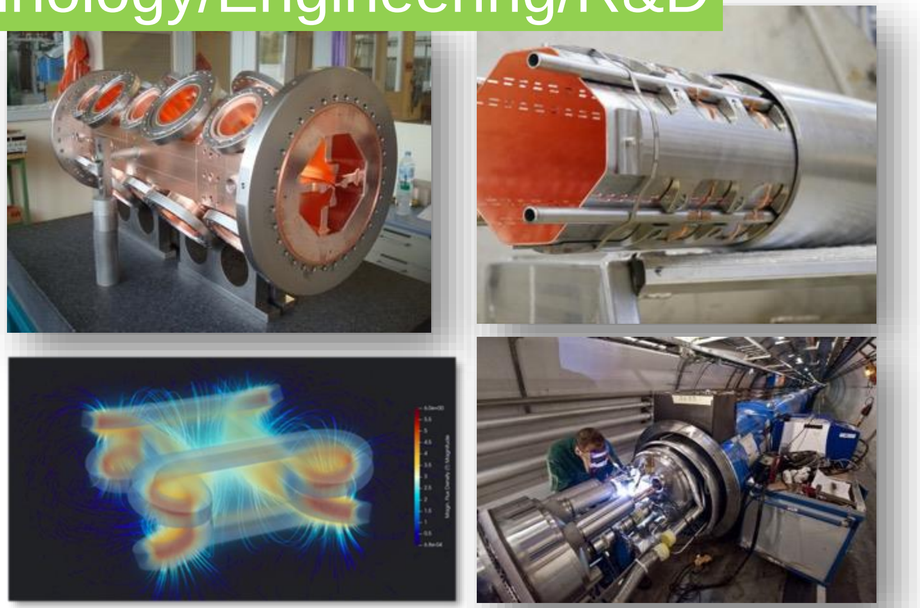


HL-LHC

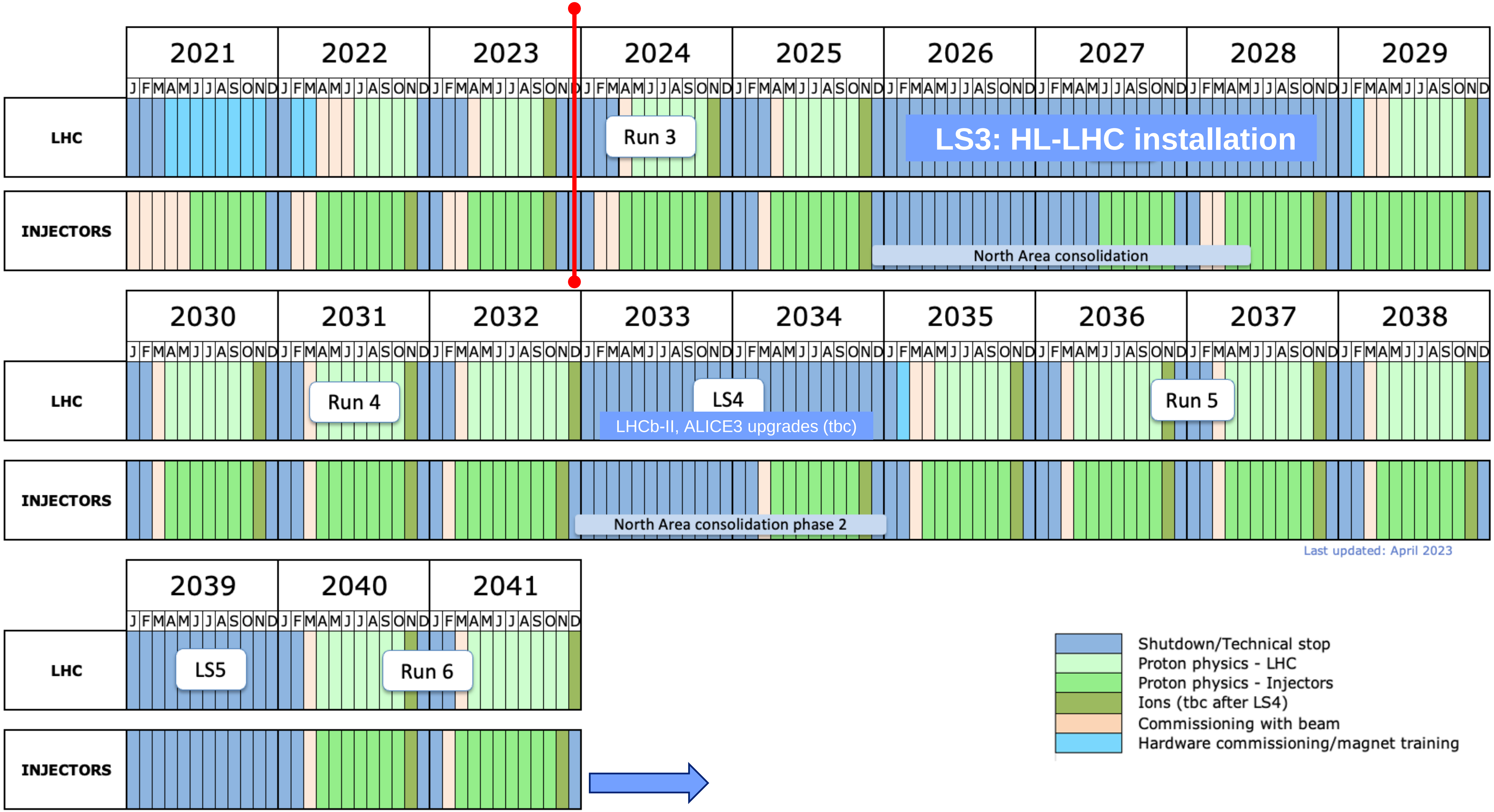


Future Options

Technology/Engineering/R&D



HL-LHC era - indicative timeline



European Strategy for Particle Physics 2020 Update

“An electron-positron Higgs factory is the highest-priority next collider.

For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.”

“Europe, together with its international partners, should investigate the 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.”

“Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

ILC, CLIC, Muon Collider also supported

Context

On the ground, the HL-LHC baseline schedule foresees operation until to the end 2041.

CERN/European Physics Community is positioning themselves to be able to start operating a new major facility in the second half of the forties (2045 - 2050).

That major new facility should be an e+e- Higgs factory.

Next ESPP update: ~2026-2027 – confirmation of priorities – down-selection

This could imply approval and resource commitment in the 2028 – 2030 timeframe, with subsequent project preparation and execution in the following decade.

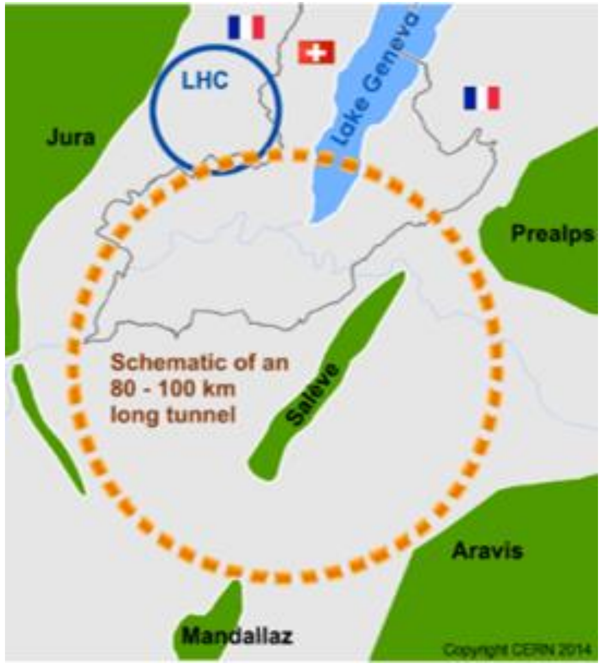
Given the projected large scale component production in the thirties, associated accelerator and detector technologies would need to be relatively mature as one moves into that phase.

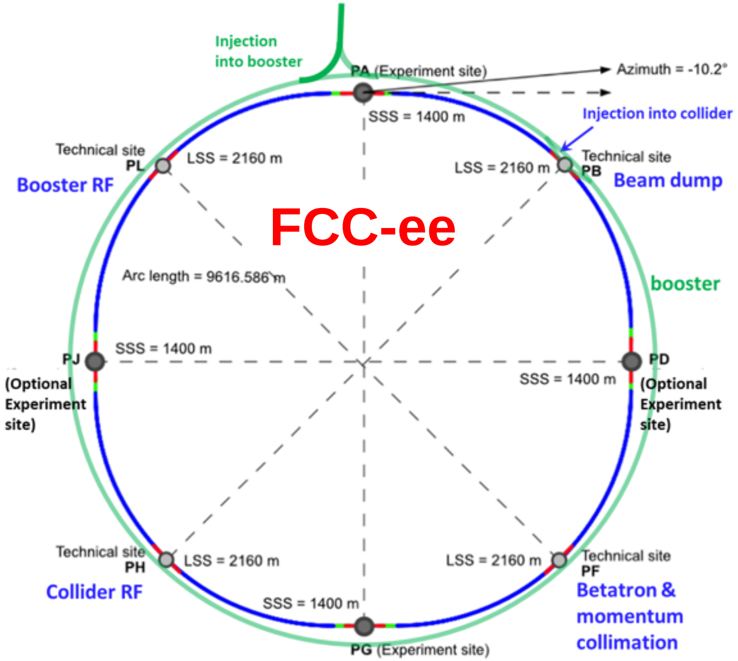
FCC

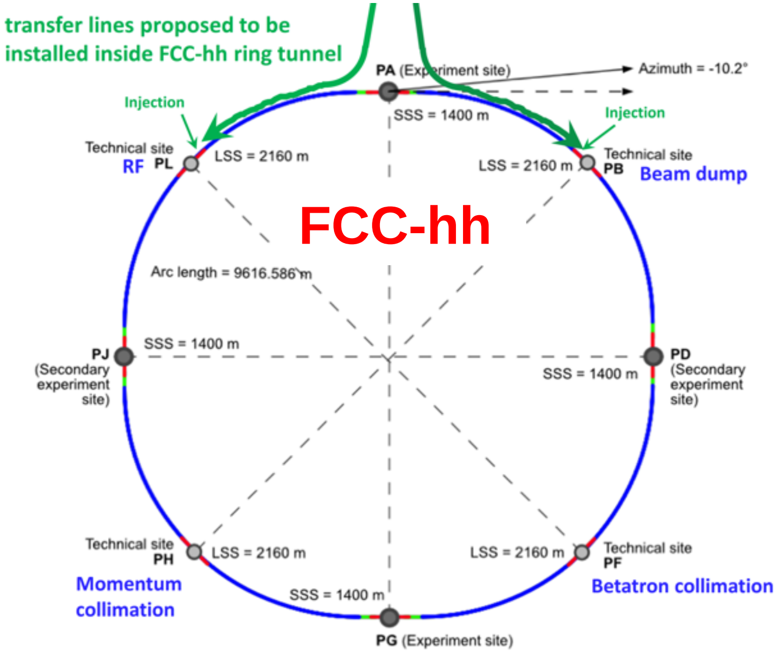
FCC Integrated Programme

Comprehensive long-term programme 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, with ion and eh options**







2020 - 2046 | **2048 - 2063** | **~2070 +**

FCC Feasibility Study 2021-2025: main objectives

Geological, technical, environmental and administrative feasibility

Optimisation of placement and layout of the ring and related infrastructure

Preparatory administrative processes

Optimisation of the design of FCC-ee and FCC-hh

Sustainable operational model for the machine and experiments

Consolidated cost estimate, as well as the funding and organisational models

Identification of substantial resources from outside CERN's budget

Consolidation of the physics case and detector concepts and technologies

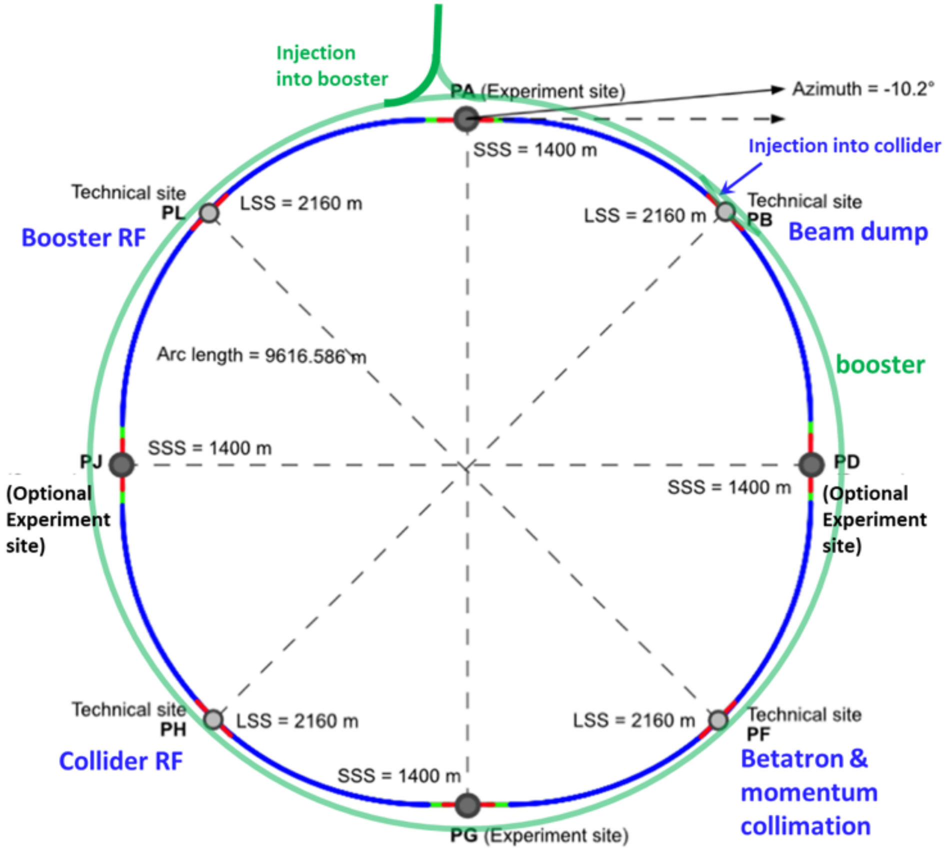
Serious mid-term review (including cost) just passed

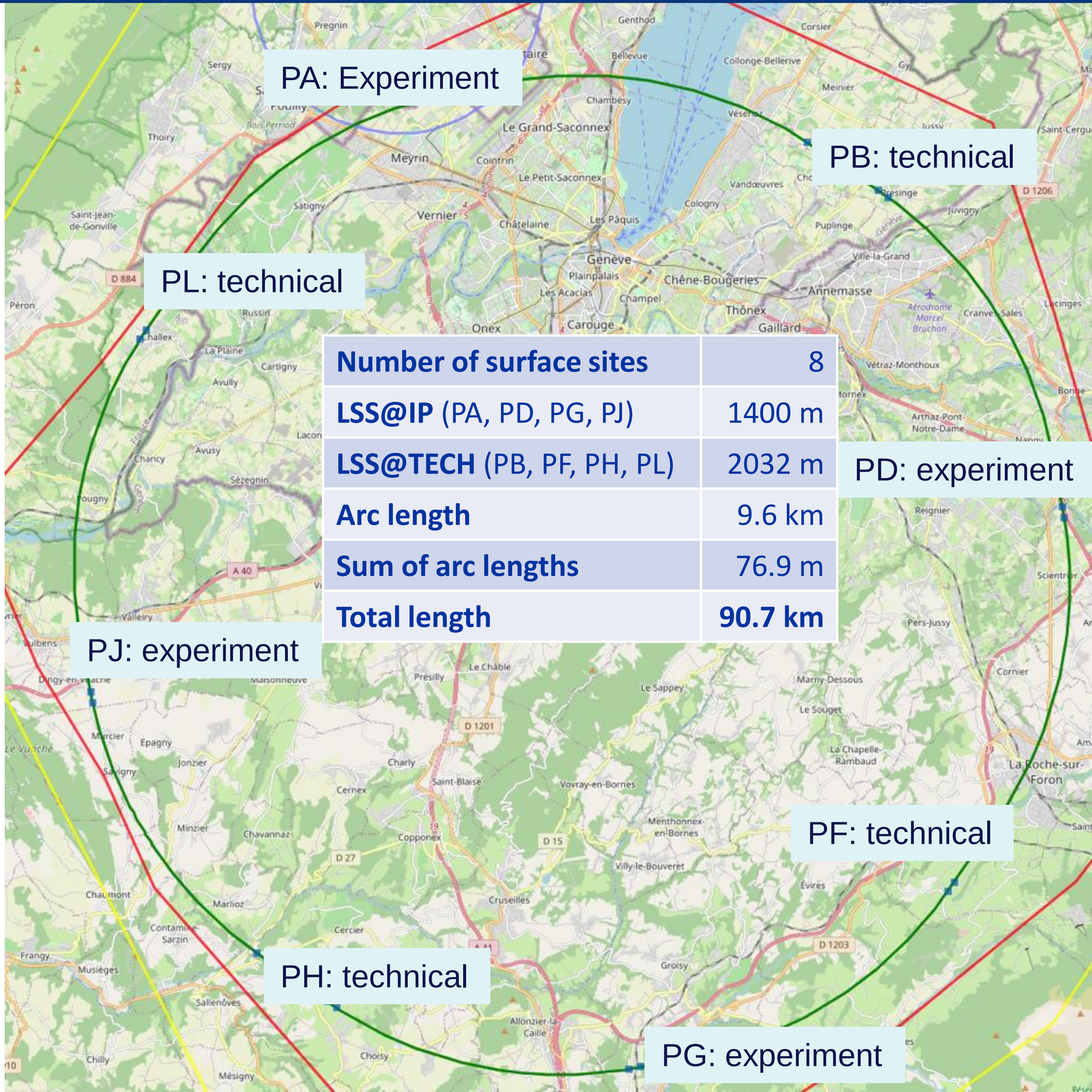
Placement

Major achievement: optimization of the ring placement
Layout chosen out of ~100 initial variants, based on geological, urban, environmental & infrastructure constraints.

Lowest-risk baseline: 90.7 km ring, 8 surface points

Whole project now adapted to this placement





Number of surface sites	8
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**

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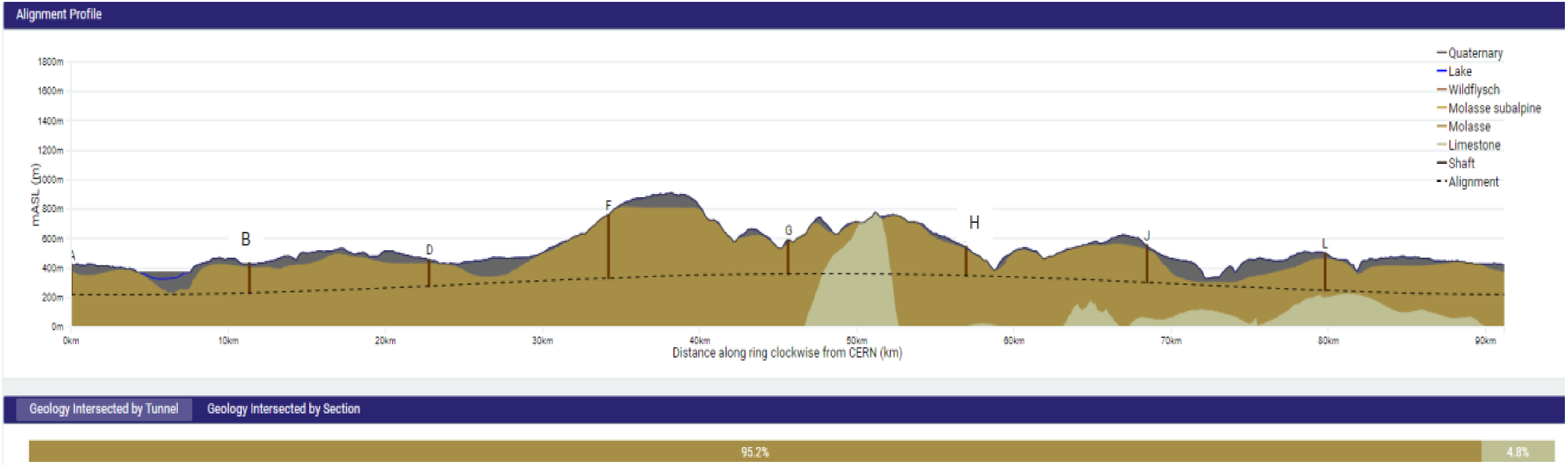
FCC tunnel implementation



Tunnel implementation summary

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

Underground Civil Engineering Schematic

Tunnel Circumference: 90.7 km

Excavated vol: 6.2 Mm^3 (in the ground)

Access shafts: 12

Construction shafts: 1

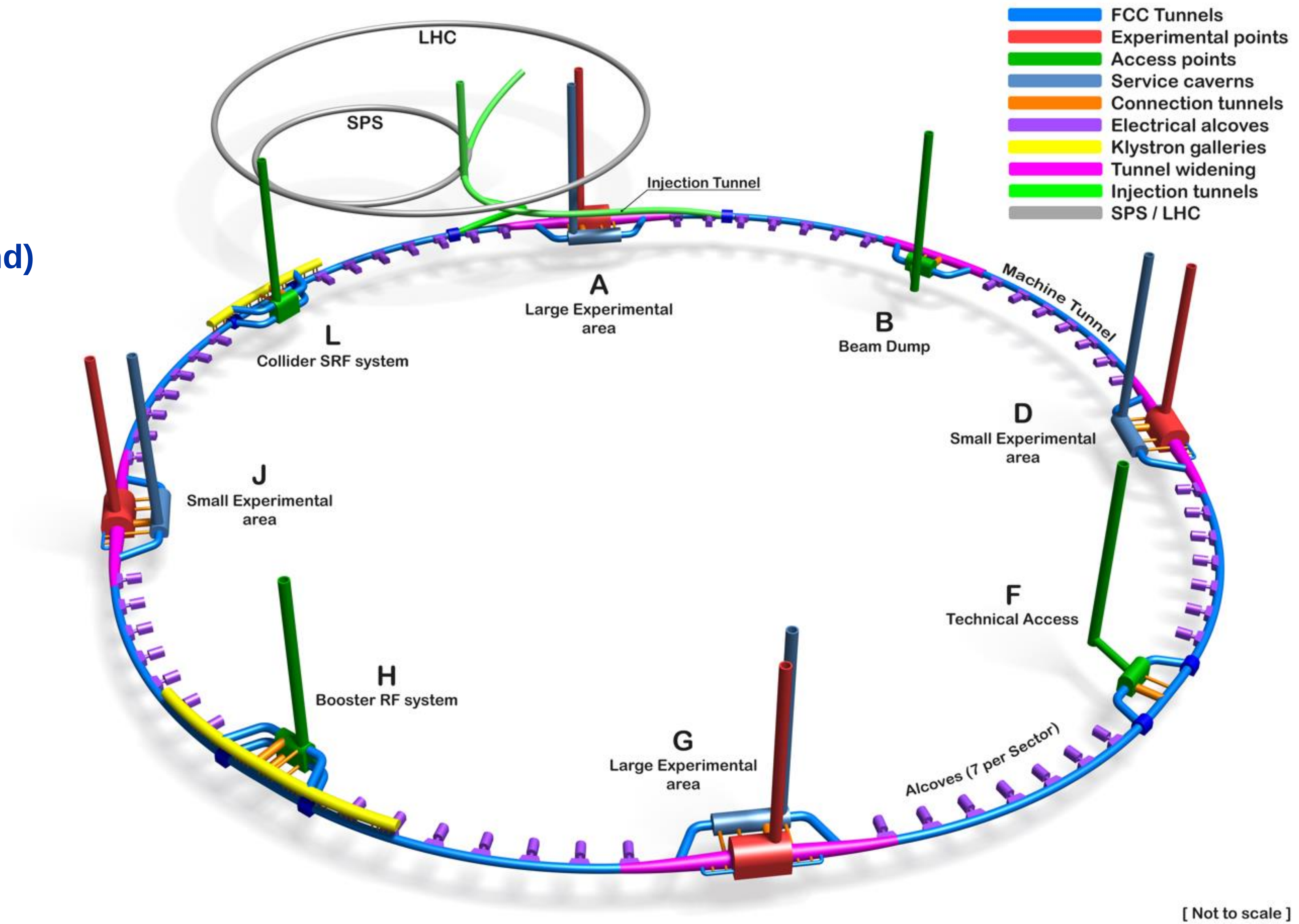
Large experiment areas: 2

Small experiment areas: 2

Technical points: 4

Deepest shaft: 400 m

Average shaft depth: 243 m



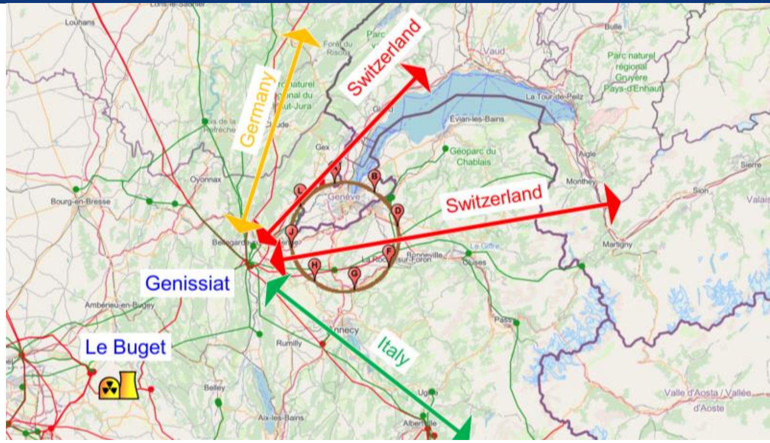
preparatory phase planning - authorisations and CE

To start the excavation of the first shafts in 2033, a significant amount of preparatory work is required. An initial consideration of these preparatory works including scheduling and resource aspects has been made:

2025-2026	**Permits and authorization for complementary site investigations**
	Tendering for environmental impact and authorisation processes contract, tendering for subsurface investigations
2027-28	**Complementary subsurface investigations**
	Tendering for CE consultants, environmental impact studies, public concertation
2028	**Project approval**
	Award of CE consultant contracts
2029-30	**Tender design**
	Preparing calls for tenders for CE construction,
	Project authorisations in France and Switzerland obtained, preparations of infrastructures for construction
2031 mid 2032	**Construction design, Tendering for construction**
mid 2032	**Award of CE construction contracts**
	Preparation of site completed (road access, electricity, water…)
2033	**Groundbreaking**

Power consumption and 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**

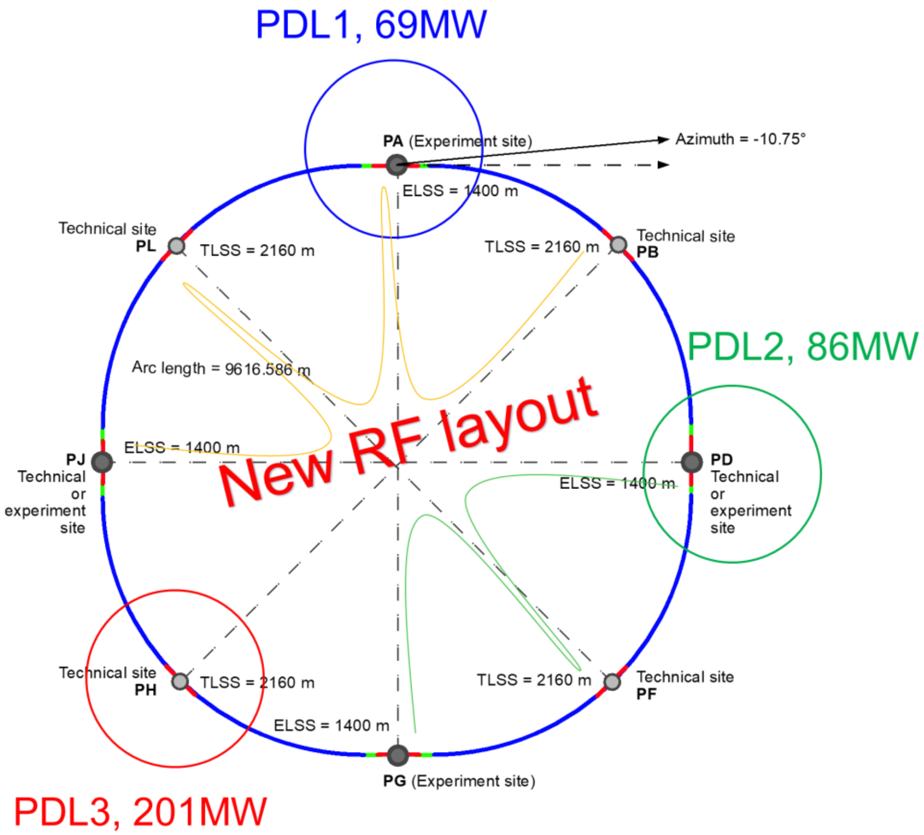


Powering concept and max power load by sub-stations:

The loads could be charged on the three sub-stations (optimum connections 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 L, with a sub-station covering PJ – PL – PA
- → Alternative to new sub-station at Point L is **reusing the existing CERN Prévessin station to PA**

- **All options pursued with RTE**
- **Powering concept and max. power rating of the three sub-stations compatible FCC-hh.**



progress with implementation baseline PA31 90.7 km

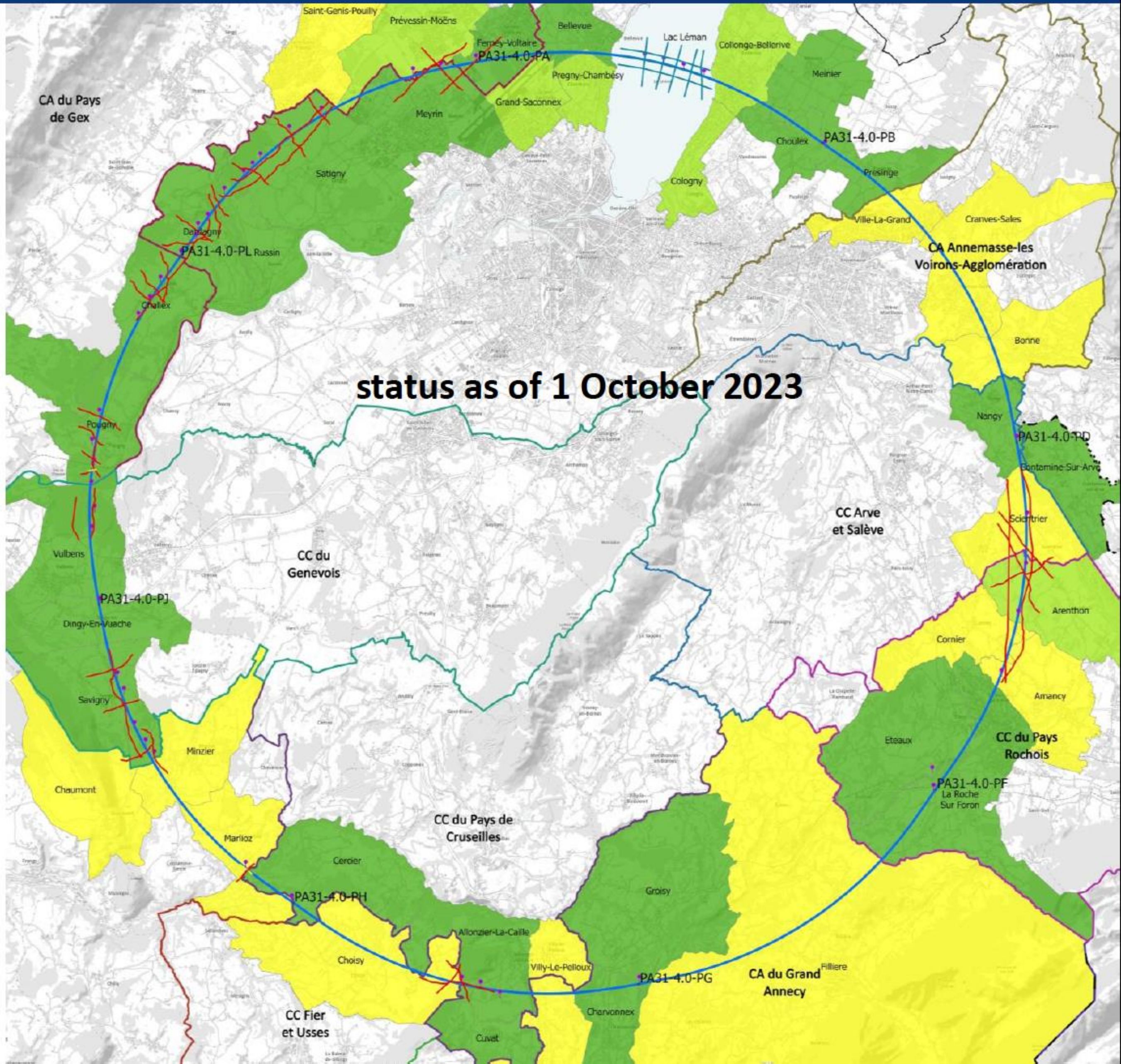
Meetings with municipalities concerned in France (31) and Switzerland (10)

- **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

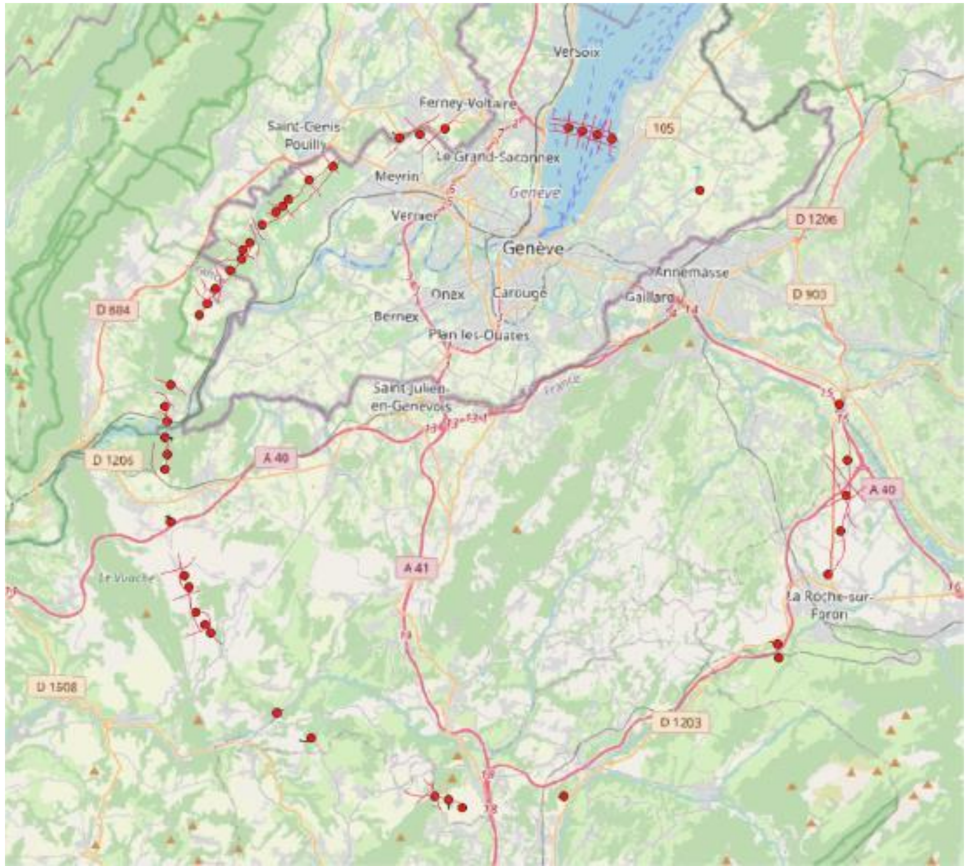
Collective meeting



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

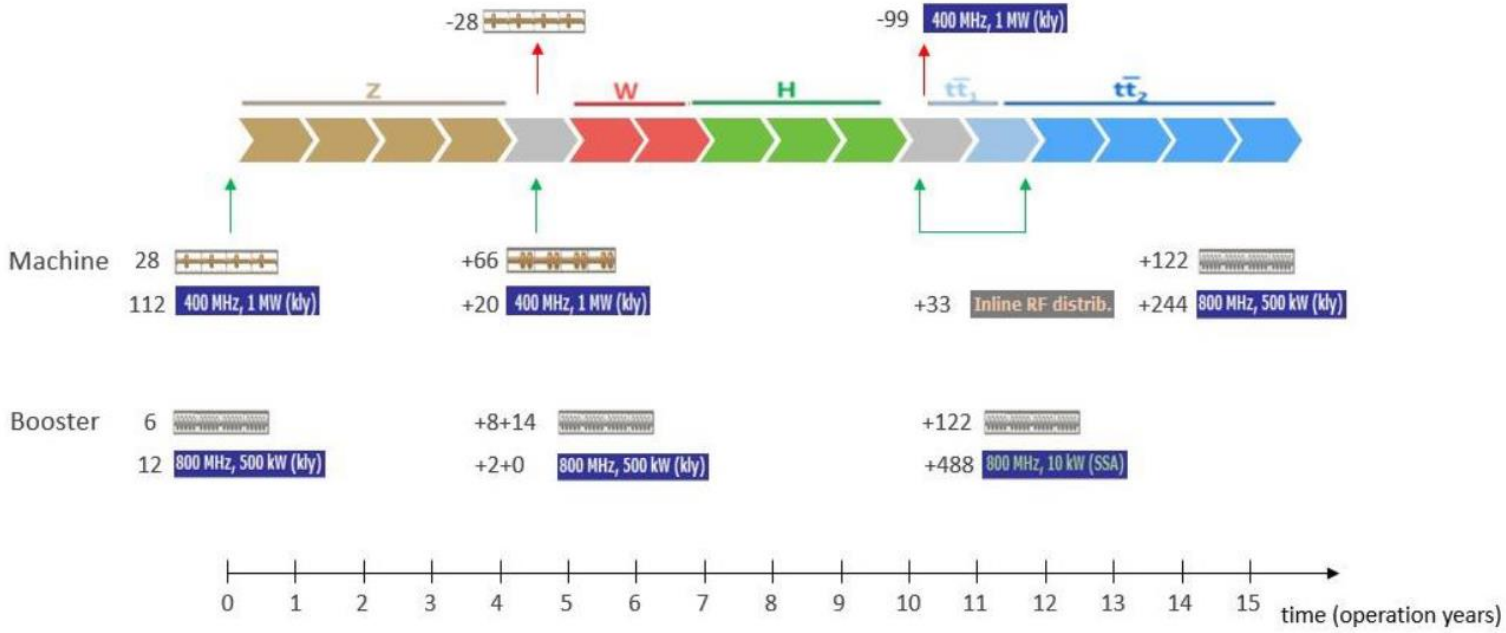
Activities on site

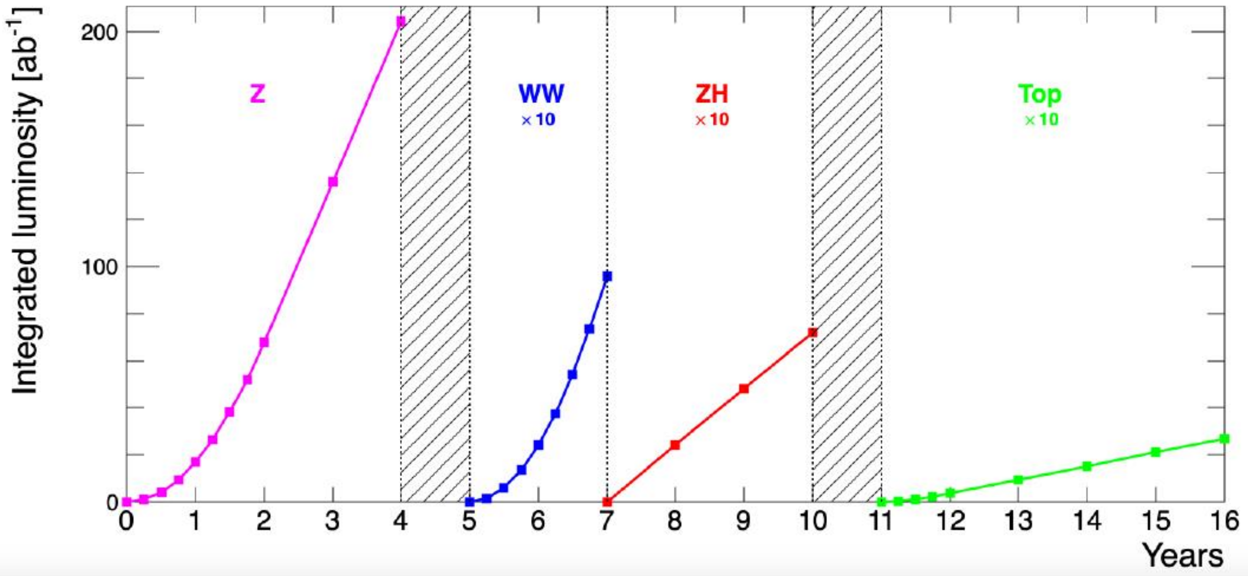
- **Environmental studies on all surface sites ongoing since February 2023**
- **Site investigations planned for 2024 and 2025 in areas with uncertain geological conditions:**
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022.
  - Direct interaction with land plot owners only after agreement with communes concerned.
  - **Interaction with host states on authorisation procedures ongoing → critical for start of drillings in March 2024.**
  - Localisation of sites:



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

baseline operational sequence starting from Z

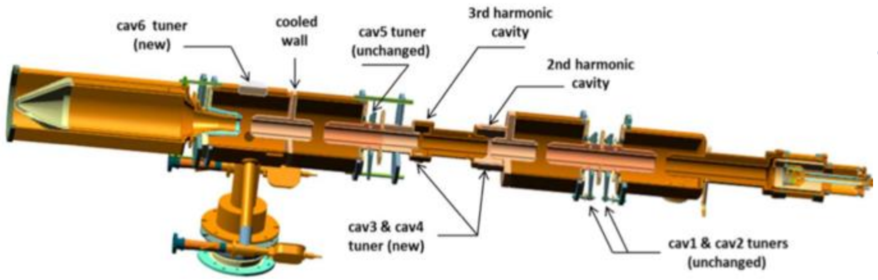




FCC-ee R&D examples

Efficient RF power sources

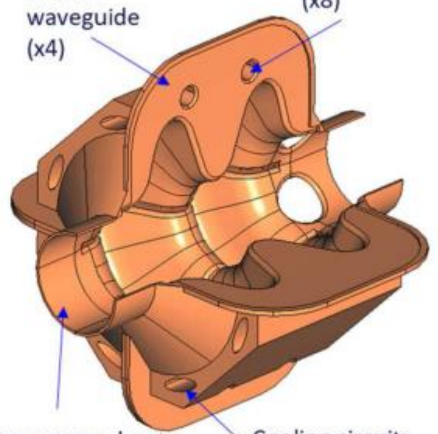
(400 & 800 MHz)



High efficiency klystrons & scalable solid-state amplifiers, FPC & HOM coupler, cryomodule, thin-film coatings

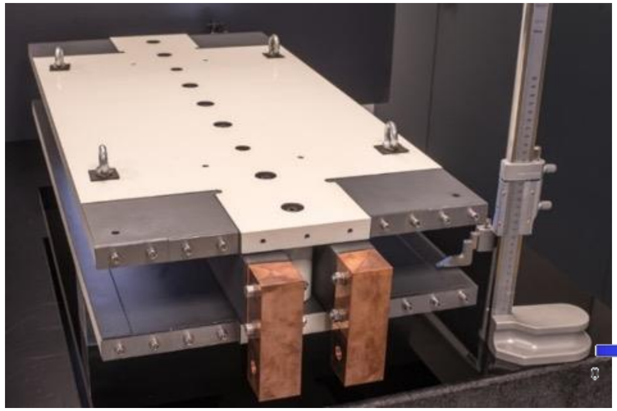
Efficient high-Q SC cavities

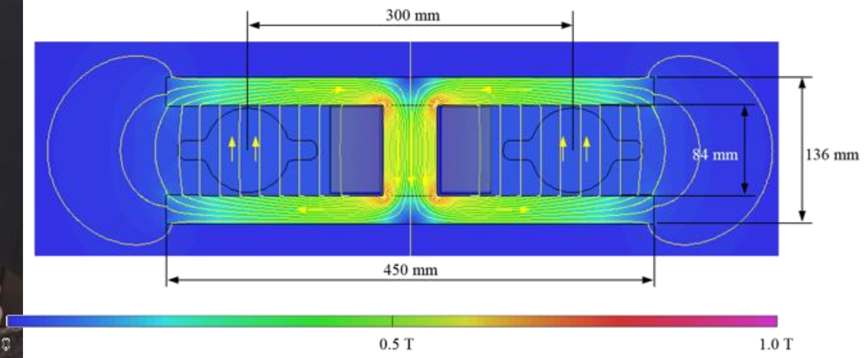
400 MHz 1 & 2 cell Nb/Cu, 4.5 K



Slotted Waveguide Elliptical cavity (SWELL) for high beam current & for high gradient

Energy **efficient** twin aperture **arc dipoles**



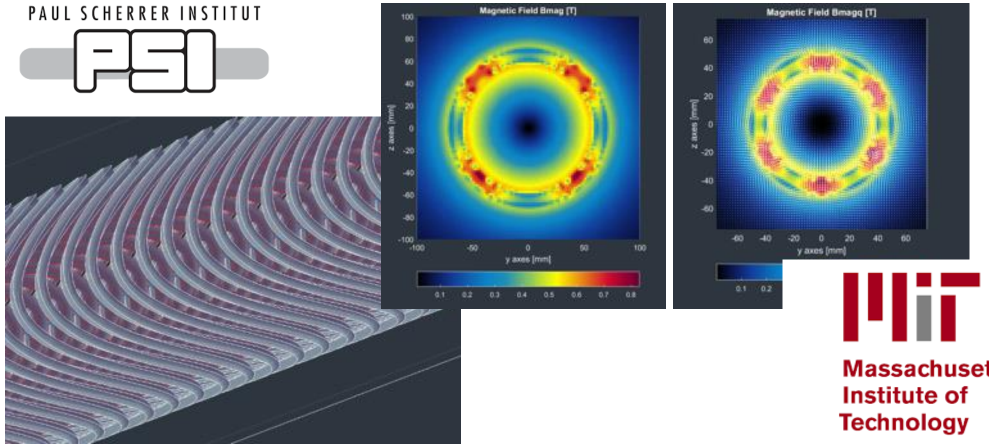


2840 x ~21 m -> 60 km

Under study: **CCT HTS quads & sexts for arcs**

- **reduce energy consumption** by O(50 MW)

PAUL SCHERRER INSTITUT PSI



Massachusetts Institute of Technology

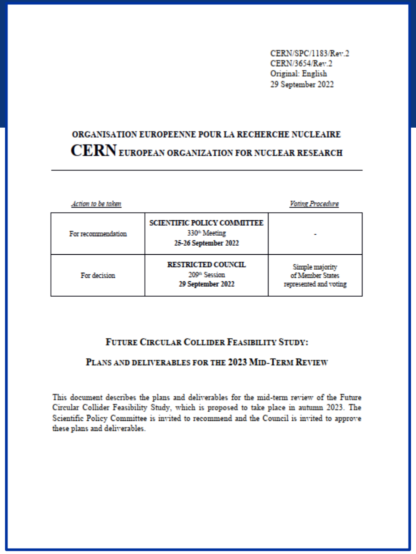
FCC Feasibility Study Mid-Term Review

FUTURE CIRCULAR COLLIDER

2023: Year of the FCC Feasibility Study Interim Report

- 703 pages: 7 chapters
  (cost and financial feasibility is a separate document)
  - Placement scenario (75 pages)
  - Civil engineering (50 pages)
  - Implementation with the host states (45 pages)
  - Technical infrastructure (110 pages)
  - FCC-ee collider design and performance (170 pages)
  - FCC-hh accelerator (60 pages)
  - (Cost and financial feasibility)
  - Physics and experiments (110 pages)
  - References (70 pages)
- Executive summary: 44 pages
- **Reviewed by FCC Scientific Advisory Committee and FCC Cost Review Panel on 16-18 Oct. 23**
- **Reviewed by SPC and FC on 20-22 Nov. 23**
- **To be reviewed by CERN Council on 2 Feb. 2024**

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



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.

296 authors

Future Circular Collider
Mid-term Report

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

Key points

- Implementation scenario well defined and all design parameters adapted to new layout
- Significant progress with host states at departmental/cantonal and local level. Direct exchange with communes concerned by surface sites as basis for detailed optimization. Environmental studies ongoing.
- 3D underground civil engineering model established for scheduling and costing.
- Significant effort in FCC-ee lattice design with two complete optics solutions. Major progress towards full performance simulations including beam-beam and full optics with alignment errors.
- Siting study for implementation of FCC-ee pre-injector on CERN Prévessin site. Flexible transfer line solutions for FCC-ee and hh for potential use of SPS tunnel/scSPS.
- FCC-ee SRF configuration and layout further optimized and international R&D collaborations being prepared
- FCC powering concept defined in cooperation with French network operator RTE.

Status of FCC global collaboration

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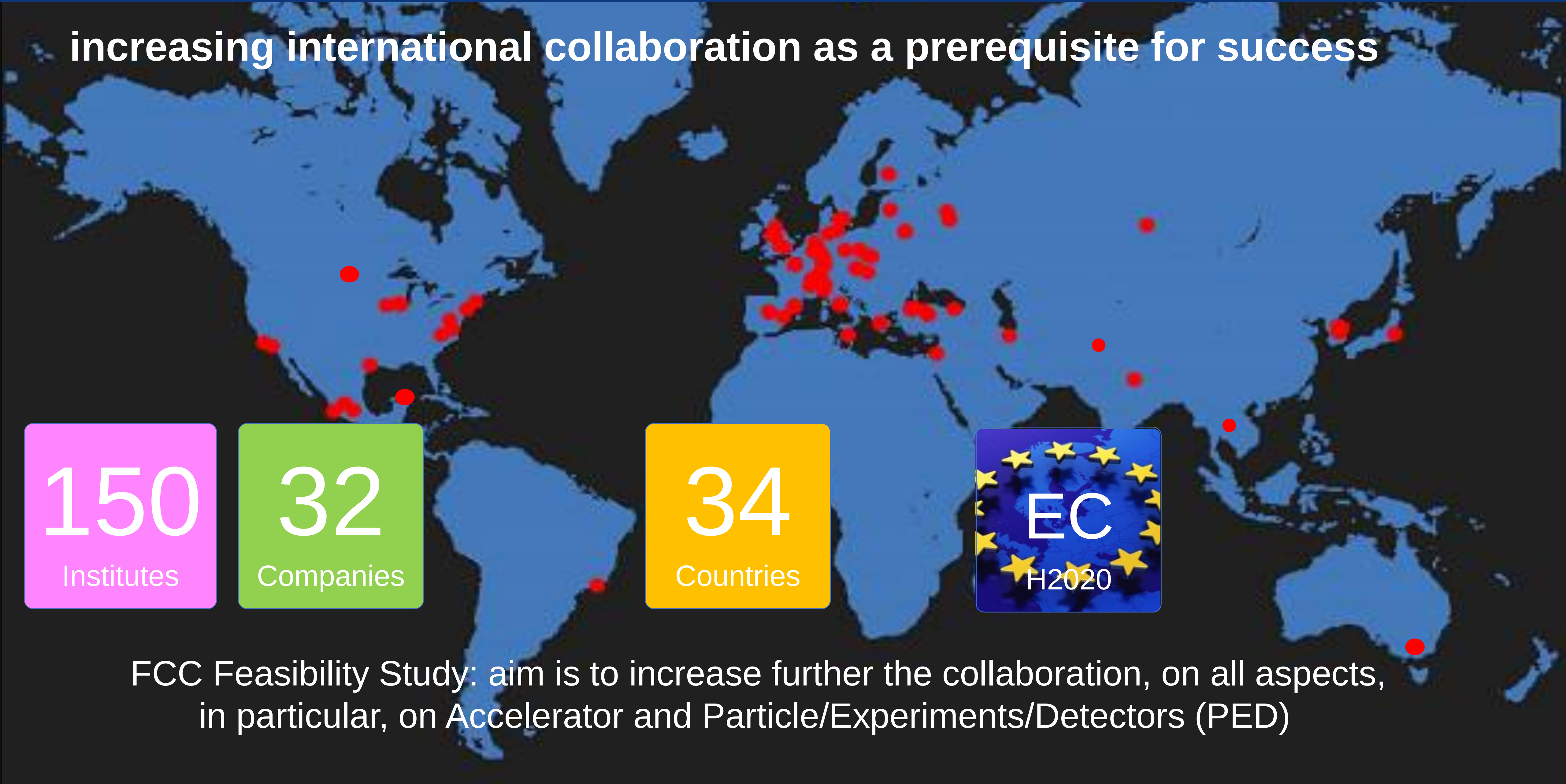

increasing international collaboration as a prerequisite for success

150 Institutes

32 Companies

34 Countries

EC H2020

FCC Feasibility Study: aim is to increase further the collaboration, on all aspects, in particular, on Accelerator and Particle/Experiments/Detectors (PED)

Why FCC ?

Fabiola Gianotti

1) **Physics : best overall physics potential of all proposed future colliders**

- FCC-ee : **ultra-precise** measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
- FCC-hh : **only** machine able to explore next **energy frontier** directly (~ x10 LHC)
- Heavy-ion collisions and, possibly, ep/e-ion collisions
- **4 collision points** → robustness; increased dataset for same machine power; specialized experiments for max. physics output

2) **Timeline**

- **FCC-ee technology is mature** → construction can proceed in parallel to HL-LHC operation and physics can start few years after end of HL-LHC operation → This would keep the community, in particular the young people, engaged and motivated.
- **FCC-ee before FCC-hh** would also allow:
  - cost of the (more expensive) FCC-hh machine to be spread over more years
  - **20 years of R&D work towards affordable magnets providing the highest achievable field (HTS)**
  - **optimization of overall investment** : FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) It's the **only facility commensurate with the size of the CERN community** (4 major experiments)

Is it feasible? Isn't it too ambitious?

-- The mid-term review has shown the status of the Feasibility Study, including the funding model.
-- **FCC is big and audacious project, but so were LEP and LHC when first conceived** → they were successfully built and performed far beyond expectation → demonstration of capability of our community to deliver on very ambitious projects with < 20% cost overrun

Backup

FCC-ee: main machine parameters

FUTURE CIRCULAR COLLIDER

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

- 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

Stage 2: FCC-hh – parameters

FUTURE CIRCULAR COLLIDER

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 119	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
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

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 ($\gamma\gamma$, $Z\gamma$, μμ)
- ❑ Final word about WIMP dark matter