FCC Feasibility Study Status

7th FCC Physics Workshop

Annecy, 29 January 2024

Michael Benedikt, 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

FCC Integrated Programme

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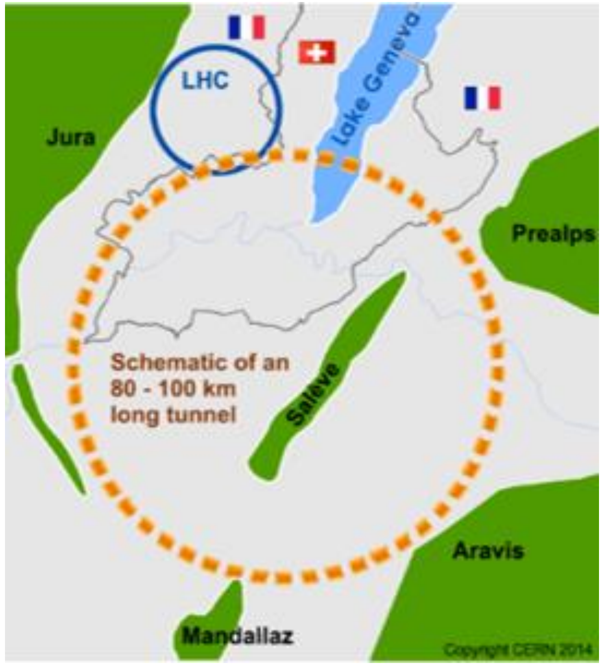
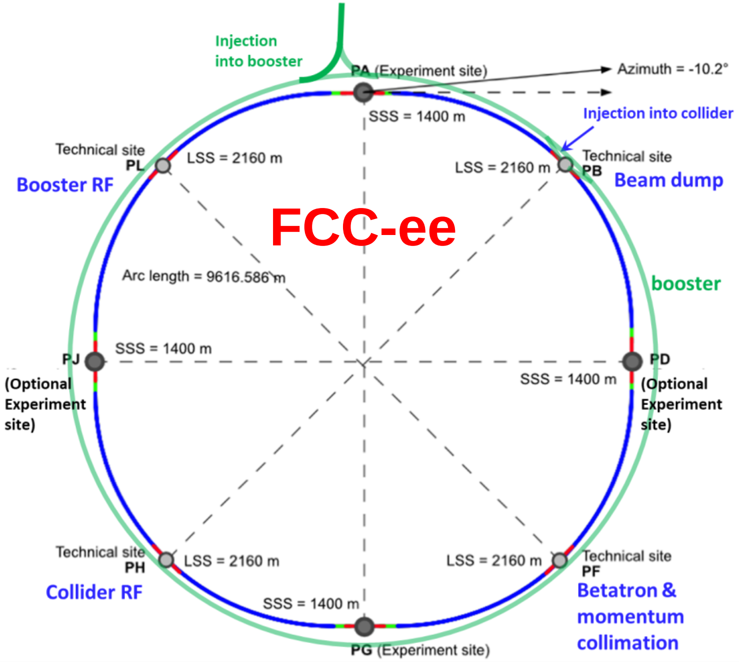
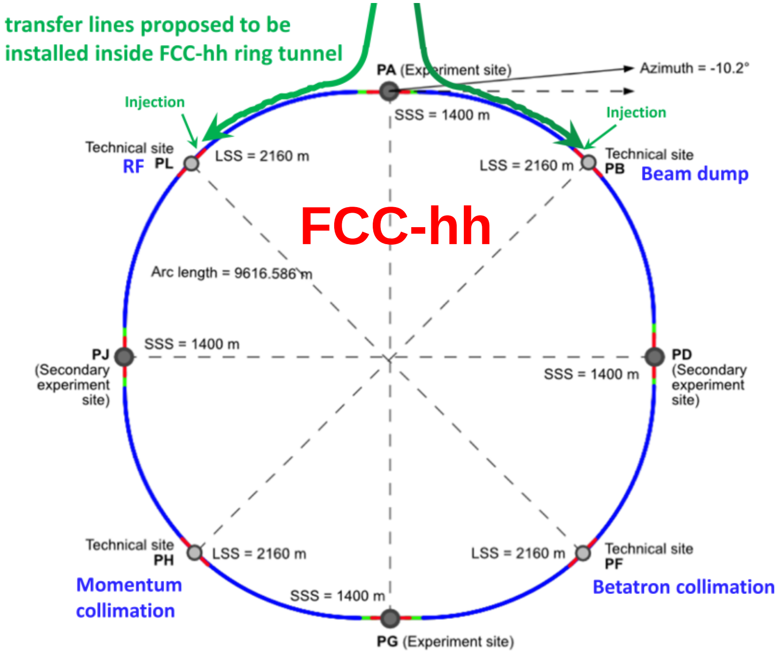
comprehensive long-term program maximizing physics opportunities

- **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







- 2040 | **2045 - 2060** | **2070 - 2095**

a similar two-stage project CEPC/SPPC is under study in China

FCC Feasibility Study Mid-Term Review: Goals, Deliverables, Status

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The goal of the FCC FS mid-term review is to assess the progress of the Study towards the final report (to be submitted in 2025).

Deliverables (approved by Council in Sept 2022):
D1 : Definition of the baseline scenario
D2 : Civil engineering
D3 : Processes and implementation studies with the Host States
D4 : Technical infrastructure
D5 : FCC-ee accelerator
D6: FCC-hh accelerator
D7: Project cost and financial feasibility
D8: Physics, experiments and detectors

https://indico.cern.ch/event/1197445/contributions/5034859/attachments/2510649/4315140/spc-e-1183-Rev2-c-e-3654-Rev2_FCC_Mid_Term_Review.pdf

Many thanks to the Host States for their strong support!

Documents:
- Mid-term report (all deliverables except D7; ~ 700 pages)
- Executive Summary of mid-term report (~ 50 pages)
- Updated cost assessment (D7)
- Funding model (D7)

Extremely positive feedback so far.
The huge amount of work and great progress appreciated by the committees.
No show-stopper found at this stage.

Review steps:
- Oct 2023: FCC Scientific Advisory Ccommittee (scientific and technical aspects) and Cost Review Panel (ad hoc committee; cost and financial aspects)
- Nov 2023: SPC and FC
- 2 Feb 2024: Council

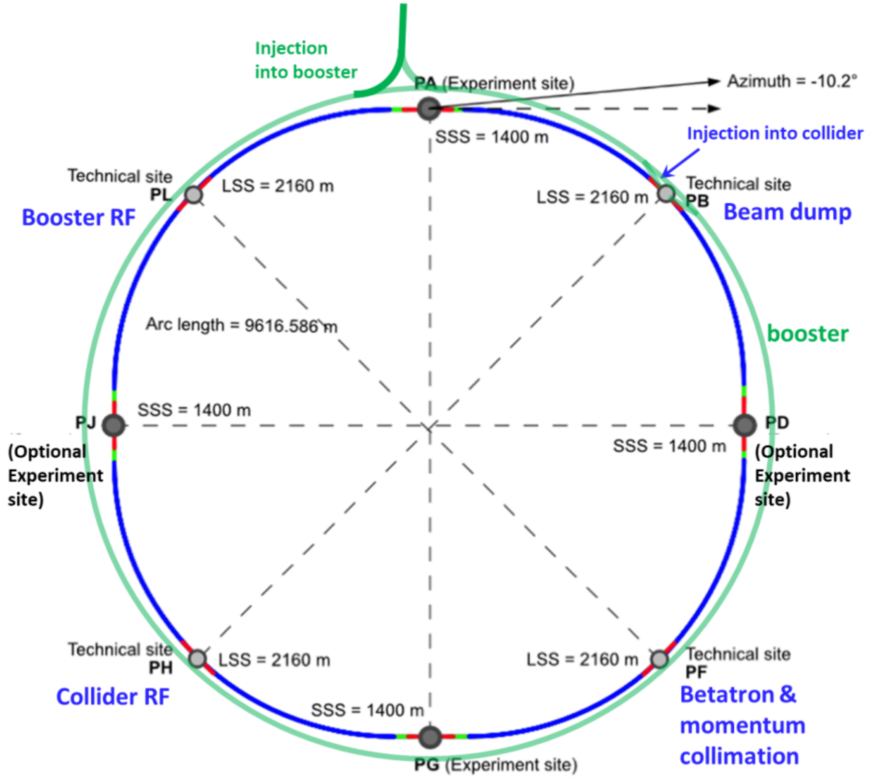
F. Gianotti

optimized placement and layout for feasibility study

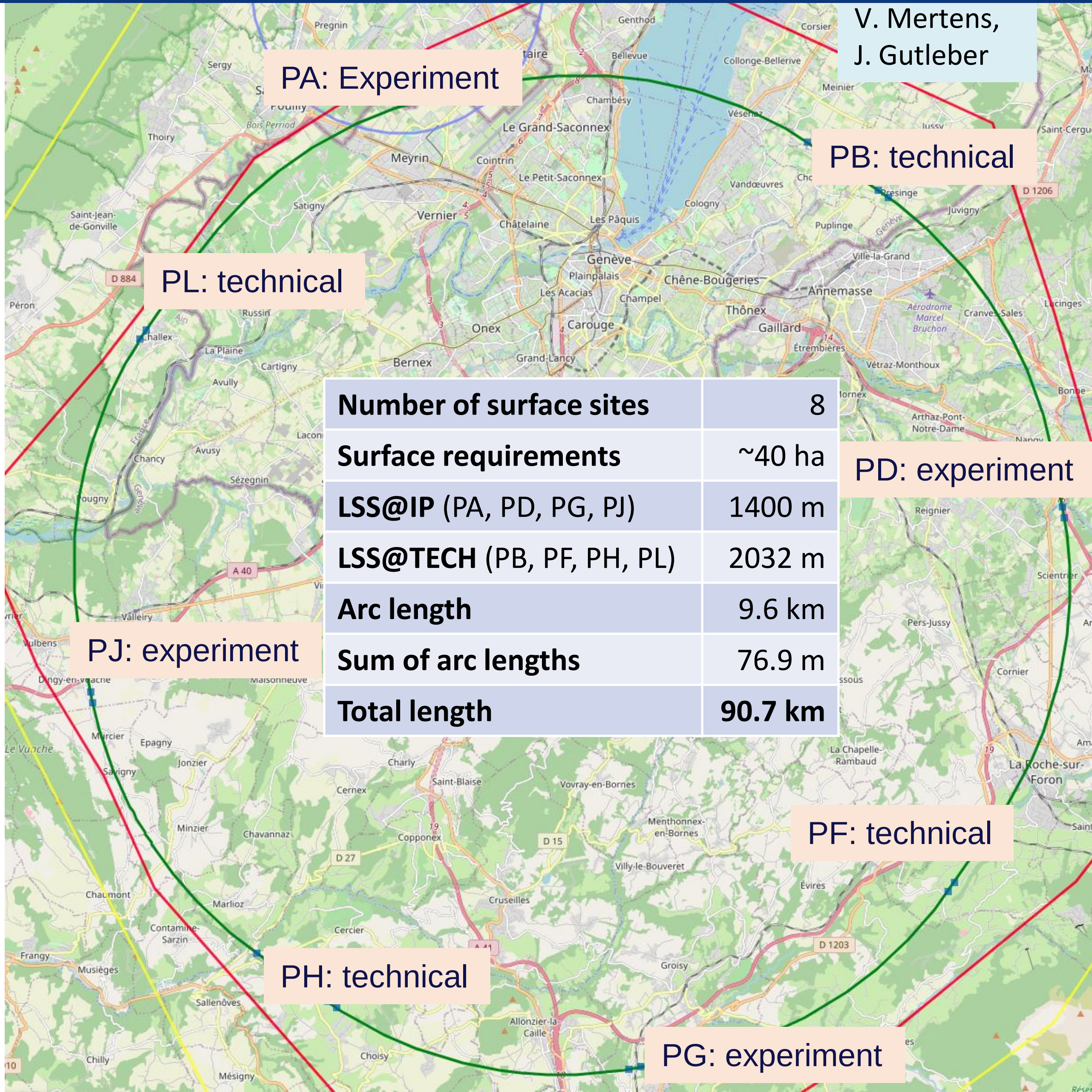
Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

"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



V. Mertens, J. Gutleber



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) – experimental site

PB – Présinge/Choulex (CH) – technical site

PD – Nangy (FR) – experimental site

PF – Roche sur Foron/Etaux (FR) – technical site

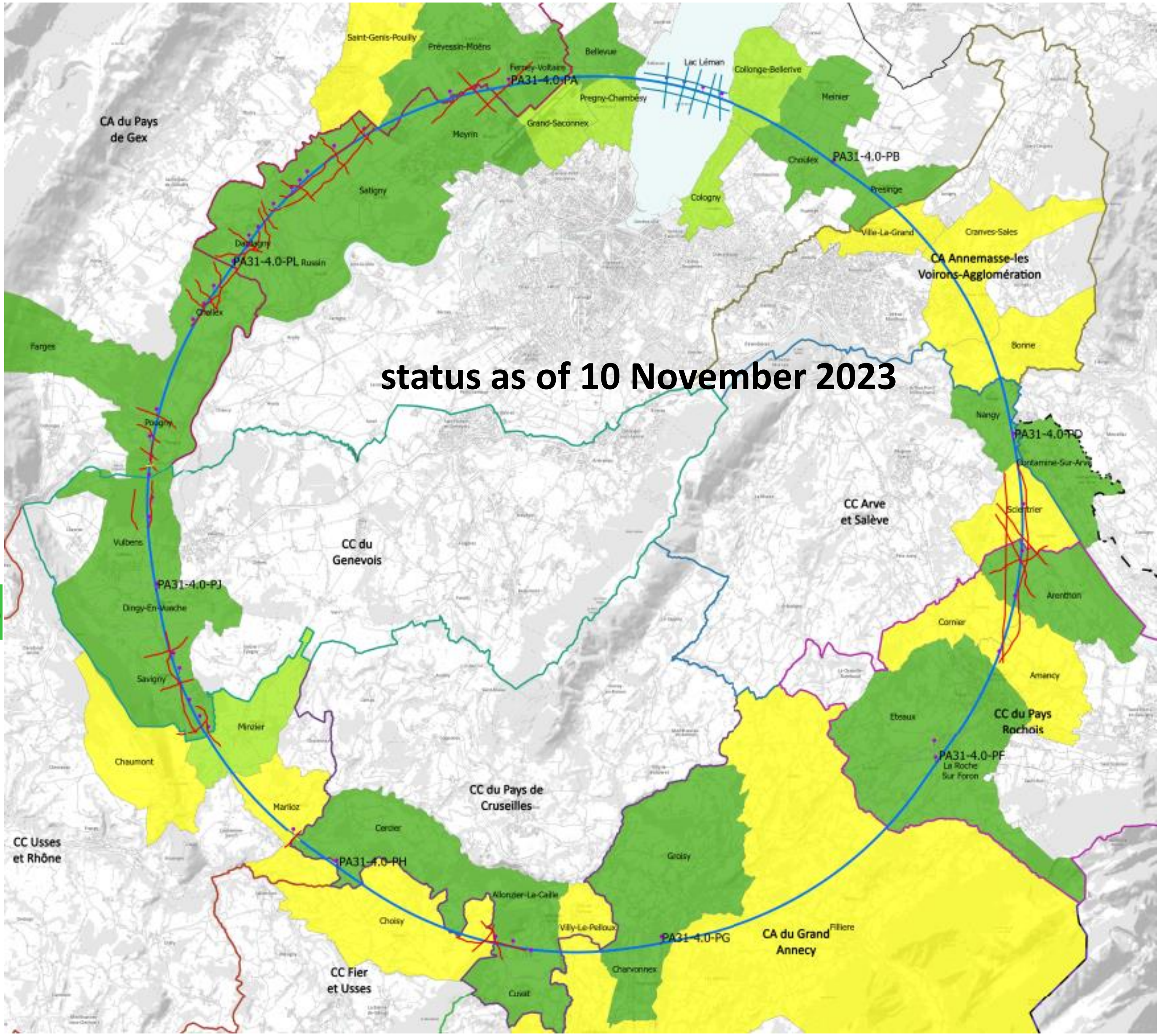
PG – Charvonnex/Groisy (FR) – experimental site

PH – Cercier (FR) – technical site

PJ – Vulbens/Dingy en Vuache (FR) experimental site

PL – Challex (FR) – technical site

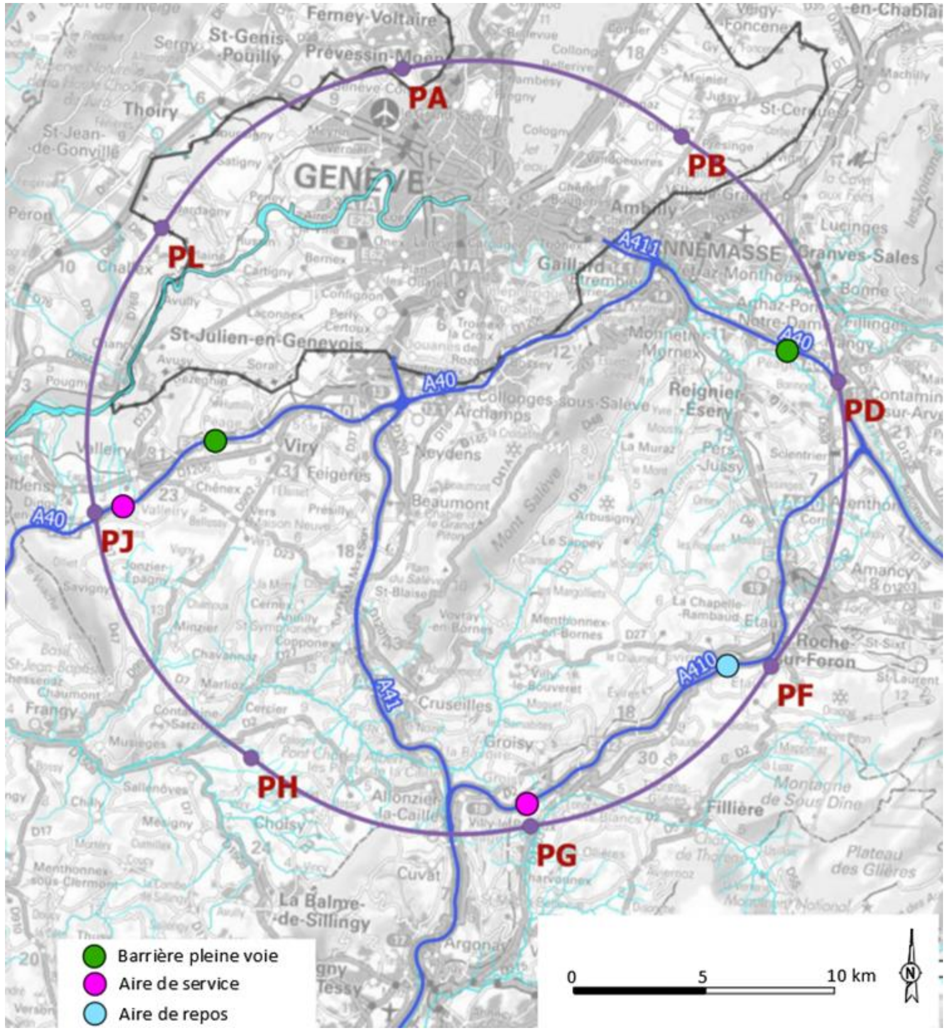
- Individual meeting
- Individual meeting planned
- Collective meeting

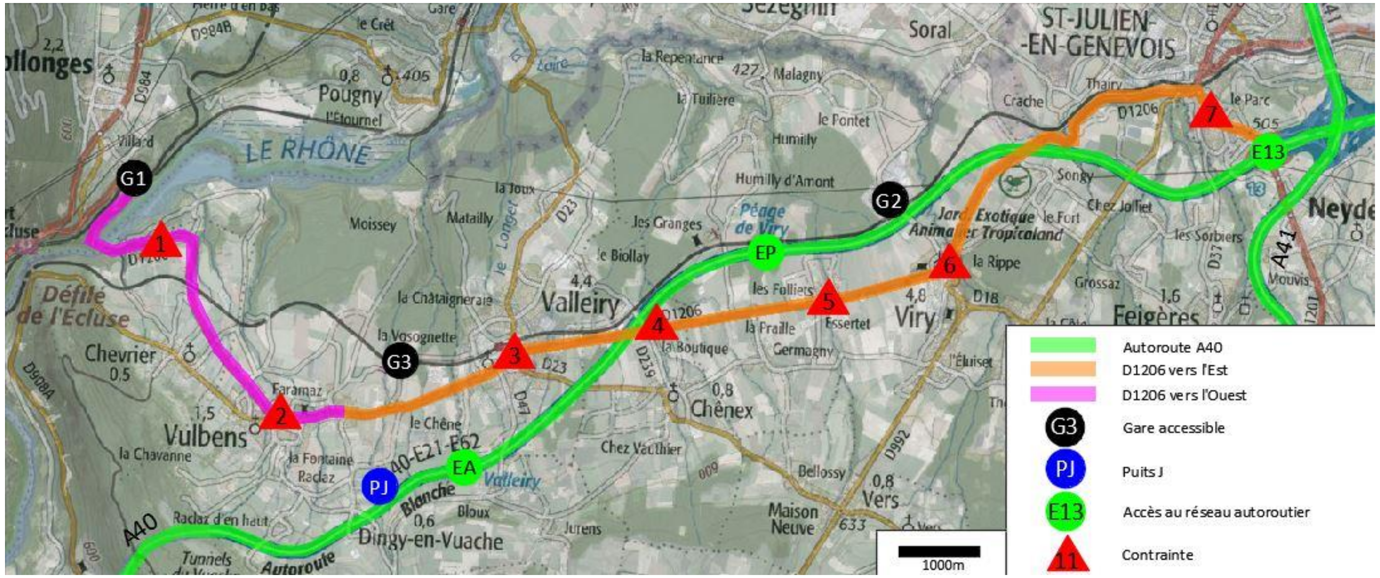


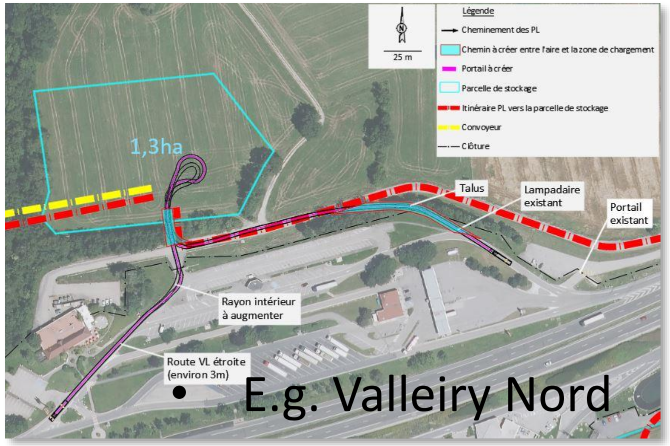
The support of the host states is greatly appreciated and essential for the study progress!

connections to transport infrastructure

- **Road accesses** identified and documented **for all 8 surface sites**
- **Four possible highway connections** defined (material transport)
- **Total amount of new roads required < 4 km** (at departmental road level)



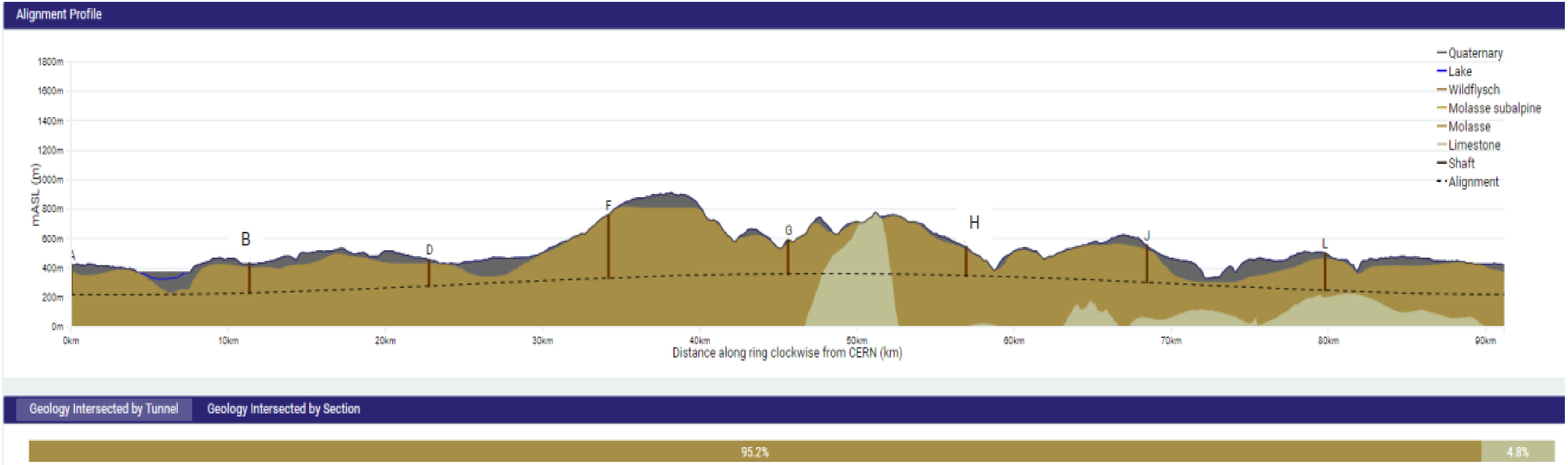




Detailed road access scenarios & highway access creation study **carried out by Cerema*, including regulatory requirements in France**

* Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning. CEREMA is **the major French public agency for developing public expertise in the fields of urban planning, regional cohesion and ecological and energy transition** for resilient and climate-neutral cities and regions.

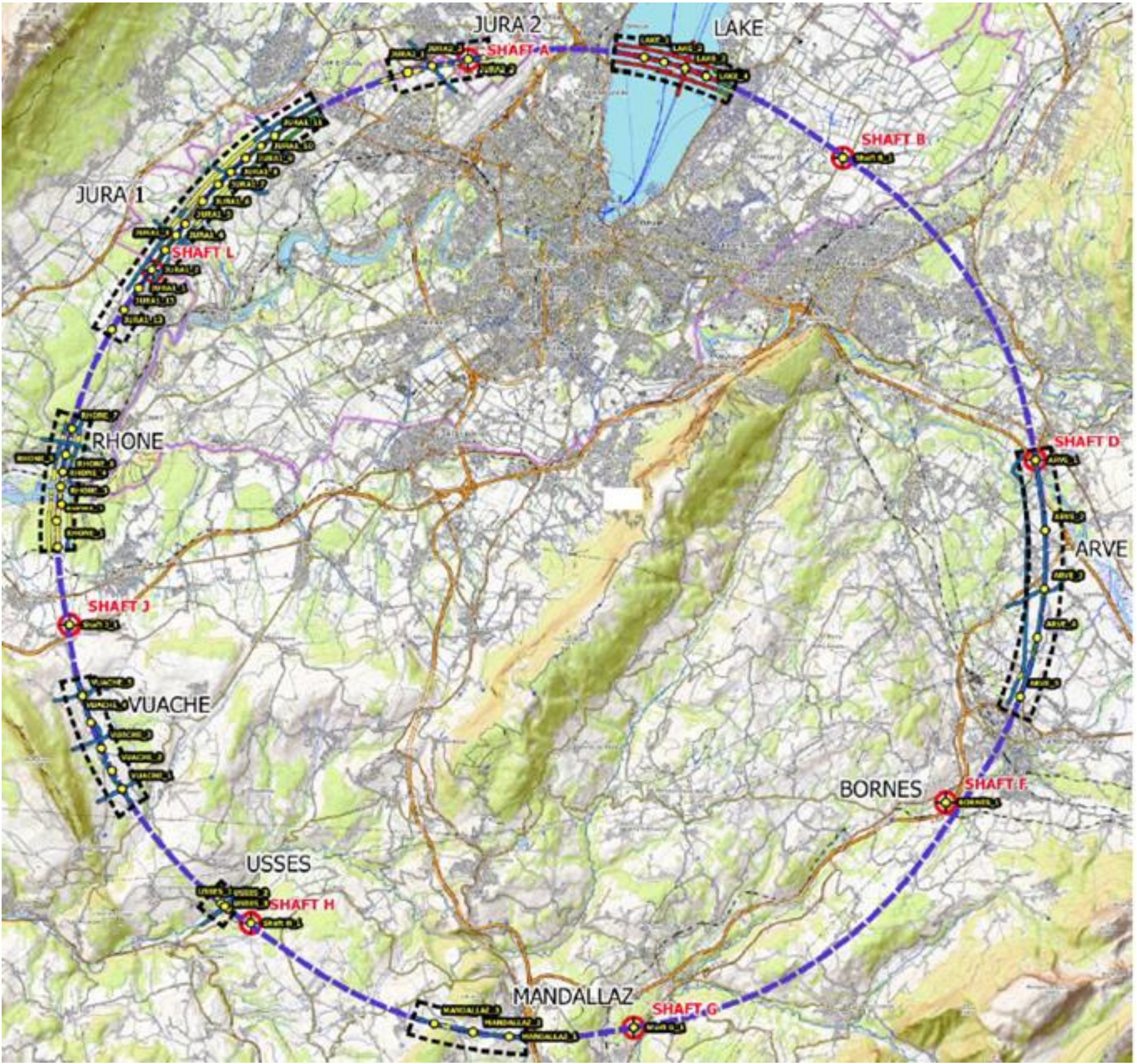
FCC tunnel implementation



tunnel implementation summary

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

status of site investigations



- **Site investigations in areas with uncertain 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 authorisation procedures. Planned start of drillings in Q2/2024**

- **Contract Status:**
  - Engineering service contracts since July 2022
  - Site investigation tendering ongoing
  - **Contract placement approved by Council in December 2023 and mobilization after contracts are signed**

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

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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	**Ground breaking**

“accelerated” schedule under discussion

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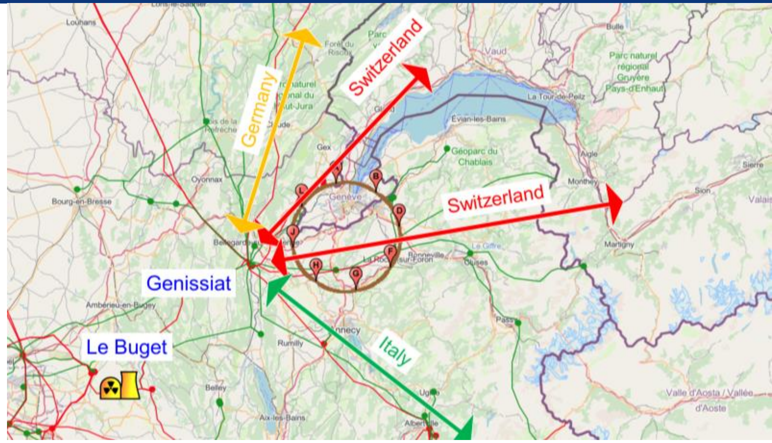
connections to electrical grid infrastructure

Updated FCC-ee energy consumtion	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 FCC-ee yearly consumption (TWh)	**1.07**	**1.2**	**1.33**	**1.77**
Yearly consumption CERN & SPS (TWh)	0.70	0.70	0.70	0.70
Total yearly consumpt. CERN & SPS & FCC-ee (TWh)	**1.77**	**1.90**	**2.03**	**2.47**



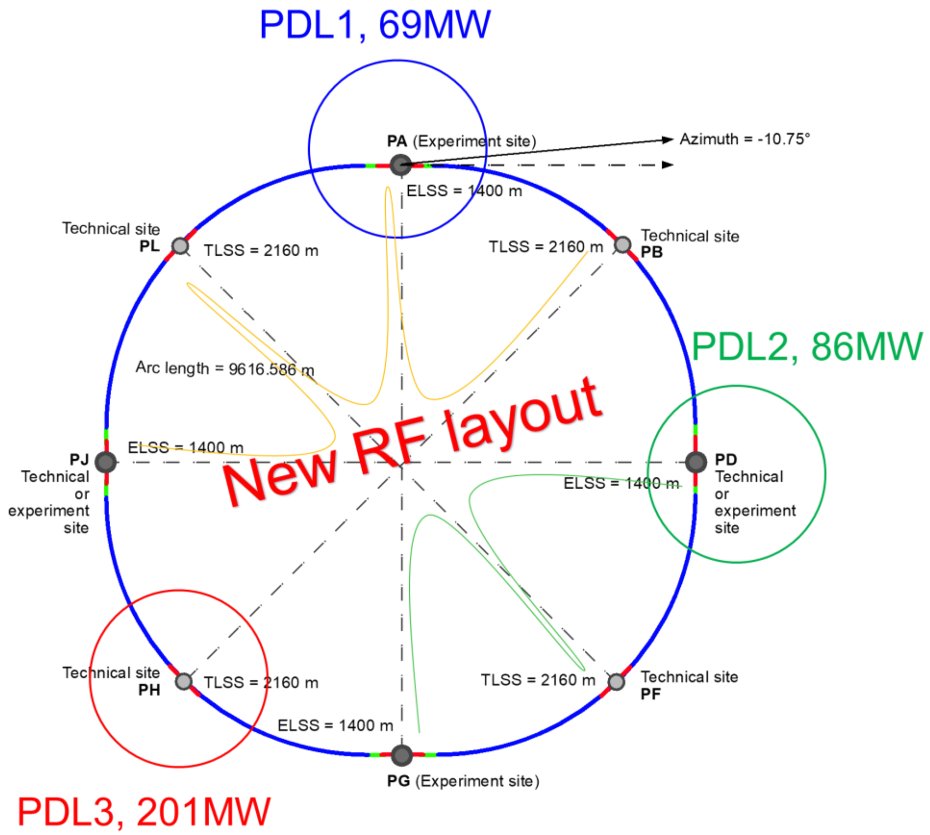
The loads could be distributed on three main sub-stations (optimally connected to existing regional HV grid):

- **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

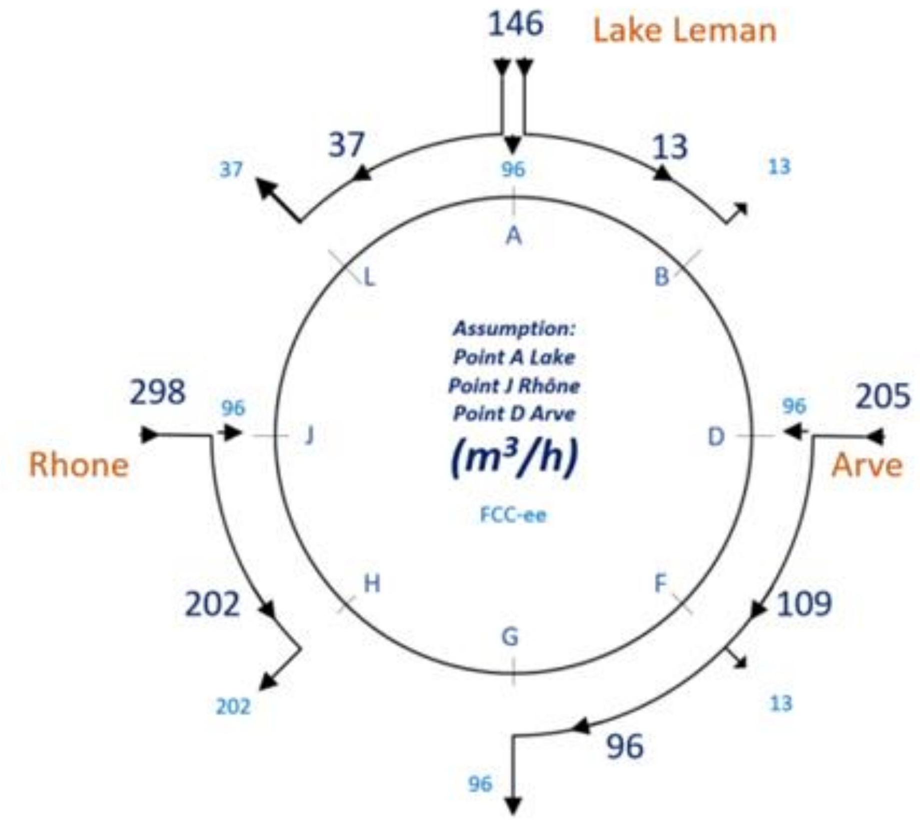
✓ **Connection concept was studied and confirmed by RTE (French electrical grid operator) ➔ requested loads have no significant impact on grid**

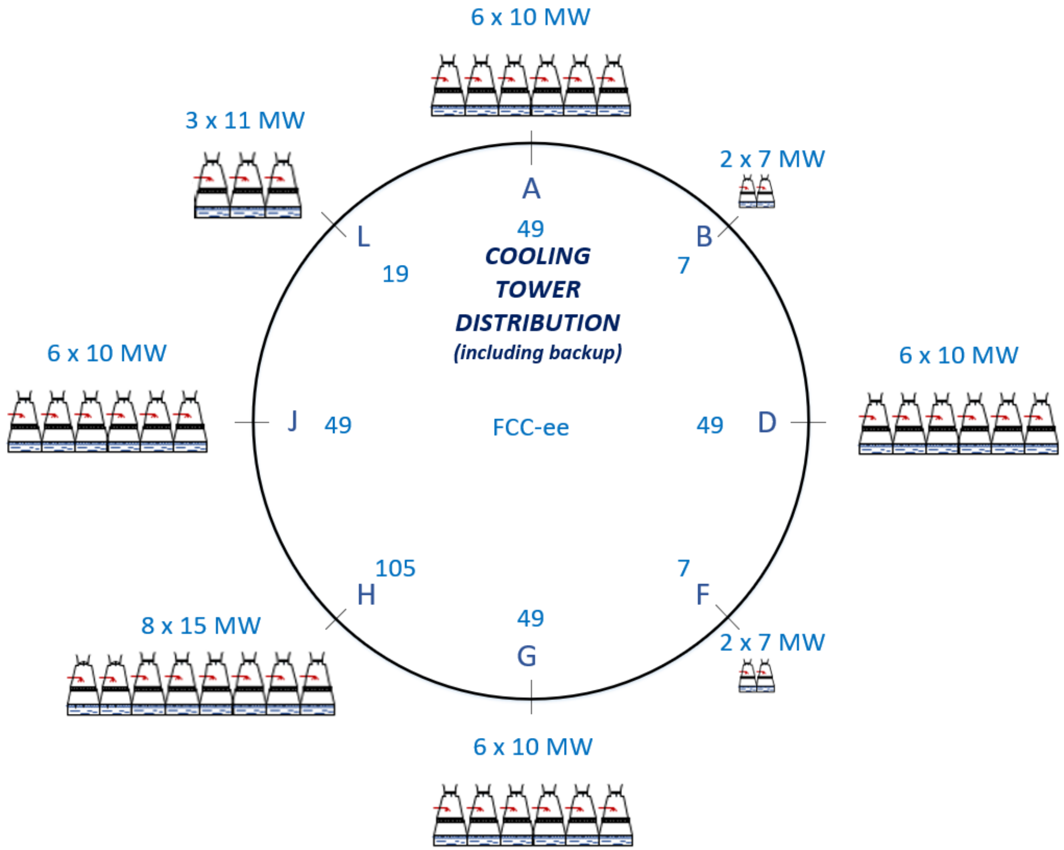
✓ **Powering concept and power rating of the three sub-stations compatible with FCC-hh**

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



cooling water supply concept





- **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**

*Services Industriels de Genève

- **Pipework in the tunnel will connect the remaining points to points PA, PD and PJ**
- **Main cooling towers placed at experiment points (PA, PD, PG, PJ), and RF sites (PL, PH)**

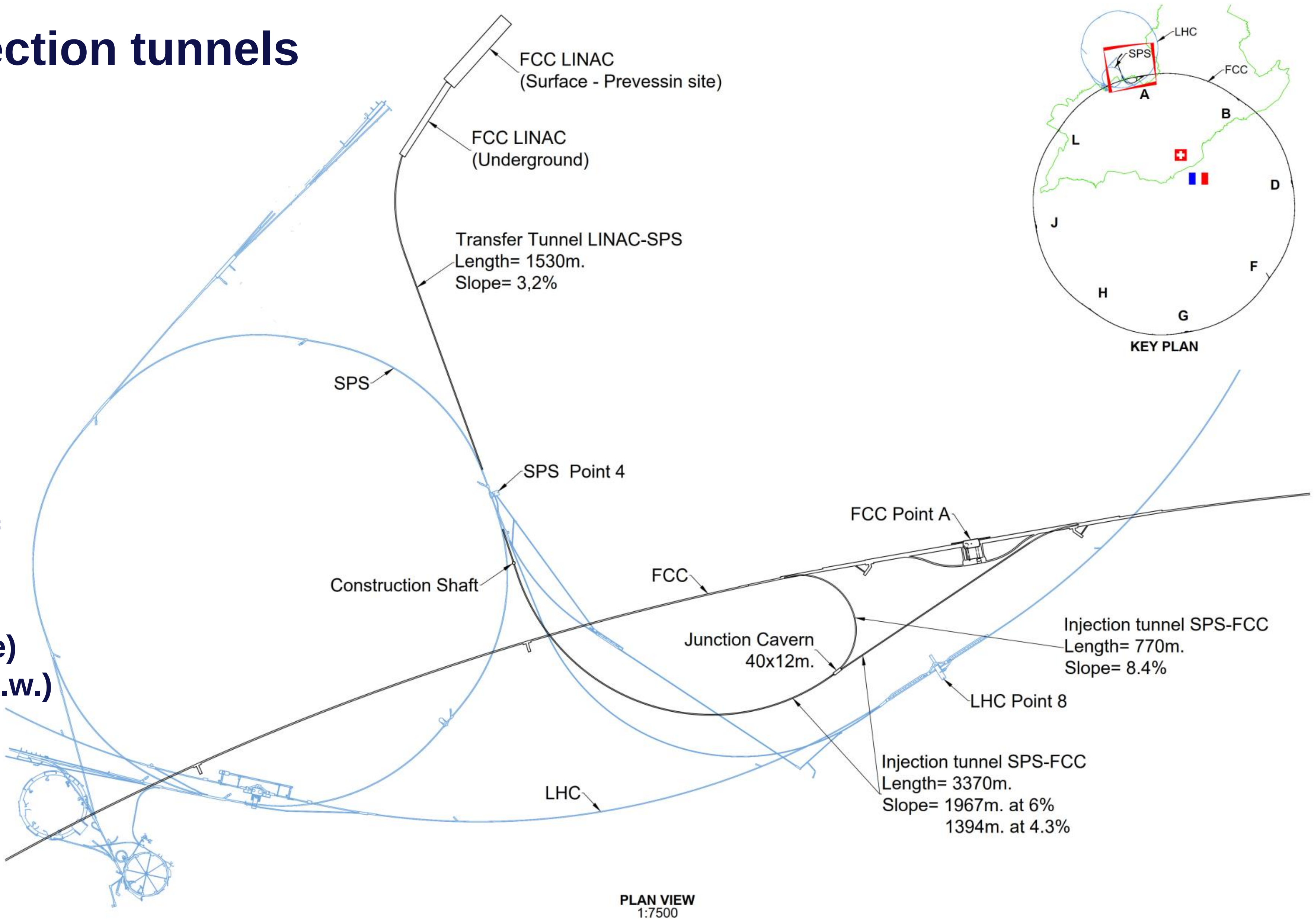
transfer line for FCC-ee (option with SPS for FCC-hh)

injector linacs and injection tunnels

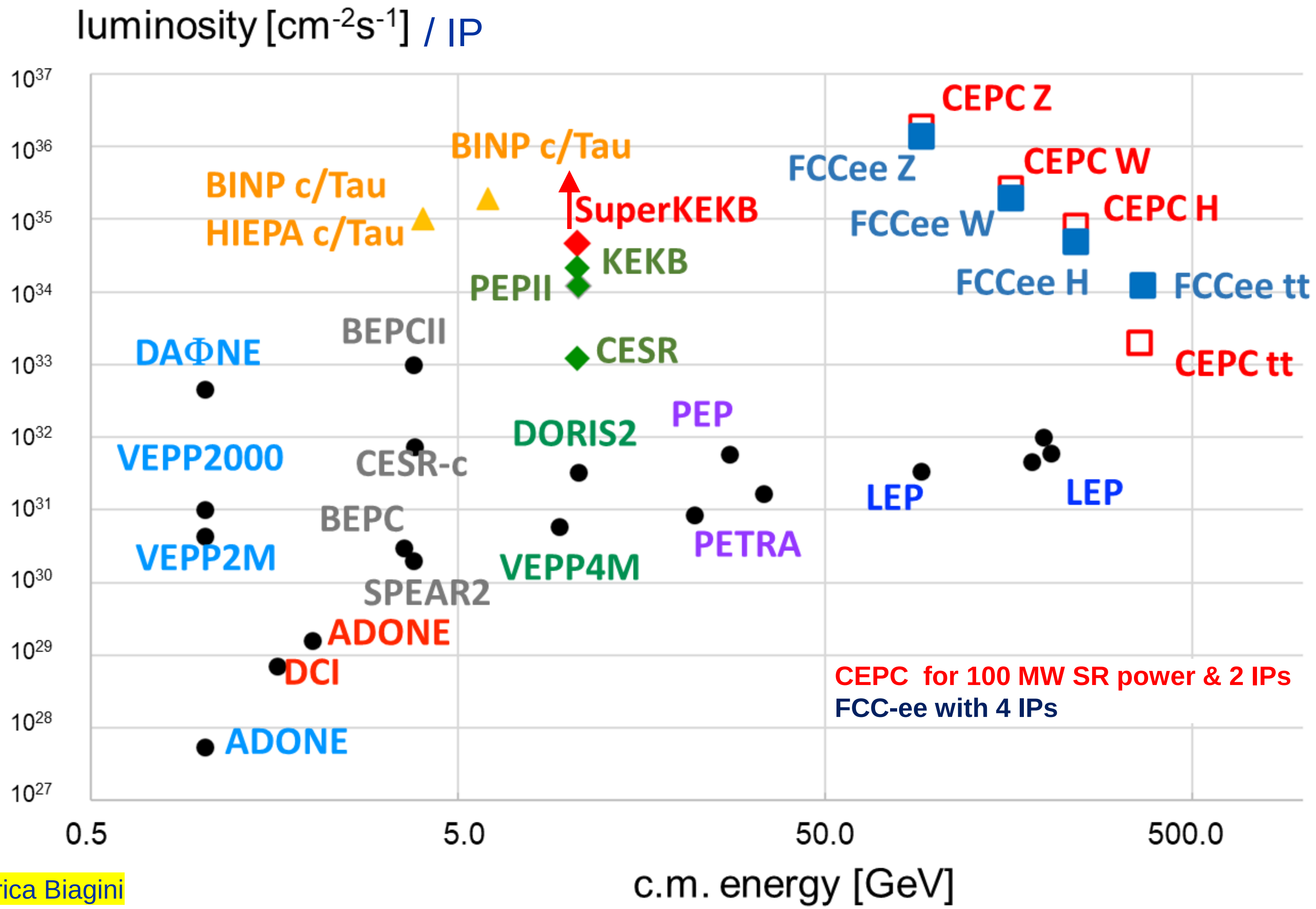
- **Designed to enable injection** either from SPS as pre-booster or **from a new high-energy linac sited at Prévessin**

- **Single tunnel with spur to enable anti-clockwise injection**

- **Design allows re-use for FCC-hh if injector in the SPS tunnel (scSPS option)**
  - SPS Point 4 to FCC (clockwise)
  - SPS Point 6 to FCC (counter-c.w.)



Stage 1: FCC-ee – 2nd highest luminosity collider



Marica Biagini

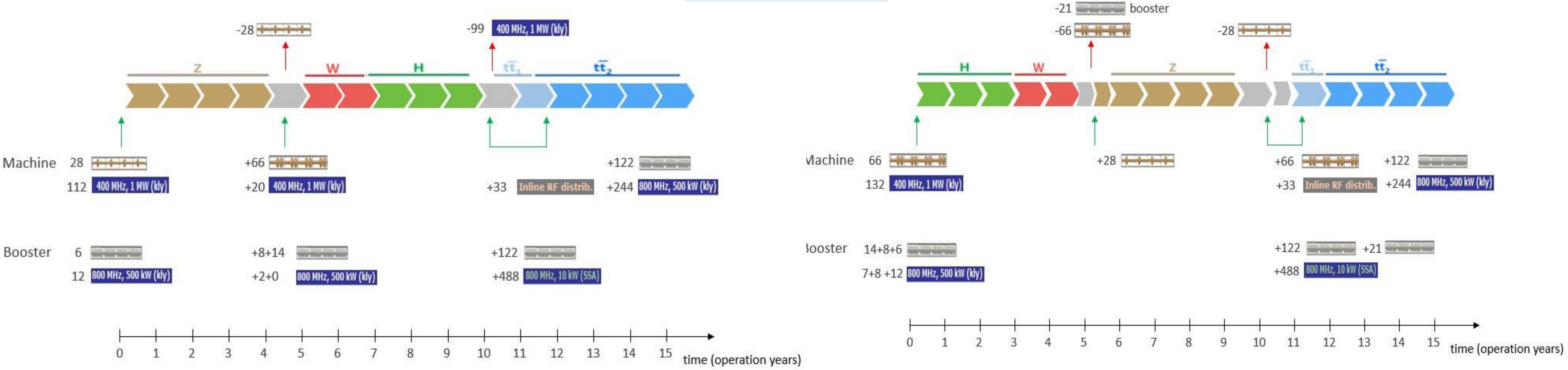
~ same accelerator design as twin machine CEPC

a few differences

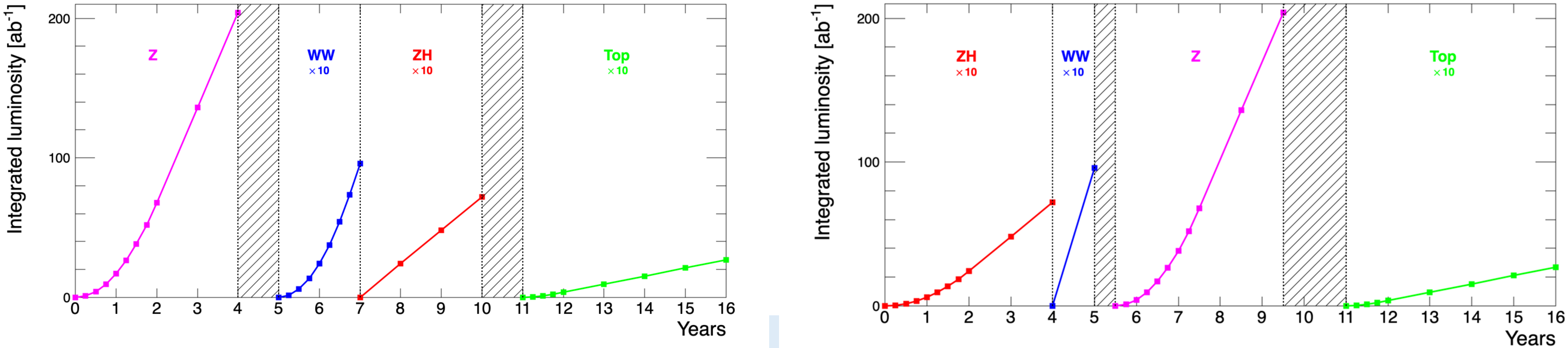
	FCC-ee	CEPC
#IPs	4 or 2	2
collider SRF up to ZH	400 MHz, 1- & 2-cell, Nb/Cu, 4.5 K	650 MHz, 2-cell, Nb, 2 K
collider SRF ttbar	800 MHz 5-cell, Nb, 2 K	650 MHz, 5-cell, Nb, 2 K
booster SRF	800 MHz 5-cell, Nb, 2 K	1.3 GHz, 9-cell, Nb, 2 K
top-up	in collider	in booster

operation sequences for FCC-ee

O. Brunner, F. Peauger



P. Janot



FCC-ee: main machine parameters

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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

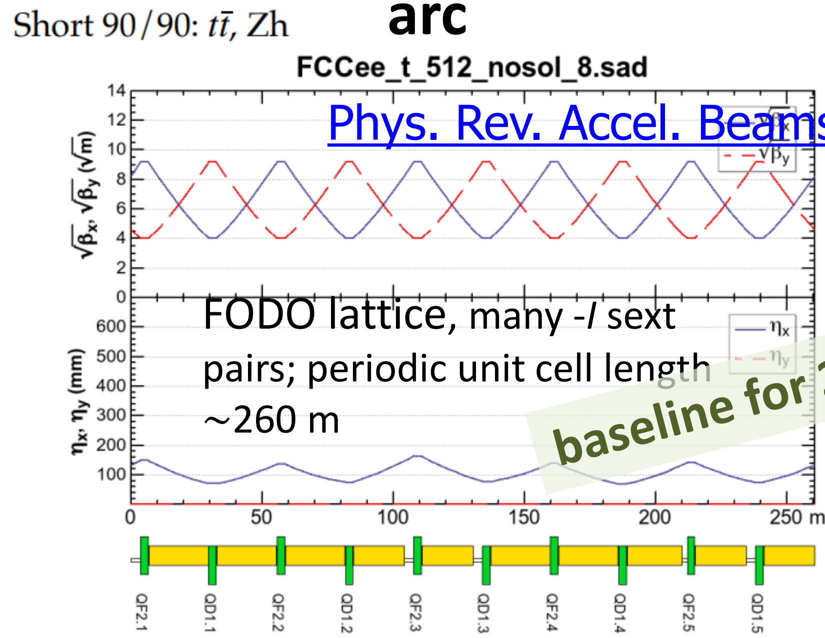
- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

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

FCC-ee collider optics: two viable options

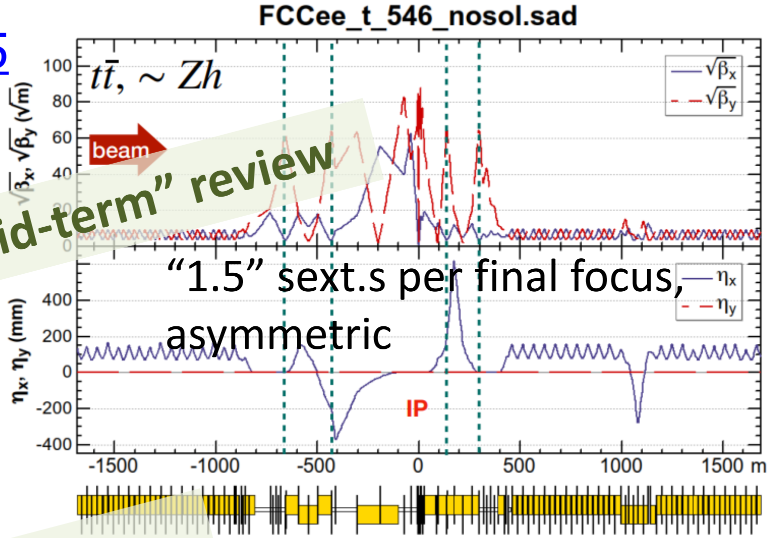
arc

interaction region



[Phys. Rev. Accel. Beams **19**, 111005]()

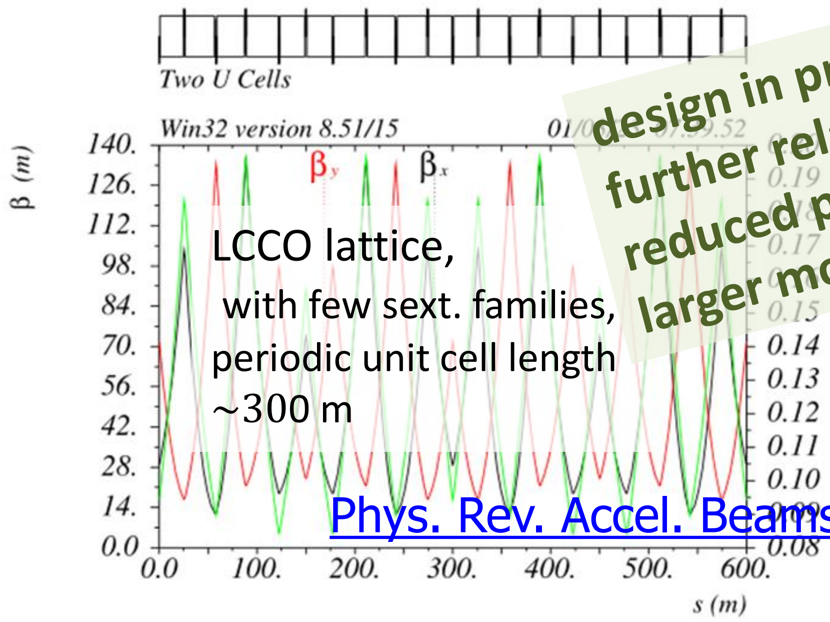
FODO lattice, many -*I* sext pairs; periodic unit cell length ~260 m



“1.5” sext.s per final focus, asymmetric

baseline for 2023 FCC “mid-term” review

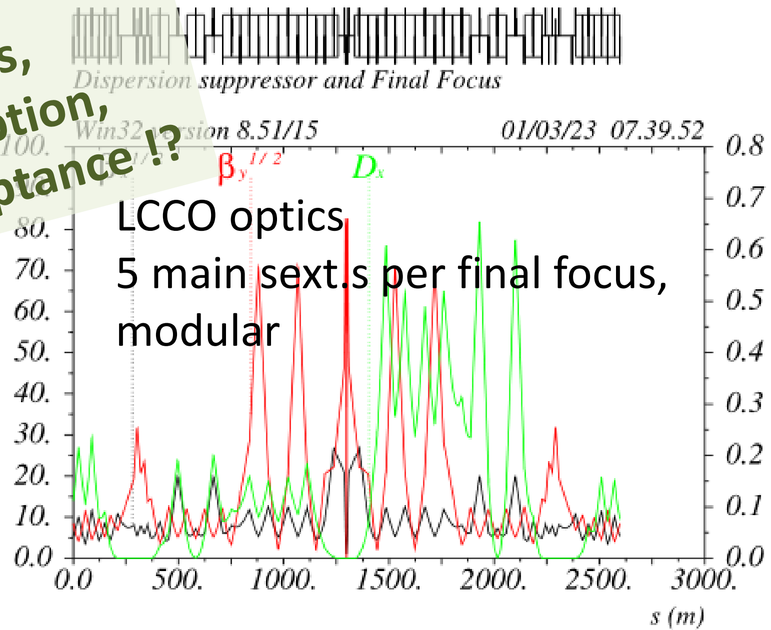
K. Oide, 2023 EPS
Rolf Wideroe award winner



LCCO lattice,
with few sext. families,
periodic unit cell length ~300 m

[Phys. Rev. Accel. Beams **26**, 021601]()

design in progress -
further relaxed tolerances,
reduced power consumption,
larger momentum acceptance !?



LCCO optics
5 main sext.s per final focus,
modular

P. Raimondi, 2017 EPS
Gersh Budker award winner

FCC-ee LCCO dynamic aperture progress

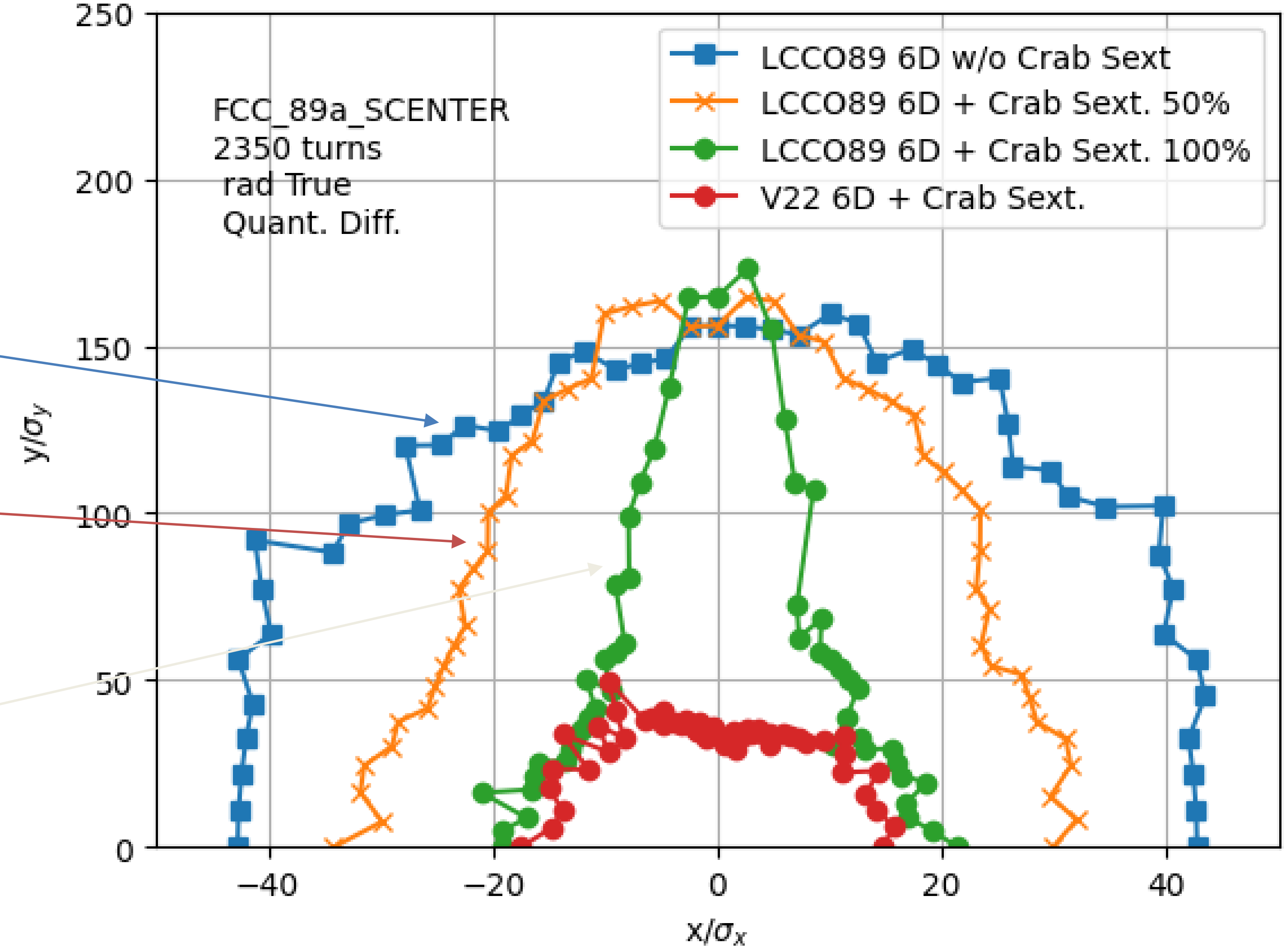
S. Liuzzo, 25 January 2024

Crab 100% = 80% of geometric value

Commissioning

Tuning with progressive increase of Crab sextupoles.

Final configuration for Luminosity production.



Prototype Q1 (left) & Interaction Region Mock-Up (right)

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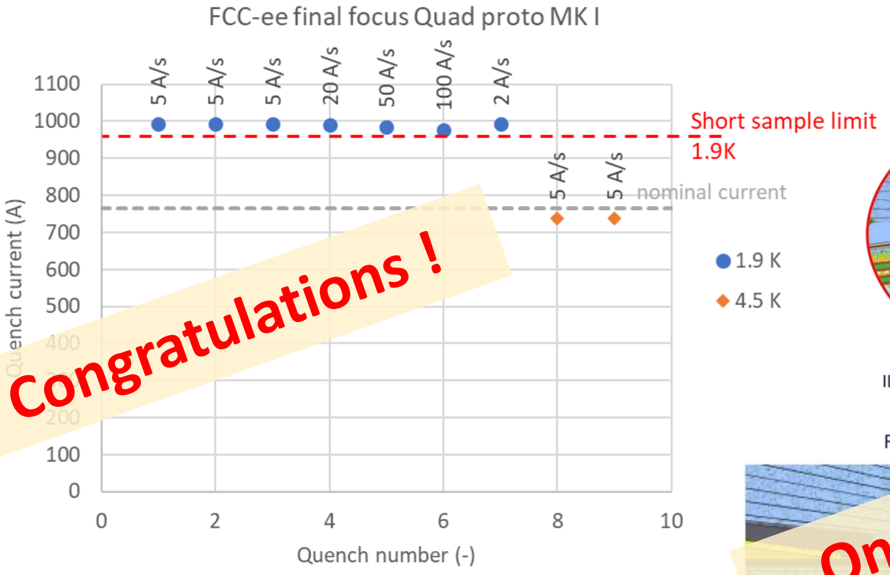
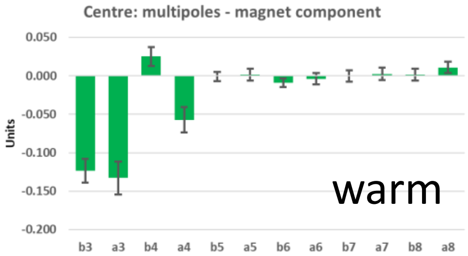
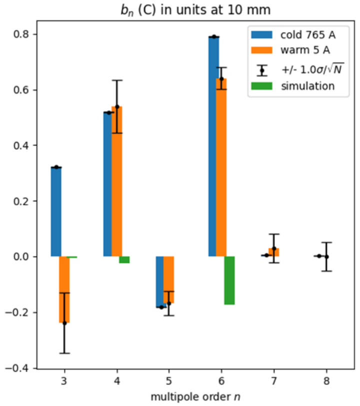
M. Koratzinos

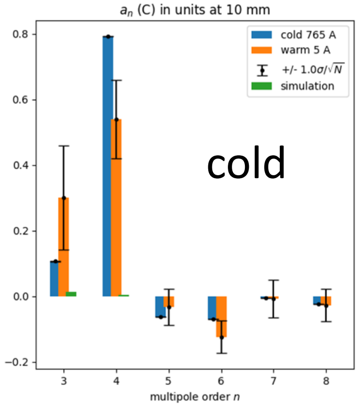
Testing at cold in SM18 (CERN), 27-31 October 2023



Congratulations !



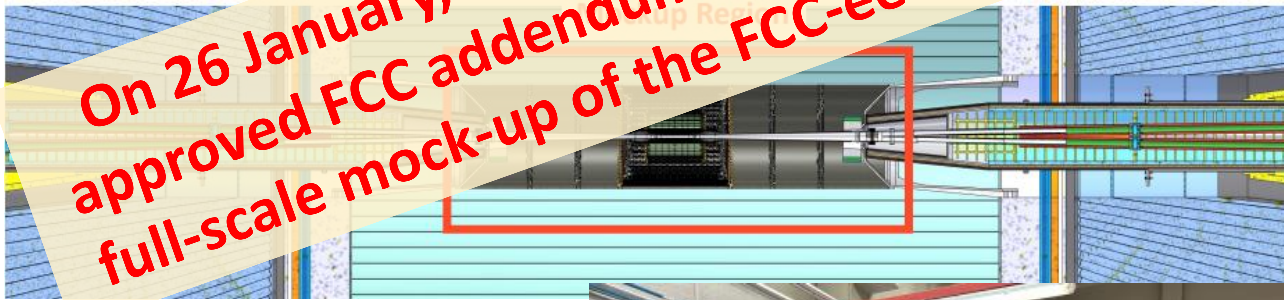




field quality:
all multipole errors <1 unit !

CERN-PSI collaboration

M. Boscolo



On 26 January, the INFN Board of Directors approved FCC addendum on construction of a full-scale mock-up of the FCC-ee IR in Frascati

FCC-ee IR mock-up assembly & test lab at INFN Frascati

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Stage 2: FCC-hh – parameters

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

High Temperature Superconductors (ReBCO, IBS): an enabling technology for high field (>15 T) magnets → R&D on HTS conductor

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, …

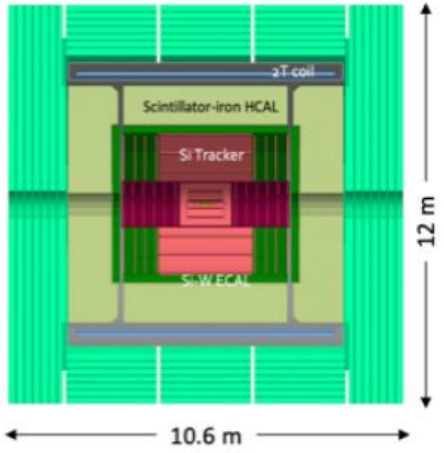
Formidable physics reach, including:

- ❑ 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

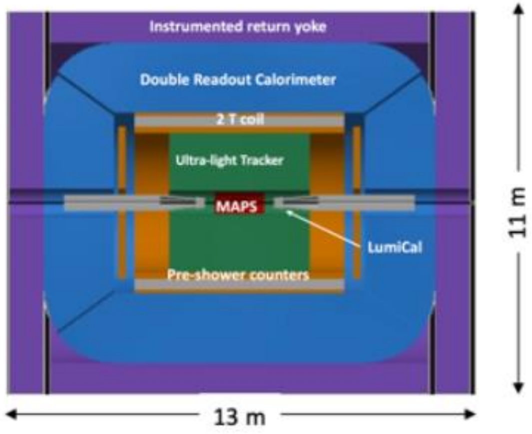
F. Gianotti

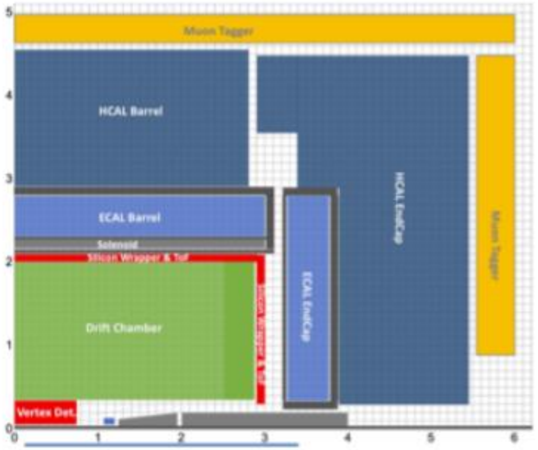
FCC-ee detector concepts under study

CLD	IDEA	Noble Liquid ECAL based ALLEGRO



CDR





new

CLD

- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker; CALICE-like calorimetry; large coil, muon system
- Engineering and R&D needed for
  - reduction of tracker material budget
  - operation with continous beam (no power pulsing: cooling of Si sensors for tracking + calorimetry)
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: timing and/or RICH?

IDEA

- Less established design
  - But still ~15y history: ILC 4th Concept
- Si vtx detector; ultra light drift chamber w powerfull PID; compact, light coil; monolitic dual readout calorimeter; muon system
  - Possibly augmented by crystal ECAL
- Active community
  - Prototype designs, test beam campains, …

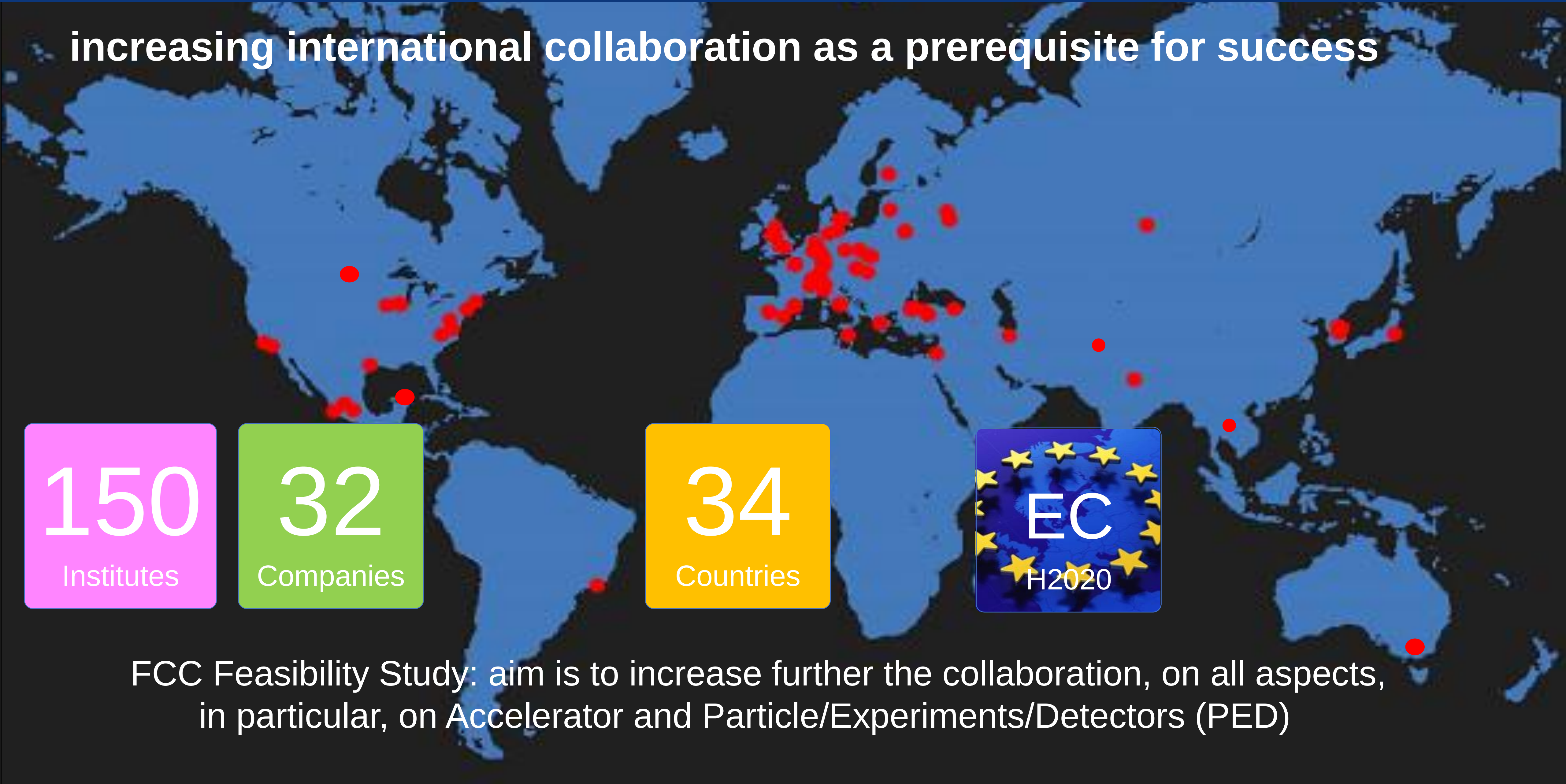
Noble Liquid ECAL based

- A design in its infancy
- High granularity Noble Liquid ECAL is core
  - Pb+LAr (or dense W+LKr)
- Drift chamber; CALICE-like HCAL; muon system.
- Coil inside same cryostat as LAr, possibly outside ECAL
- Active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

M. Dam, et al.

Status of FCC global collaboration

FUTURE CIRCULAR COLLIDER



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 ?

F. Gianotti

1) **Physics : best overall physics potential of all proposed future colliders; matches the vision of the 2020 European Strategy:** "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."

- 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)
- Also provides for heavy-ion collisions and, possibly, ep/e-ion collisions
- **4 collision points** → robustness; specialized experiments for maximum physics output

2) **Timeline**

- **FCC-ee technology is "mature"** → construction can start in the early 2030s and physics a few years after the end of HL-LHC operation (currently 2048, earlier if more resources available) → 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?

-- Ongoing Feasibility Study showing spectacular progress

-- **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

-- FCC is the **best project for future of CERN** (for above reasons) → **we have to work to make it happen**

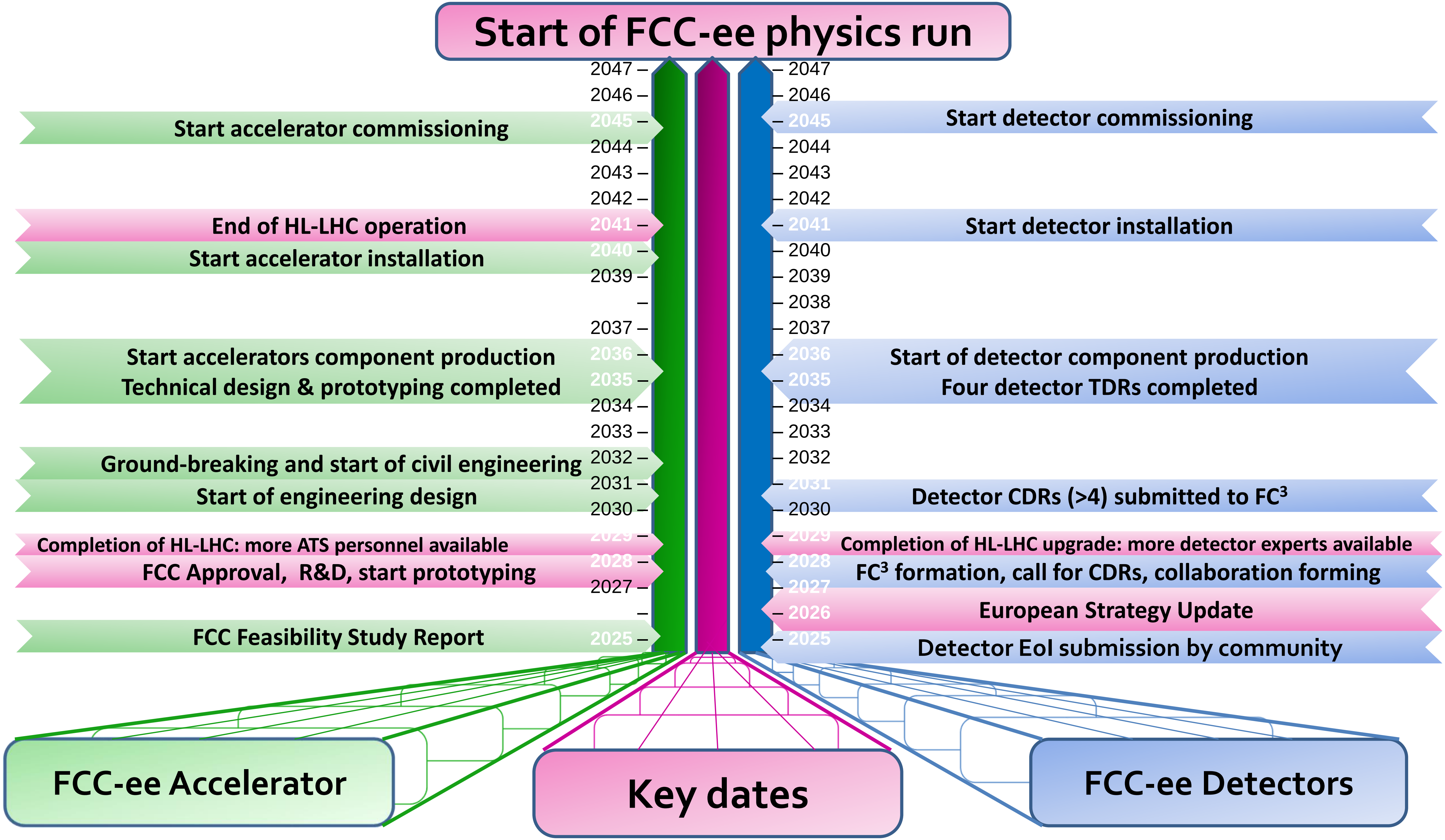
Visit of Swiss President A. Berset and French President E. Macron on 16 Nov.'23

"A pivotal event for CERN: strong support expressed by both Presidents for CERN, its future and the FCC"

F. Gianotti

President Macron's declaration:

"Si j'ai voulu venir là aujourd'hui c'est pour témoigner ma confiance aux équipes et notre volonté, notre ambition de conserver la première place dans ce domaine." ["My visit here bears witness to my trust in CERN personnel and France's will and ambition to keep the leadership in this domain."]



Start of FCC-ee physics run
2047
2046
2045
2044
2043
2042
2041
2040
2039
2038
2037
2036
2035
2034
2033
2032
2031
2030
2029
2028
2027
2026
2025
Start accelerator commissioning
End of HL-LHC operation
Start accelerator installation
Start accelerators component production
Technical design & prototyping completed
Ground-breaking and start of civil engineering
Start of engineering design
Completion of HL-LHC: more ATS personnel available
FCC Approval, R&D, start prototyping
FCC Feasibility Study Report
Start detector commissioning
Start detector installation
Start of detector component production
Four detector TDRs completed
Detector CDRs (>4) submitted to FC³
Completion of HL-LHC upgrade: more detector experts available
FC³ formation, call for CDRs, collaboration forming
European Strategy Update
Detector EoI submission by community
FCC-ee Accelerator
Key dates
FCC-ee Detectors

Should we change our plans ?

F. Gianotti

1) Only a new European Strategy can modify the plans of a previous one, taking into account Europe's ambitions within the global context (e.g. P5/US support for an off-shore Higgs factory, CEPC in China, etc.)

2) Recommendation of 2020 European Strategy for future colliders:
"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."
Note: the Strategy does not state that a Higgs factory should be built in Europe. However, a Higgs factory is the highest priority for the European community → wherever it will be built, it should allow for significant participation from Europe

3) Furthermore, skipping FCC-ee and going directly to FCC-hh implies a long gap (>> 10 years) between the end of HL-LHC and beginning of next collider at CERN, for reasons of cost and of readiness of high-field magnet technology
→ risk to lose the community, in particular the young generations.

4) The only colliders that are technically mature enough to start operation in early 2040s are e^+e^- Higgs factories, and to be time-competitive with the CEPC (if approved), a circular Higgs factory is needed (much higher luminosity than linear colliders)

⬇

Should we change our plans ? NO

Should we accelerate our planning ? YES
→ CERN Directorate will discuss these matters with the CERN Council in the coming months

further faster steps in San Francisco !

FUTURE
CIRCULAR
COLLIDER

thank you for your attention!

spare slides

FCC Feasibility Study (2021-2025): 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.

Results will be summarised in a Feasibility Study Report to be released in 2025

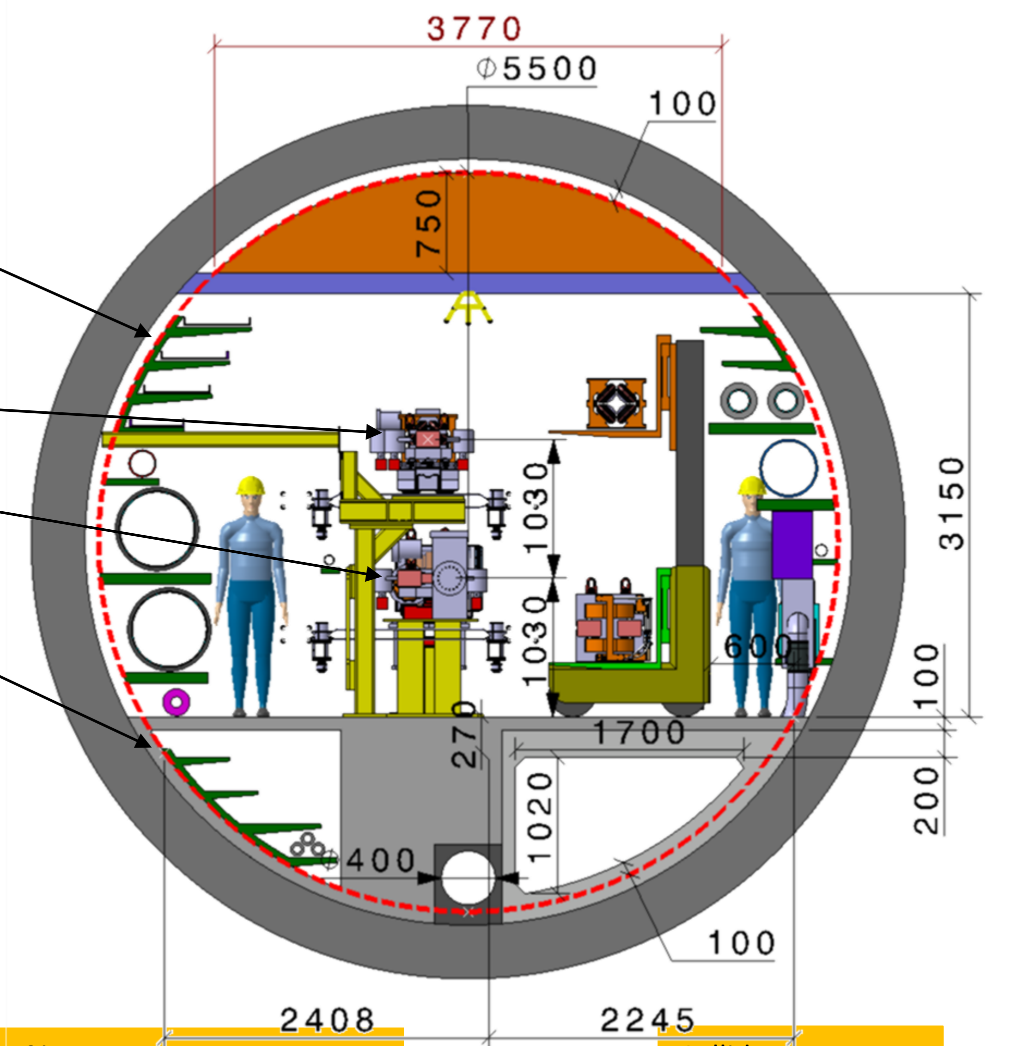
F. Gianotti

R&D on HTS high-field magnets

- **High Temperature Superconductors**: an **enabling technology** for high field ($\geq$ 15 T) magnets - a **sustainable opportunity** for future accelerator technology
- **Focus** of the LDG Accelerator R&D Roadmap is presently on **REBCO**, but alternative options are also considered (**IBS** as in China)
- To exploit the potential, a rigorous **R&D program** is required
- **R&D on conductor** is essential for subsequent successful implementation in HTS magnets. This requires:
  - reaching **controlled**, **homogeneous** and **reproducible properties** on industrially available conductor;
  - achieving **long** (~ 1 km) **lengths** of industrially available conductor;
  - **innovation** via development of **high-current cables**;
  - validation of the technology via **a parallel programme** of small **demonstrator coils**; this is needed to provide feedback to conductor R&D and to support/launch magnet design and development

regular arc tunnel cross section & element integration

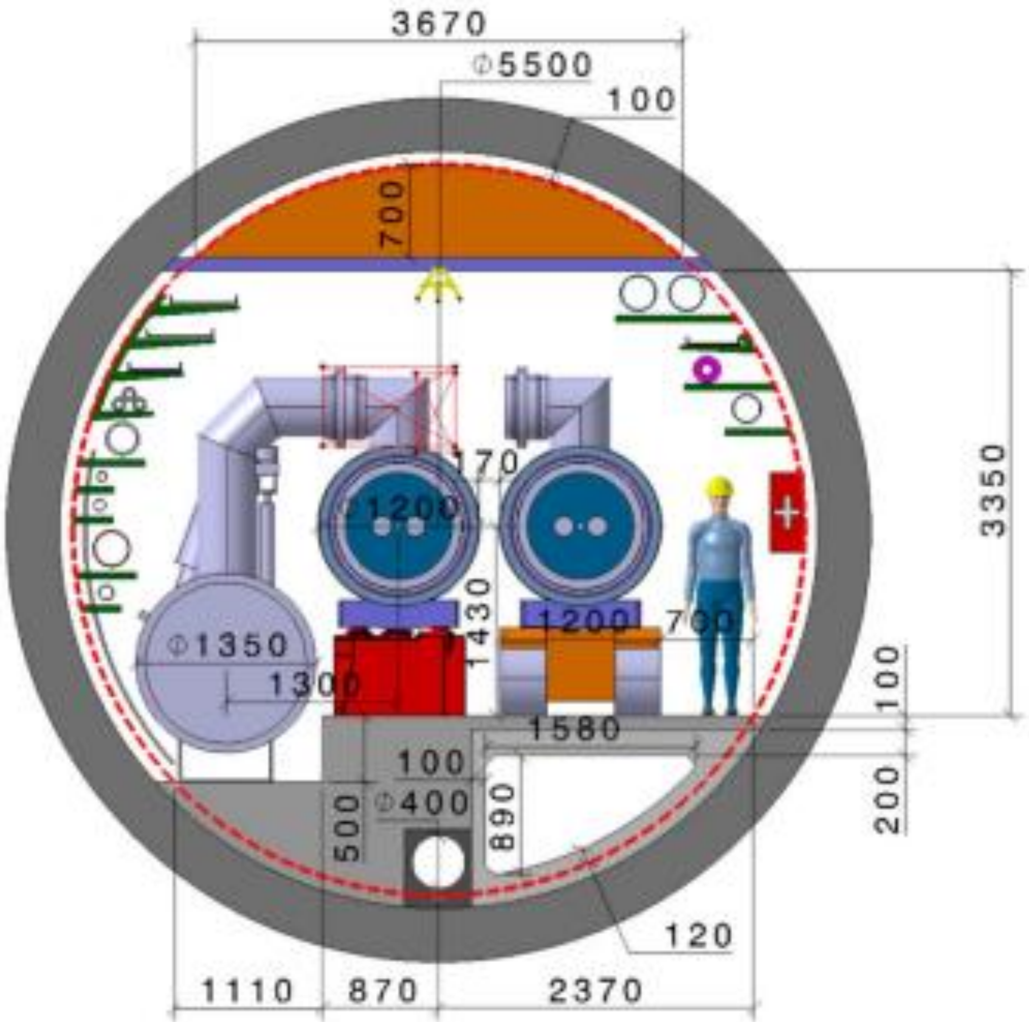
FCC-ee



Main ring below of booster ring
Main ring and booster ring 1.03 m apart

Collider Center

FCC-hh (from CDR 2019)

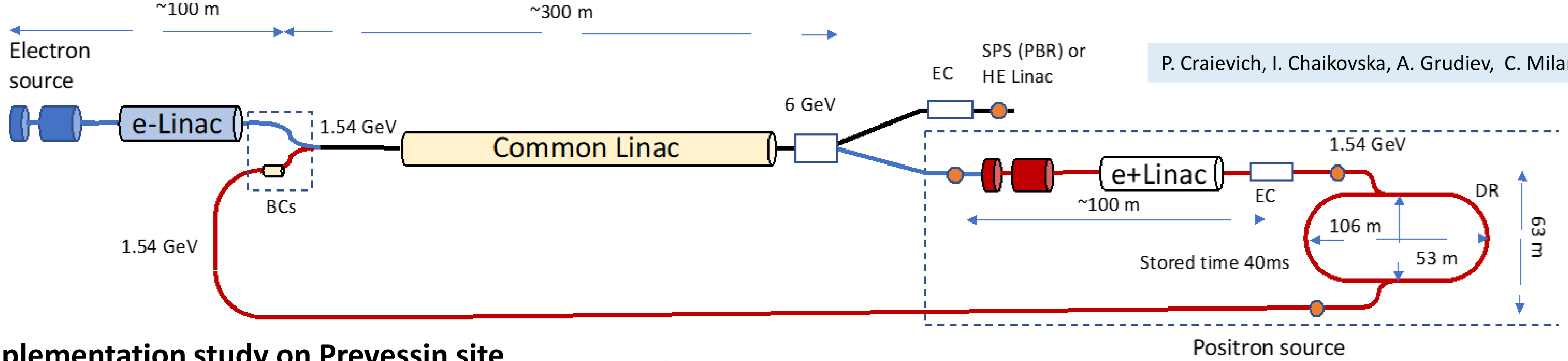


*Size of QRL to be reduced

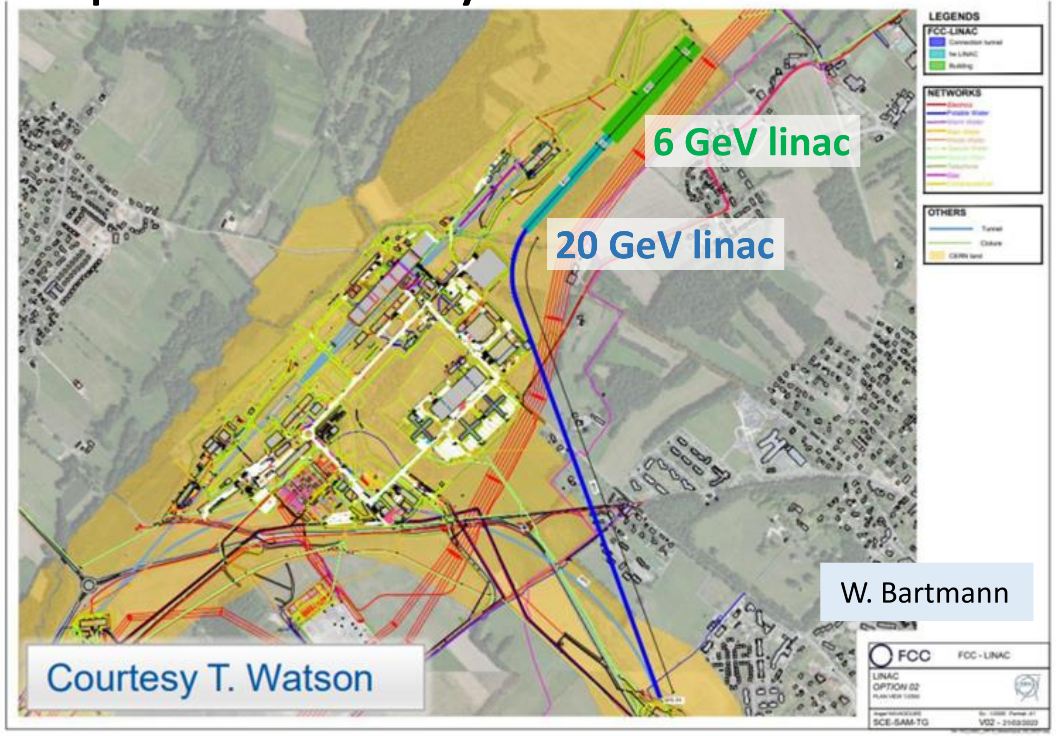
F. Valchkova

FCC-ee injector layout & implementation

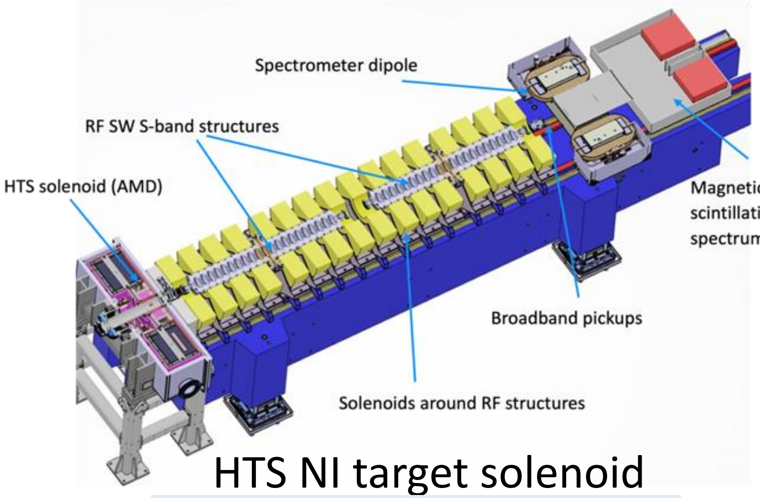
P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

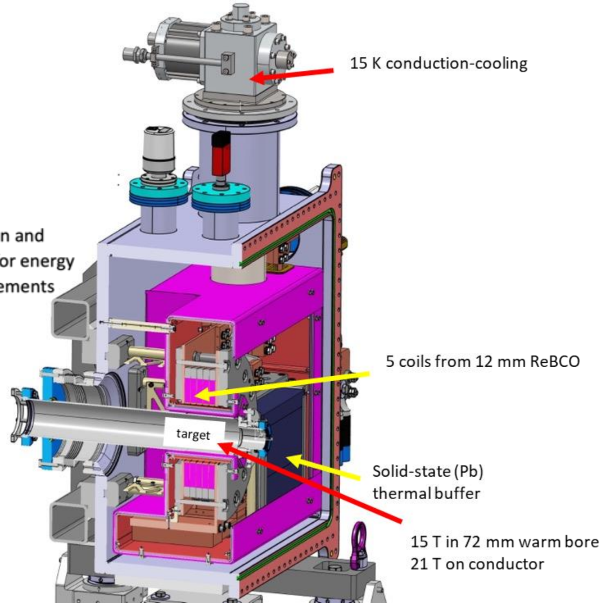


implementation study on Prevessin site



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



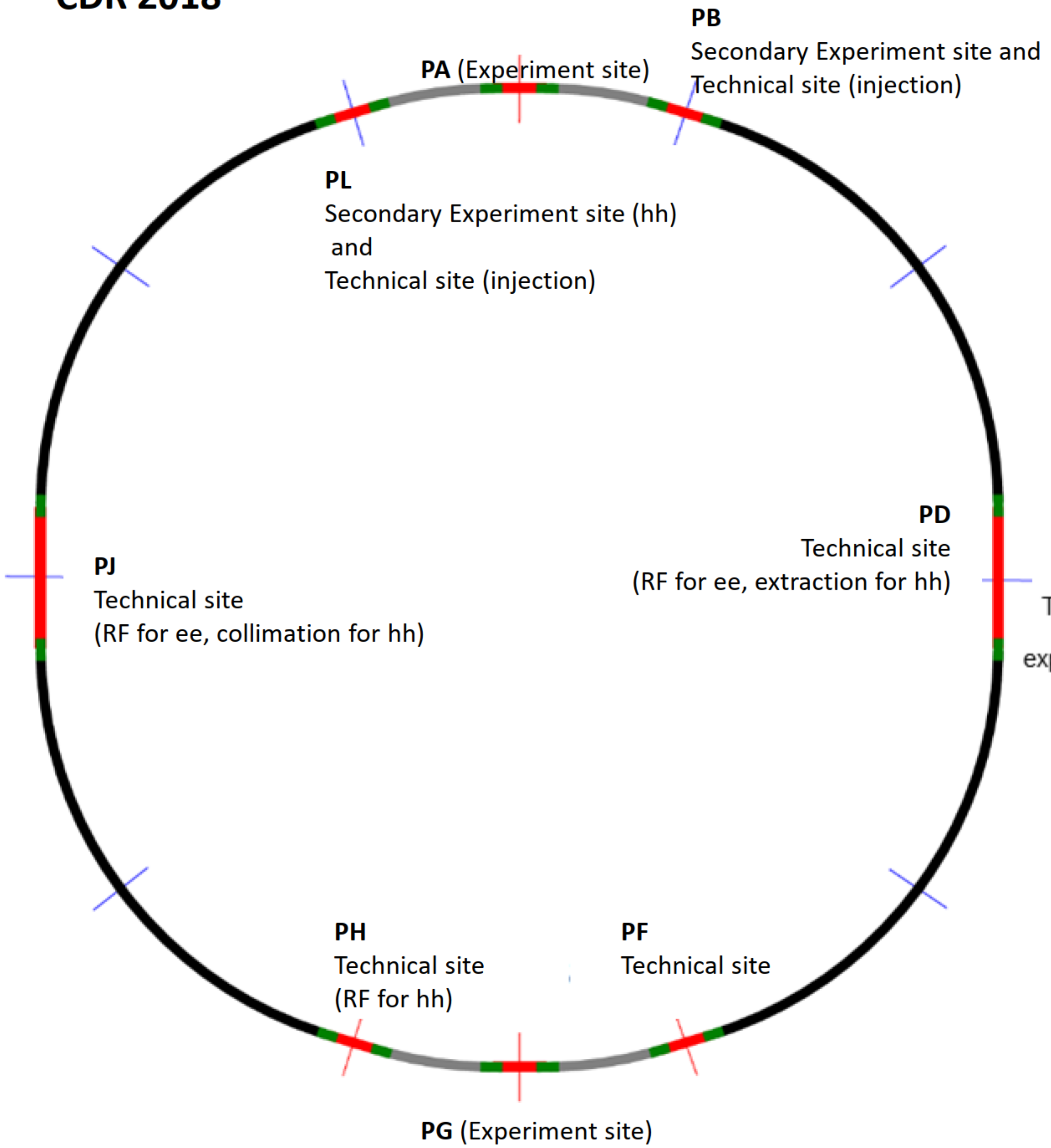


HTS NI target solenoid

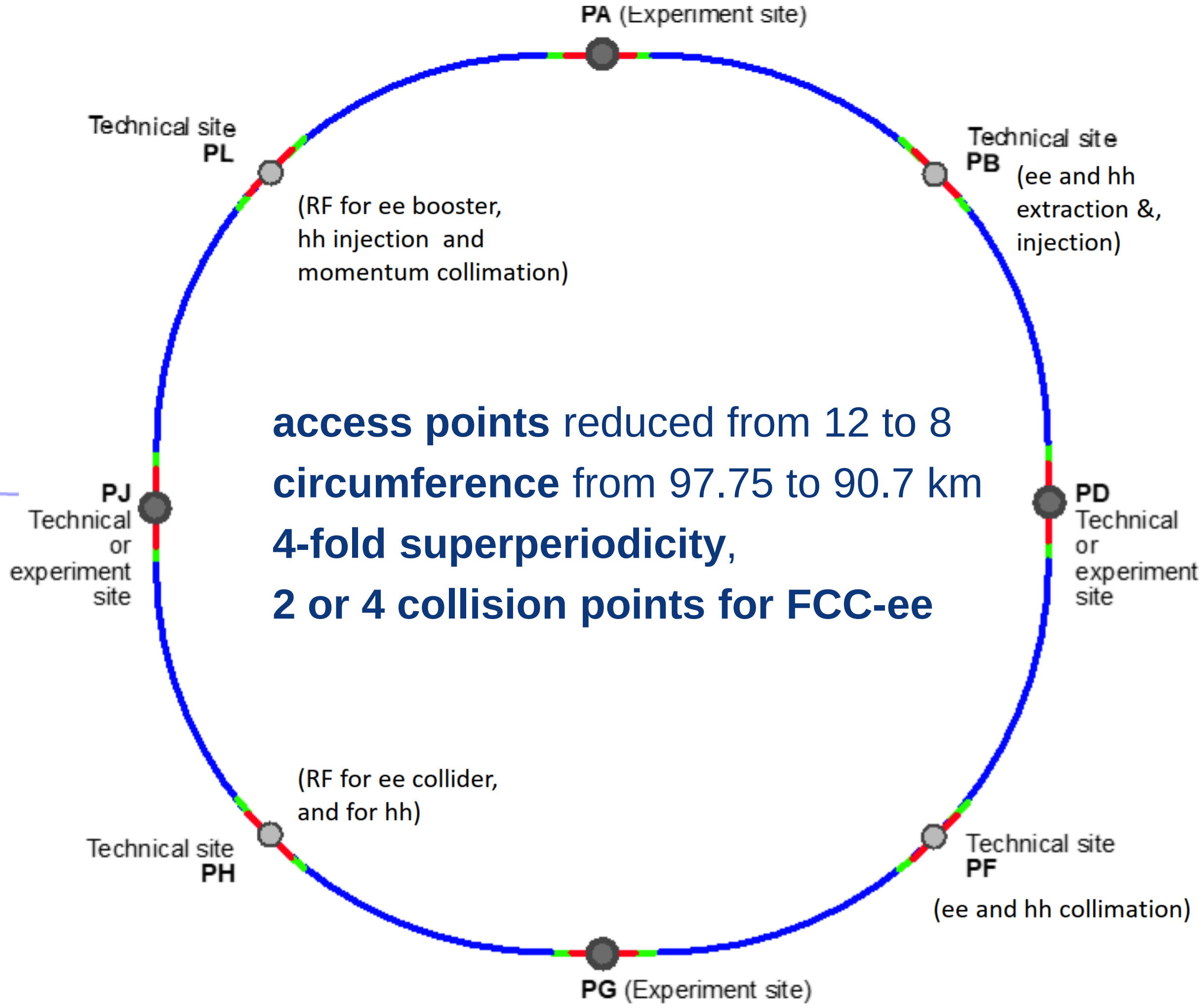
J. Kosse, T. Michlmayr, H. Rodrigues

Revised layout and geometry

CDR 2018



"Optimised" Midterm 2023



access points reduced from 12 to 8

circumference from 97.75 to 90.7 km

4-fold superperiodicity,

2 or 4 collision points for FCC-ee

M. Dam, et al.

Main geometrical parameters

Main changes

- **# access points** reduced from 12 to 8
- facilitating placement and reducing the overall surface area required
- **circumference has shrunk** from 97.75 km to 90.657 km
- new layout with **4-fold superperiodicity**, enabling FCC-ee operation with either **2 or 4 collision points**
- **hadron collider** RF system now **shares** a **klystron gallery tunnel with lepton collider**
- new circumference matched to both LHC and the SPS tunnels, corresponding to 400 MHz harmonic ratios of h_{FCC}/h_{LHC}=1010/297 & h_{FCC}/h_{SPS}=1010/77, **allowing for hadron beam injection from either the LHC or from a new superconducting SPS**, with bunch spacings of 2.5, 5.0, 7.5, 10, 12.5, 15, 20, and 25 ns

Parameter	unit	2018 CDR [1]	2023 Optimised
Total circumference	km	97.75	90.657
Total arc length	km	83.75	76.93
Arc bending radius	km	13.33	12.24
Arc lengths (and number)	km	8.869 (8), 3.2 (4)	9.617 (8)
Number of surface sites	—	12	8
Number of straights	—	8	8
Length (and number) of straights	km	1.4 (6), 2.8 (2)	1.4 (4), 2.031 (4)
superperiodicity	—	2	4

Communication aspects

- **CERN press release in February 2023 to inform about FS and organisation**
- **Prepared with France and Switzerland « groupe de dialogue territoriale »**

- **Press visit at CERN for local medias in April 2023**

- **11 journalistes**
- **90 press clippings**
- **31 countries**

FCC FS Council Documents, June ‘21

Organisational Structure of the FCC Feasibility Study

http://cds.cern.ch/record/2774006/files/English.pdf

CERN/SPC/1155/Rev.2
CERN/3566/Rev.2
Original: English
21 June 2021

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken		*Voting Procedure*
For decision	**RESTRICTED COUNCIL** 203rd Session **17 June 2021**	Simple majority of Member States represented and voting

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:

PROPOSED ORGANISATIONAL STRUCTURE

This document sets out the proposed organisational structure for the Feasibility Study of the Future Circular Collider, to be carried out in line with the recommendations of the European Strategy for Particle Physics updated by the CERN Council in June 2020. It reflects discussion at, and feedback received from, the Council in March 2021 and is now submitted for the latter’s approval.

Main Deliverables and Timeline of the FCC Feasibility Study

http://cds.cern.ch/record/2774007/files/English.pdf

CERN/SPC/1161
CERN/3588
Original: English
21 June 2021

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

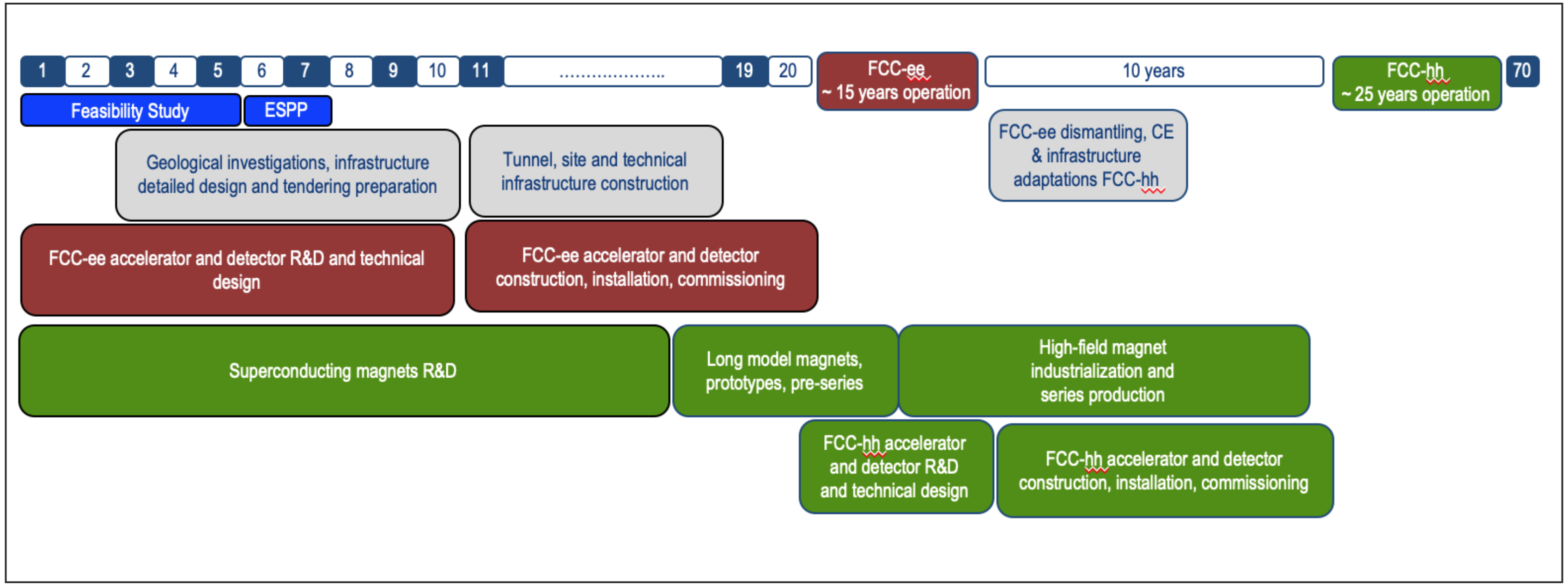
Action to be taken		*Voting Procedure*
For information	**RESTRICTED COUNCIL** 203rd Session **17 June 2021**	-

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:

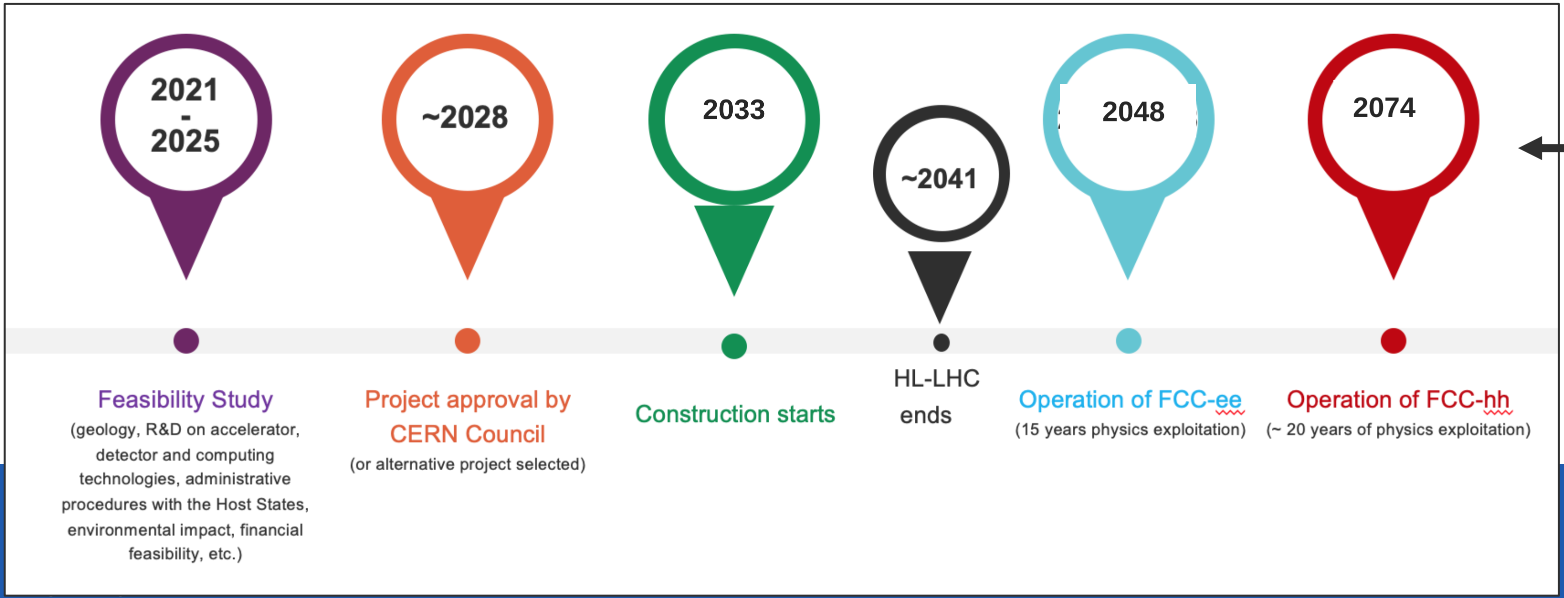
MAIN DELIVERABLES AND MILESTONES

This document describes the main deliverables and milestones of the study being carried out to assess the technical and financial feasibility of a Future Circular Collider at CERN. The results of this study will be summarised in a Feasibility Study Report to be completed by the end of 2025.

FCC integrated program - timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018

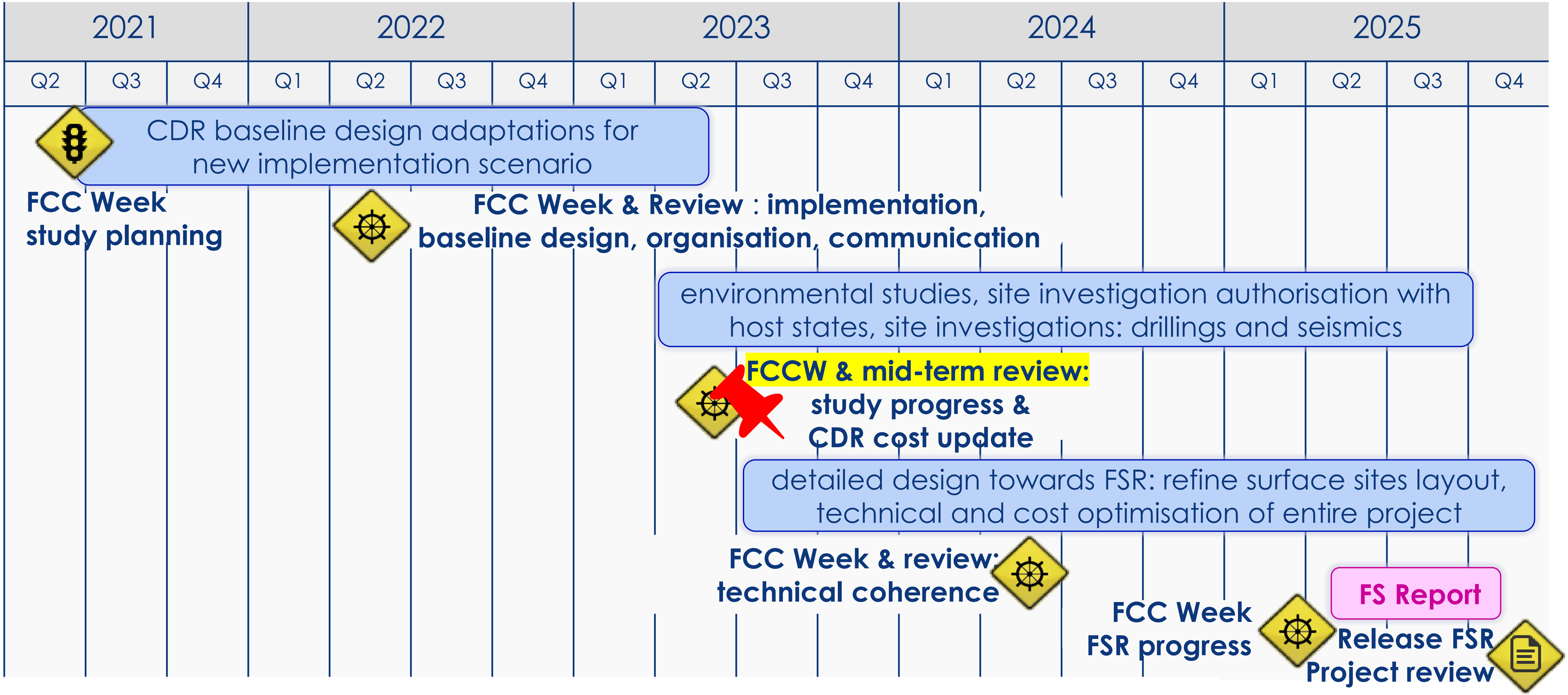


“Realistic” schedule taking into account:

- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041

Can be accelerated if more resources available

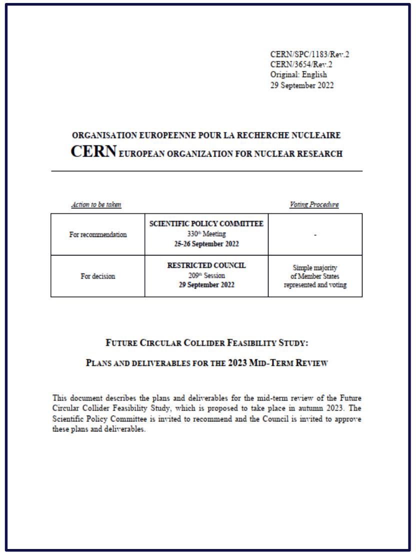
Feasibility Study timeline and main activities/milestones



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

FCC Feasibility Study – mid-term status summary

The first half of the FCC Feasibility Study is being completed with the mid-term review

- 20 – 22 November 2023: SPC and FC review meetings on mid-term review
- 2 February 2024: CERN Council meeting on mid-term review

Focus 2021 - 2023:

- identifying best placement & layout and adapting entire project to new placement
- this provided the input for the mid-term review documentation and cost estimate update

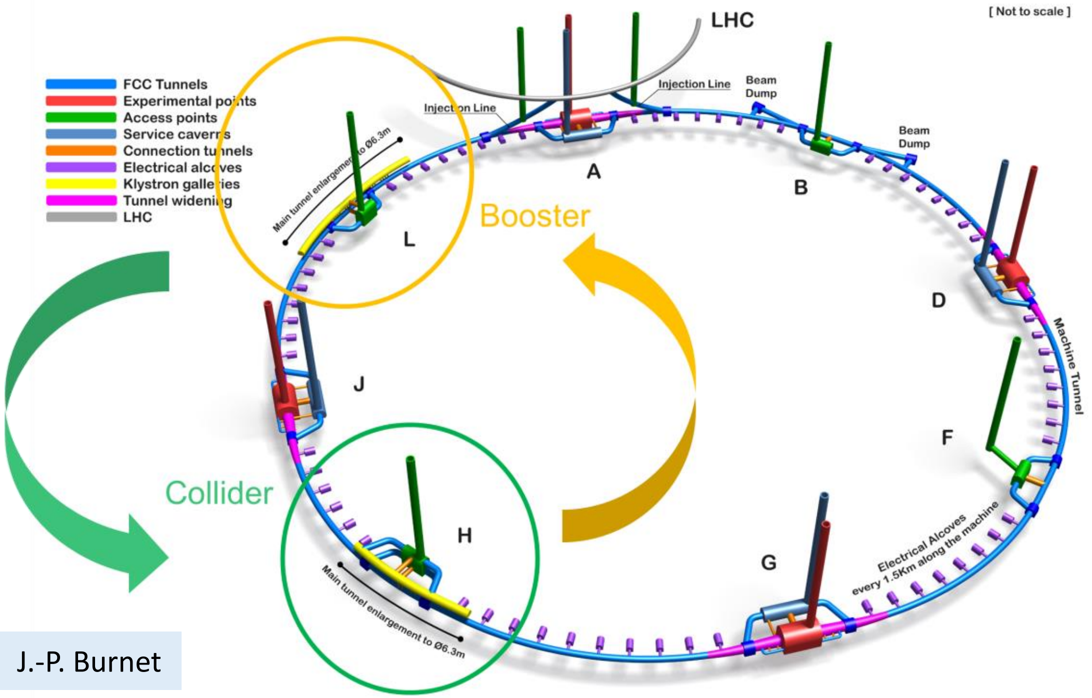
Fruitful collaboration between scientific & technical actors, in close cooperation with the host state services concerned, at departmental/cantonal and local level. Direct exchange in place with communes concerned by surface sites. Environmental studies ongoing.

Focus 2024 - 2025:

- Subsurface investigations, further optimization of implementation, surface sites, synergies, etc.
- Full design iteration in view of technical and cost optimisation of entire project.

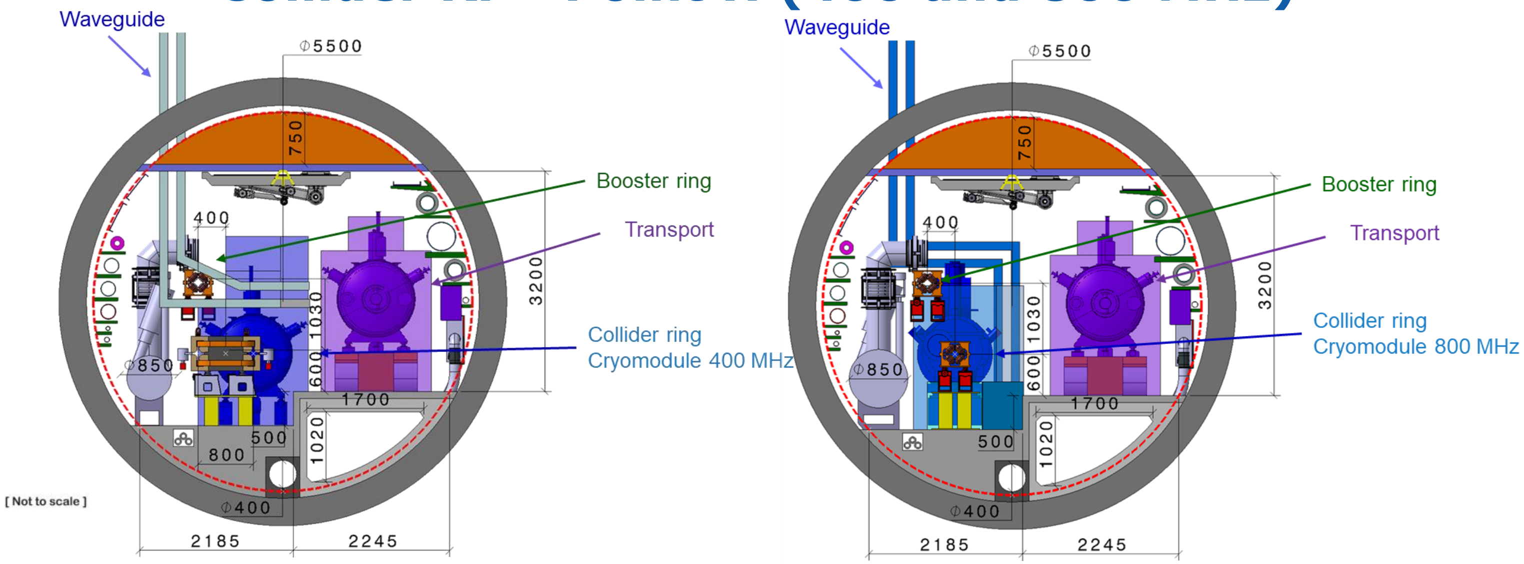
modified FCC-ee RF layout

- 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

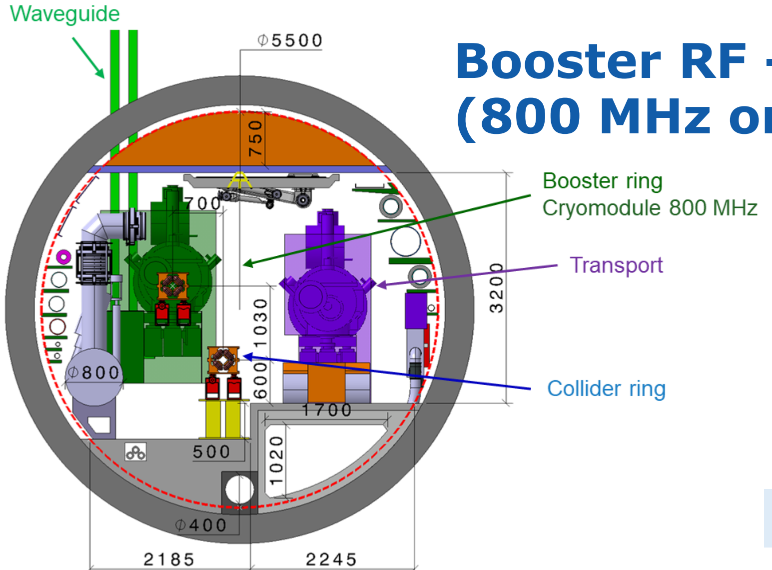


J.-P. Burnet

Collider RF - Point H (400 and 800 MHz)



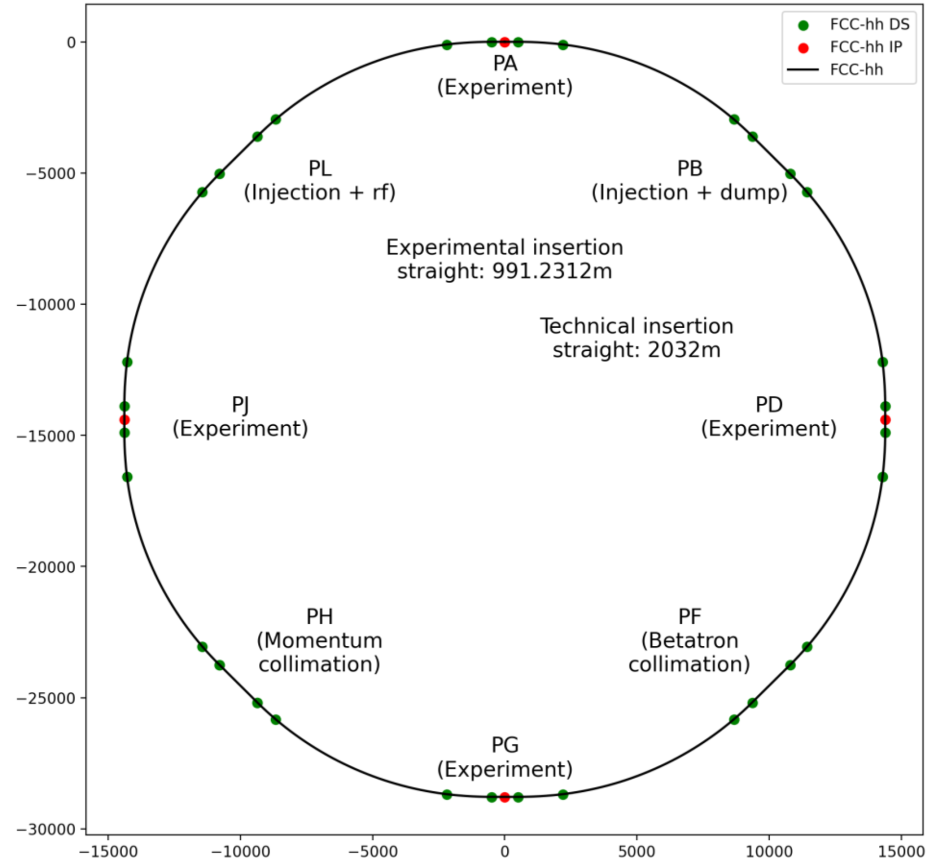
Booster RF - Point L (800 MHz only)



F. Valchkova, F. Peauger

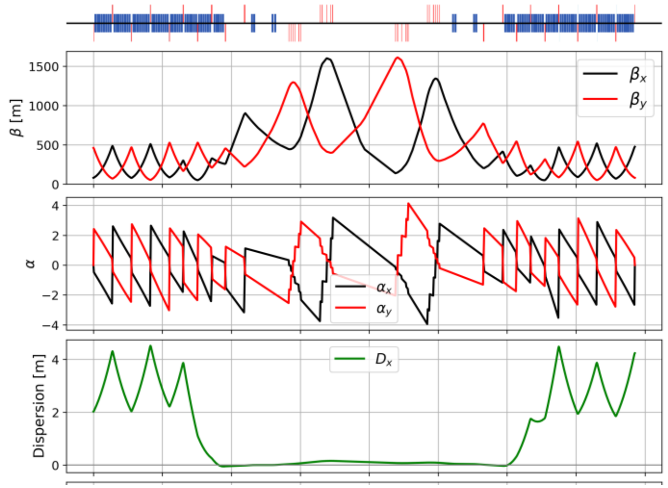
FUTURE CIRCULAR COLLIDER

FCC-hh layout, optics work, geom. integration

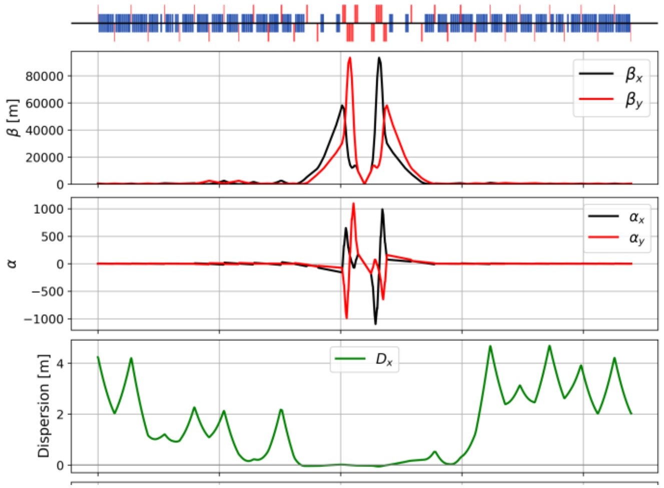


- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)
- move hh IPs on top of ee IP to optimise tunnel and cavern widths.

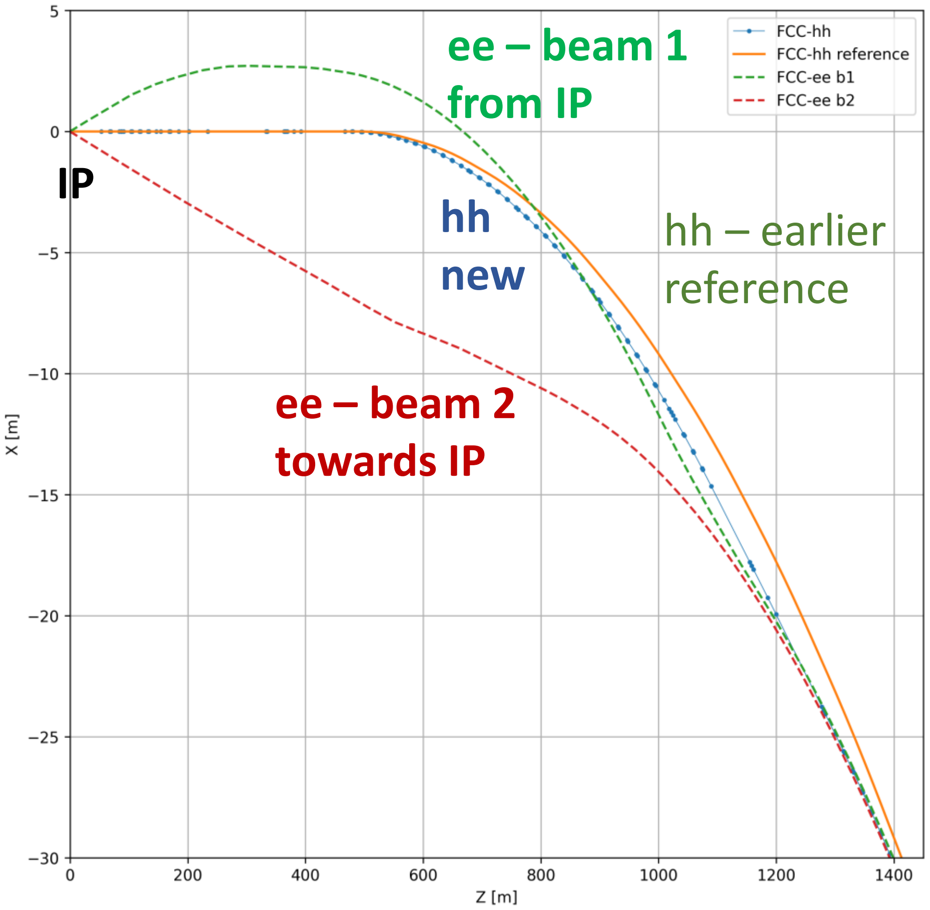
betatron collimation straight



experimental straight



3 - beam footprint at interaction point

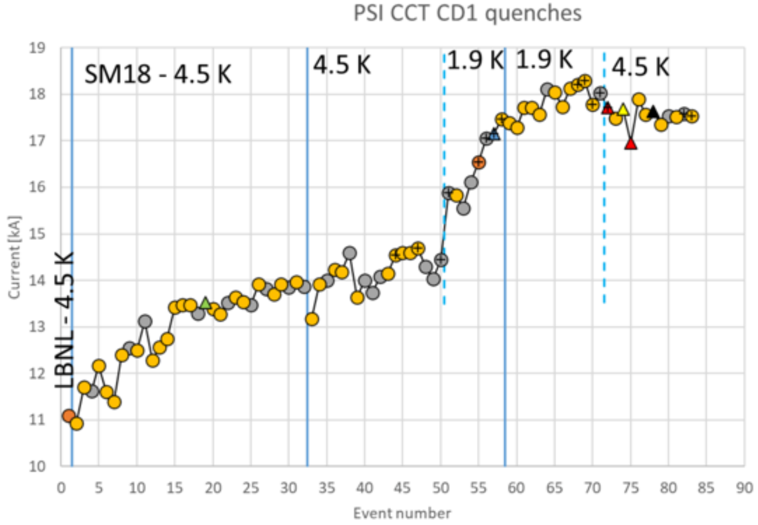


M. Giovannozzi, T. Risselada, G. Perez Segurana, M. Hofer, K. Oide

high-field magnets for FCC-hh: Nb_3Sn & HTS R&D

FUTURE CIRCULAR COLLIDER

PSI Nb3Sn CCT «CD1» main test carried out in 2022/23



It trained *A LOT*. It reached **100% of maximum field at 4.5 K**. No conductor degradation occurred from handling, assembly, powering, or thermal cycling.

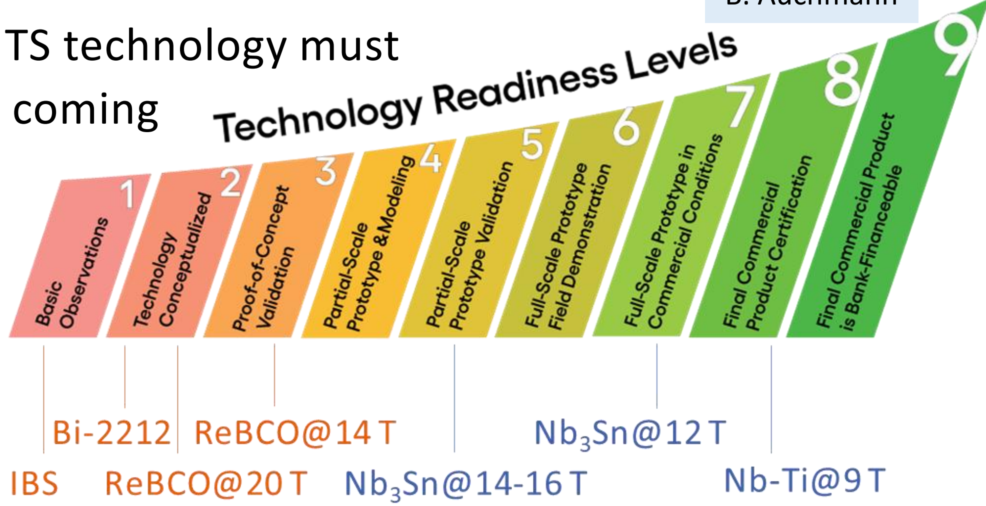
Stress-management works, CD1 is a robust magnet.

B. Auchmann

Rough estimates

Bottom line: HTS technology must catch over the coming 10 years in TRL to LTS

B. Auchmann



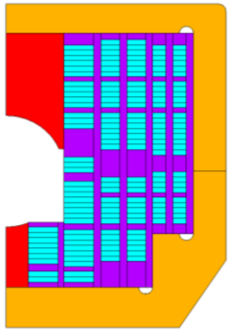
Next: FCC-hh SM-CC Demonstrator

Goal: demonstrate robust and cost-efficient Nb3Sn technology for next ESPPU.

Novel concept: Stress-managed and asymmetric common coils.

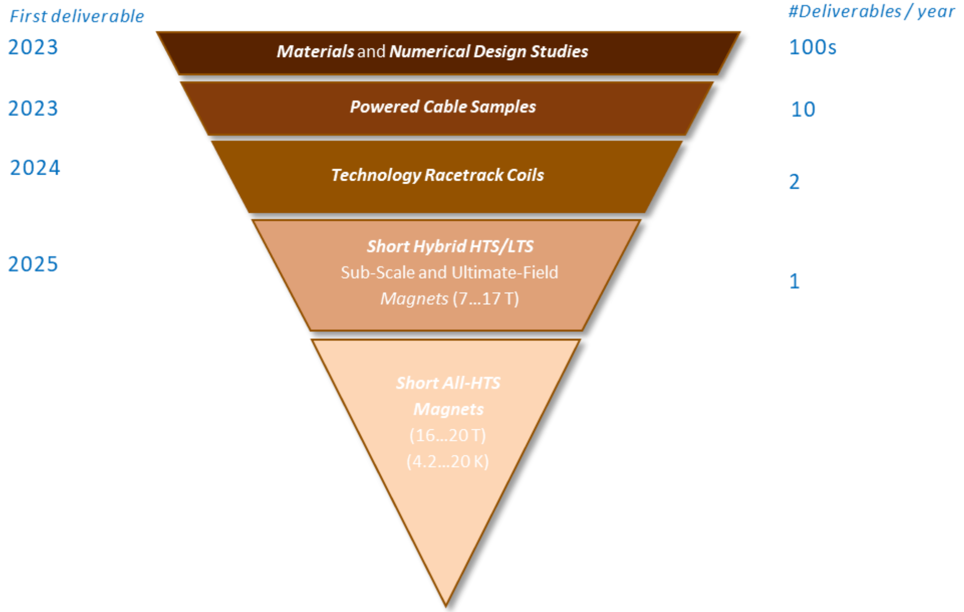
D. Araujo

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



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

HTS Innovation Funnel for HFM

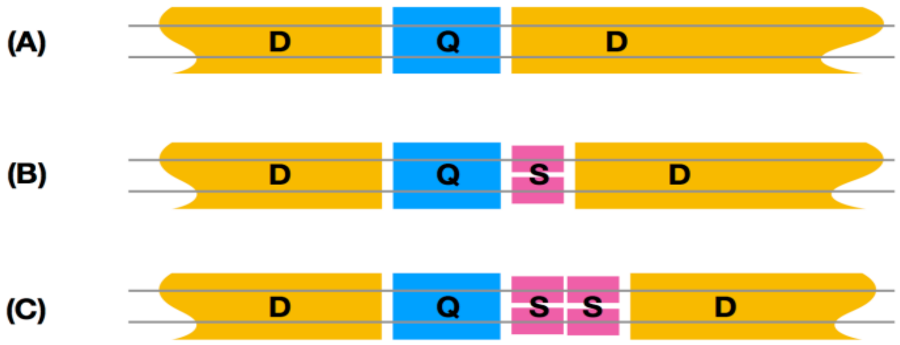


HTS option for FCC-ee (!) arc quads and sextupoles

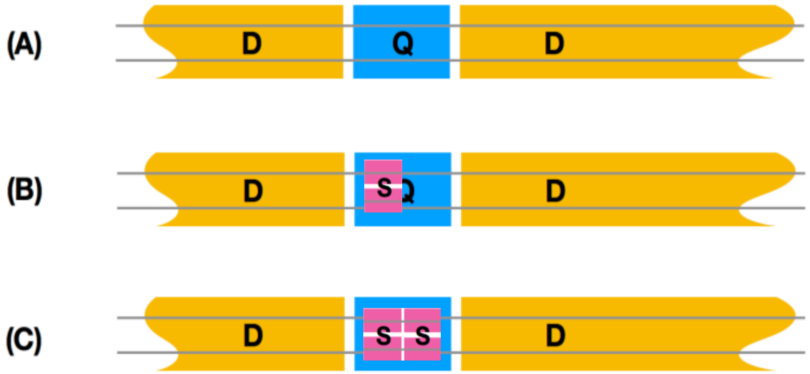
CDR: 2900 quads & 4700 sextupoles

- Normal conducting, ~50 MW @ ttbar
- 3 different types of short straight sections

CDR arc lattice



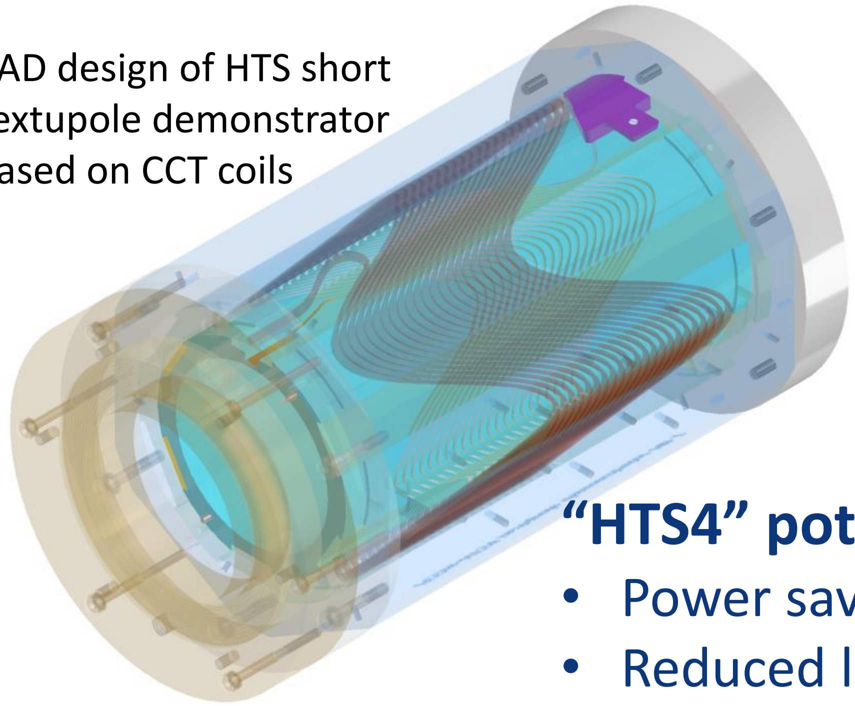
HTS option

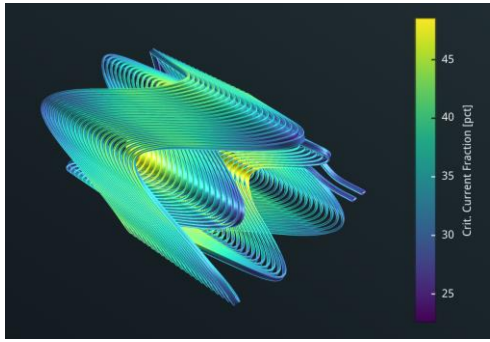


"HTS4" project within CHART collaboration

- Nested SC sextupole and quadrupole.
- HTS conductors operating at around 40K.
- Cryo-cooler supplied cryostat
- Produce a ~1m prototype by 2026

CAD design of HTS short sextupole demonstrator based on CCT coils





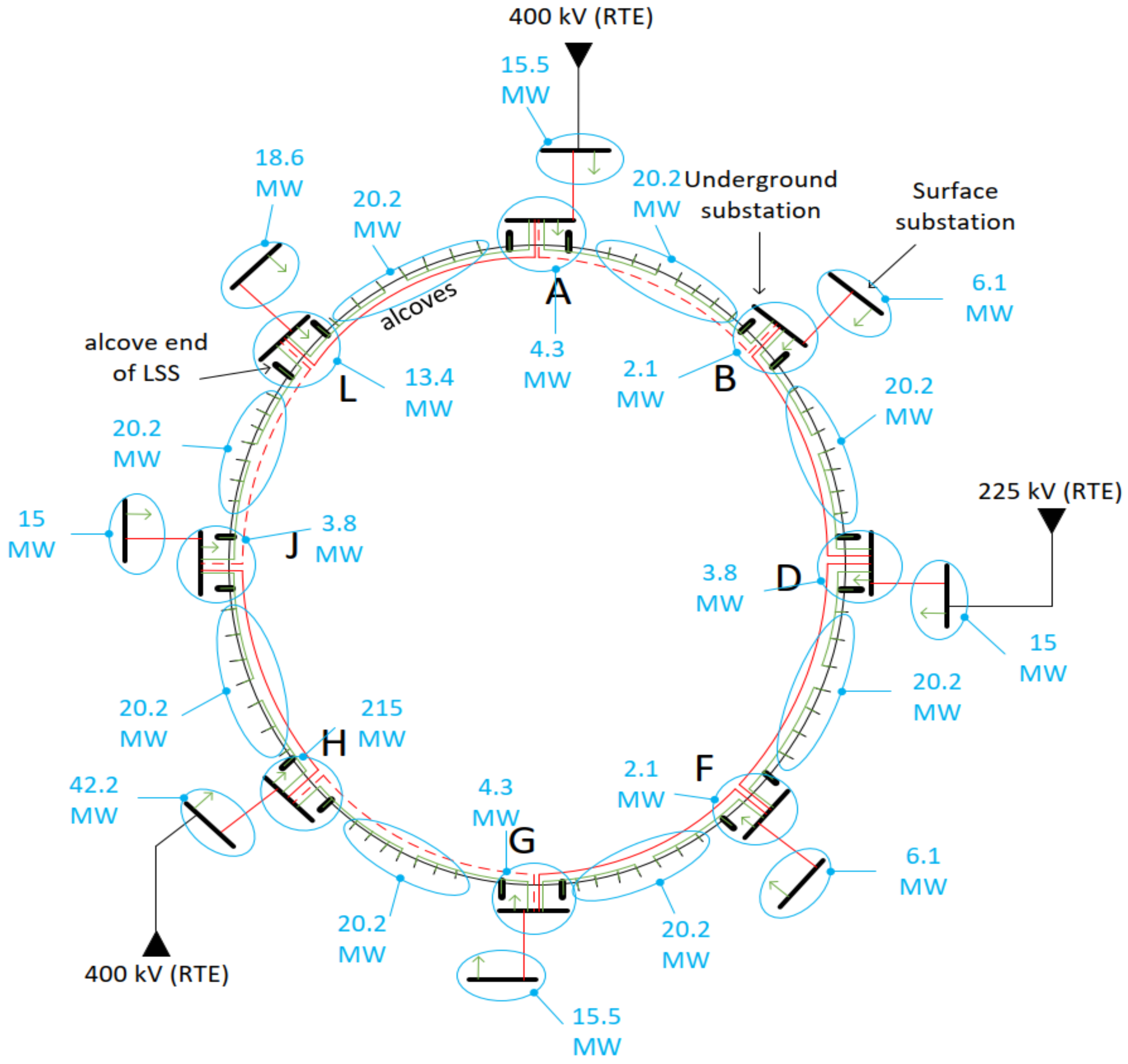
M. Koratzinos, B. Auchmann

"HTS4" potential

- Power saving
- Reduced length and increased dipole filling factor
- Optics flexibility

Electrical network

- **Electrical Power from the French network fed into the FCC at three points (A, H and D).**
- **Further distribution via the FCC ring.**
- **Covers all configurations of FCC-ee without need to build new sub-stations.**

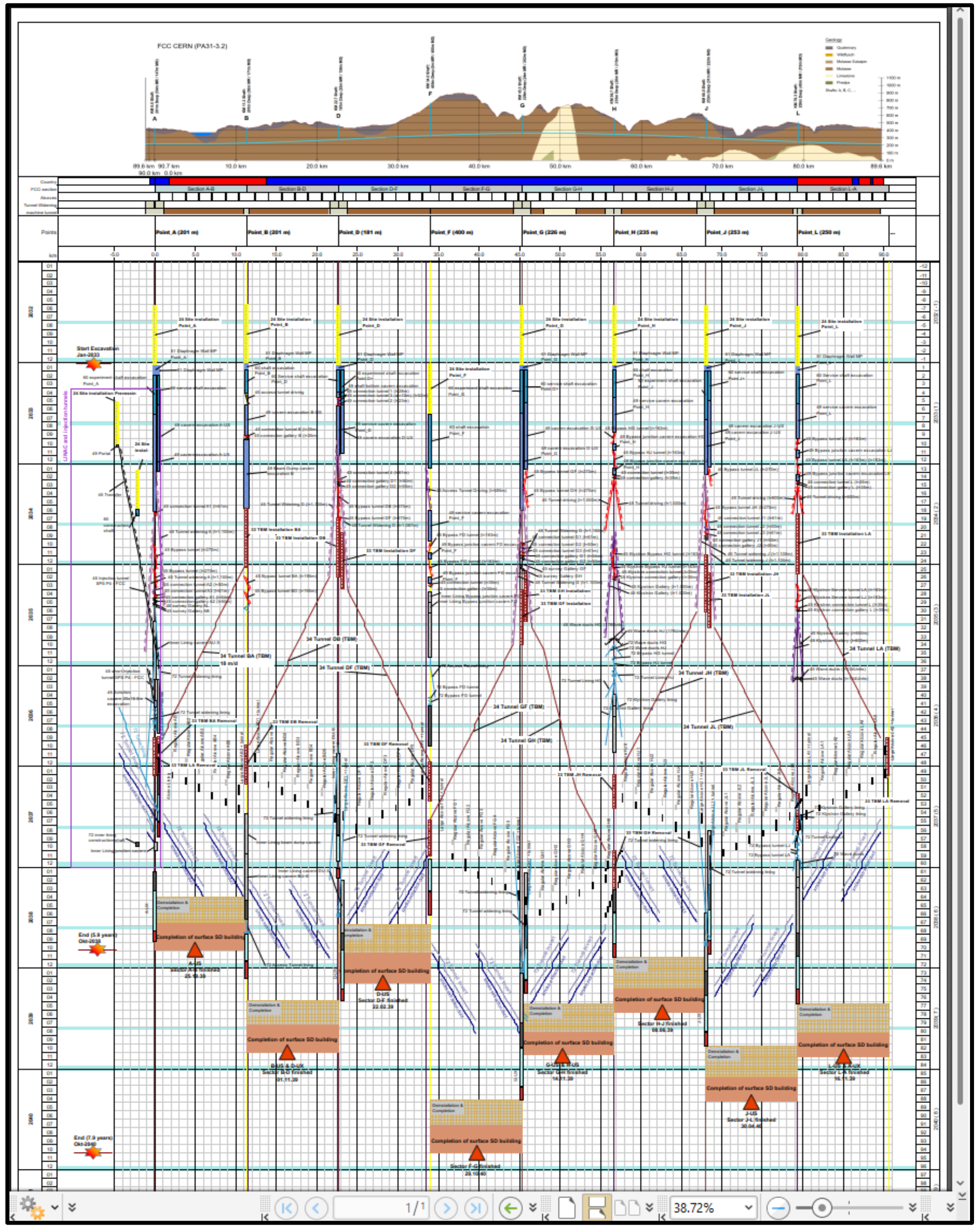


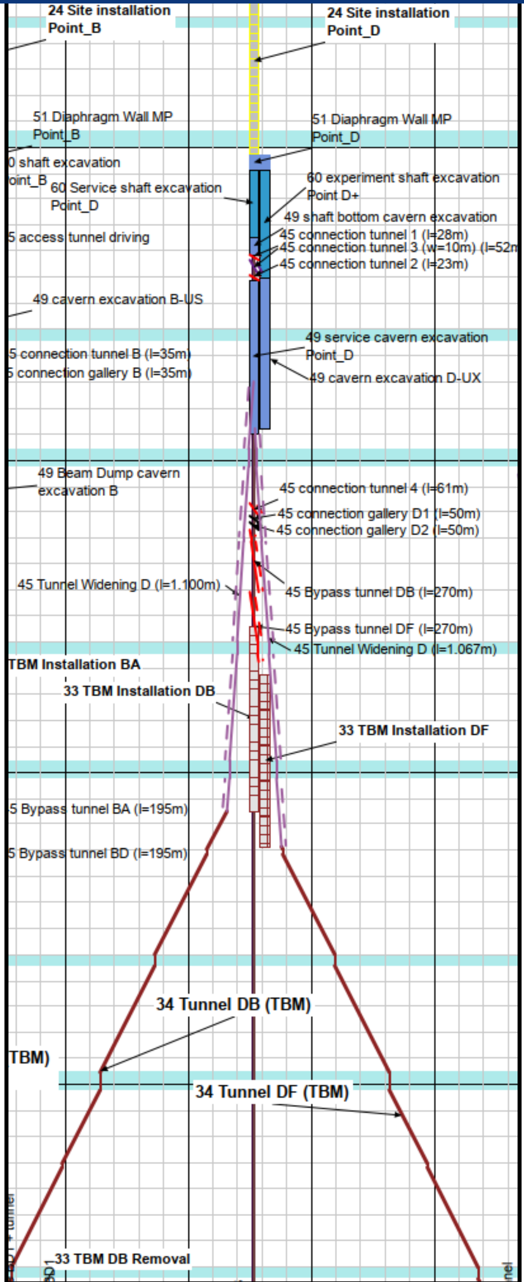
FUTURE CIRCULAR COLLIDER

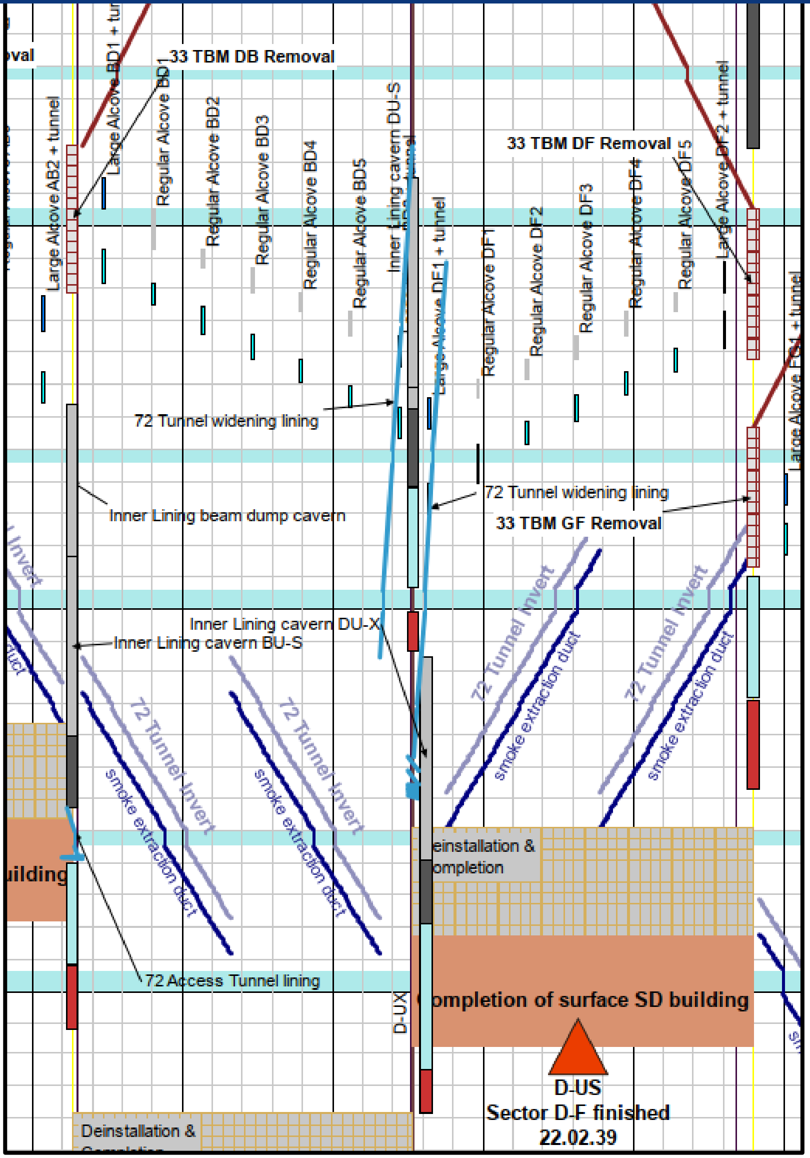
CE construction schedules (example)

T. Watson

CE linear construction schedule





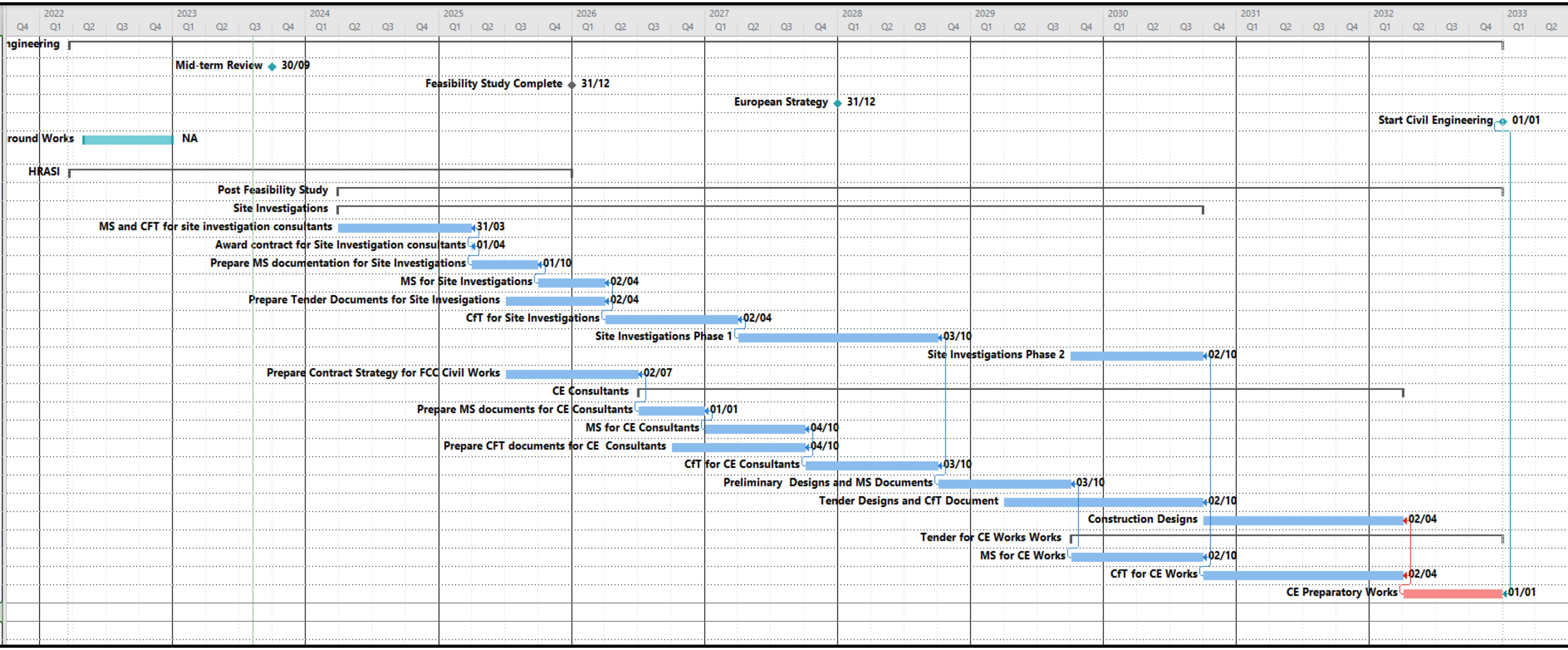


Point D – Example of linear schedule

FUTURE CIRCULAR COLLIDER

Preparatory phase planning civil engineering

Task Name	Duration
FCC Civil Engineering	**2813 days**
Mid-term Review	0 days
Feasibility Study Complete	0 days
European Strategy	0 days
Start Civil Engineering	0 days
ILF Prepare Cost and Schedule update for underground Works	175 days
HRASI	**986 days**
Post Feasibility Study	**2286 days**
Site Investigations	**1698 days**
MS and CFT for site investigation consultants	261 days
Award contract for Site Investigation consultants	1 day
Prepare MS documentation for Site Investigations	131 days
MS for Site Investigations	131 days
Prepare Tender Documents for Site Invesigations	196 days
CfT for Site Investigations	261 days
Site Investigations Phase 1	392 days
Site Investigations Phase 2	261 days
Prepare Contract Strategy for FCC Civil Works	261 days
CE Consultants	**1501 days**
Prepare MS documents for CE Consultants	131 days
MS for CE Consultants	196 days
Prepare CFT documents for CE Consultants	261 days
CfT for CE Consultants	261 days
Preliminary Designs and MS Documents	261 days
Tender Designs and CfT Document	392 days
Construction Designs	392 days
Tender for CE Works Works	**848 days**
MS for CE Works	260 days
CfT for CE Works	392 days
CE Preparatory Works	196 days



Stage 1: FCC-ee – highest luminosity lepton collider

double ring e^+e^- collider, with full-energy booster

2 or 4 interaction points

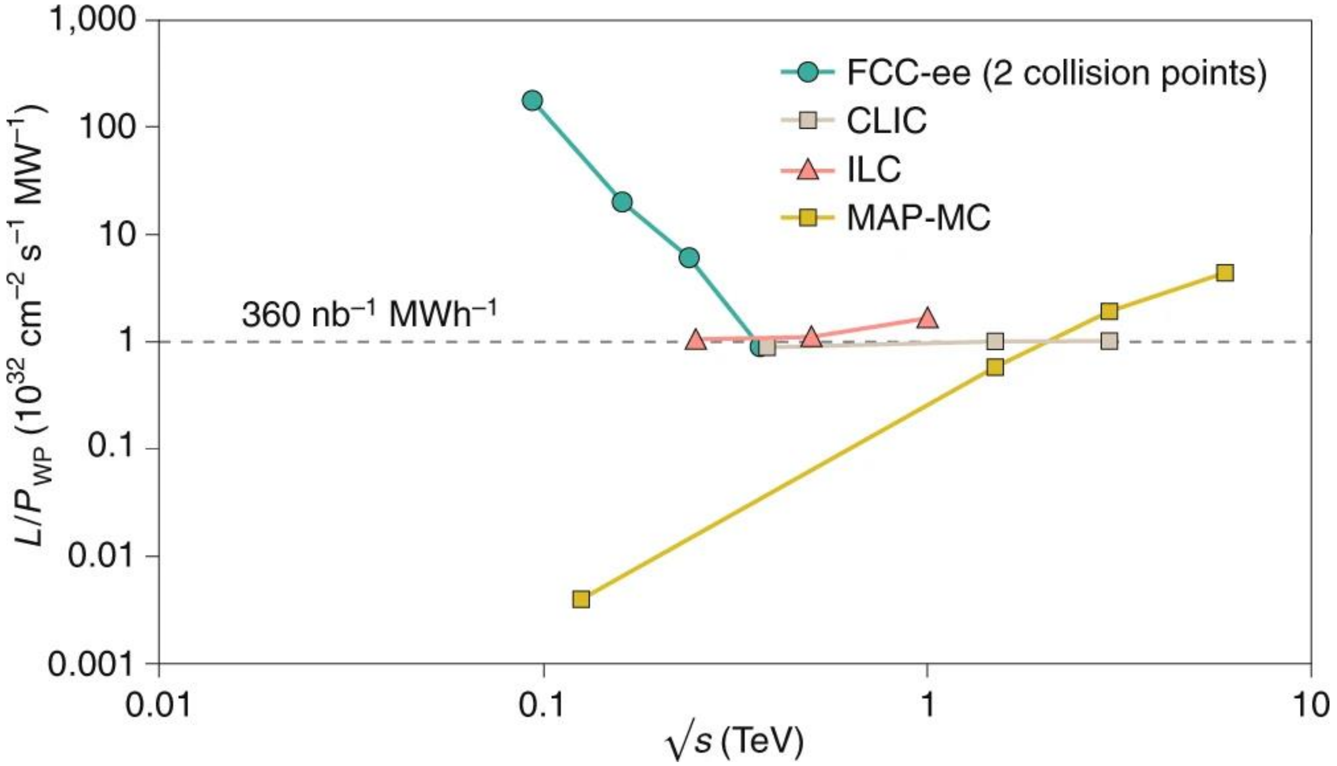
efficient $\mathcal{L}$ from Z to $t\bar{t}$

thanks to twin-aperture magnets, high-Q SRF, efficient RF power sources, top-up injection, etc.

>2.5 ab^{-1} with ~0.5×10^6 H / IP (3y)

>75 ab^{-1} with ~2×10^{12} Z / IP (4y)

luminosity vs. electricity consumption



enormous performance increase: collects LEP data statistics in few minutes

highest lumi/power of all *H* fact. proposals

Nature Physics 16, 402–407 (2020)

FCCIS Workshops – mid November

FUTURE CIRCULAR COLLIDER

FUTURE CIRCULAR COLLIDER
Innovation Study

FCCIS 2023 WP2 “Collider Design” Workshop, Pontifical University, Rome, 13-15 November 2023 (56 participants)

Topics:

- collider performance and beam lifetime
- mechanical alignment tolerances, misalignment models
- trim coil baseline and beam-based alignment
- collider and booster optics, accelerator code development
- vibration and ripple tolerances plus mitigations
- booster vacuum system, booster impedance
- electron cloud & ion effects
- beam studies at KARA, PETRA III, SuperKEKB and DAΦNE (conversion to future test facility?)

FCCIS MDI and IR mock-up workshop, INFN-LNF, Frascati, 16-17 November 2023 (42 participants)

Topics:

- interaction region (IR) mock-up critical concepts
- beam losses in the IR
- synchrotron radiation
- IR higher-order mode calculations
- vertex detector integration & cooling
- accelerator and detector constraints in the IR

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.

FUTURE CIRCULAR COLLIDER

Synchrotron radiation in tunnel

	LEP-II (1999-2000)	FCC-ee Z	FCC-ee W	FCC-ee ZH	FCC-ee ttbar
Beam energy	98-104.5 GeV	45.6 GeV	80 GeV	120 GeV	182.5 GeV
Bending radius	3.1 km	10 km			
Beam current	6.2 mA (@98 GeV)	2 x 1270 mA	2 x 137 mA	2 x 26.7 mA	2 x 4.86 mA
Energy loss/turn (arcs)	2.6 GeV (@98 GeV) 3.4 GeV (@104.5 GeV)	0.04 GeV	0.37 GeV	1.9 GeV	10.3 GeV
Power loss (arcs)	16 MW (@98 GeV)*	100 MW			
Total arc length	23 km	77 km			
Power loss/unit length (arcs)	0.7 kW/m (@98 GeV)*	1.3 kW/m			
Critical energy	0.7 MeV – 0.8 MeV	0.02 MeV	0.1 MeV	0.4 MeV	1.3 MeV

**Indicative value (beam current decreased from 98 GeV to 104.5 GeV)*

A. Lechner et al.

- **Source term comparable to LEP operation, higher critical energy for ttbar run.**
- **Baseline with distributed (water cooled) photon stops every ~6 m.**
- **Different shielding strategies for (Z, W, ZH) vs ttbar?**

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:

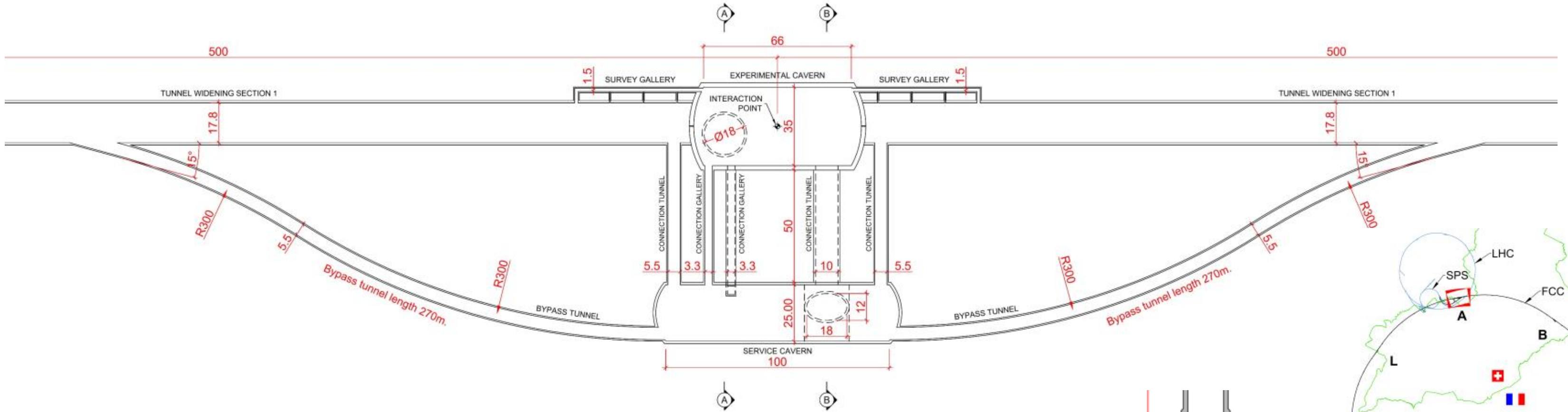
"Europe, together with its international partners, should investigate technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."

CE underground progress

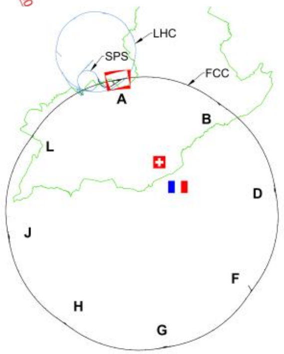
- **Full 3D model of underground structures as basis for costing exercies**
- **Update of scheduling and costing with external consultant ongoing**
- **Independent second costing exercise based on same bill of quantities w[illegible] done**

- **Experiment Site (PA)**

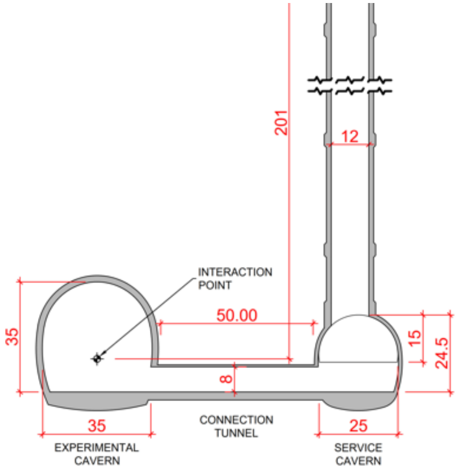
PLAN VIEW
1:3000

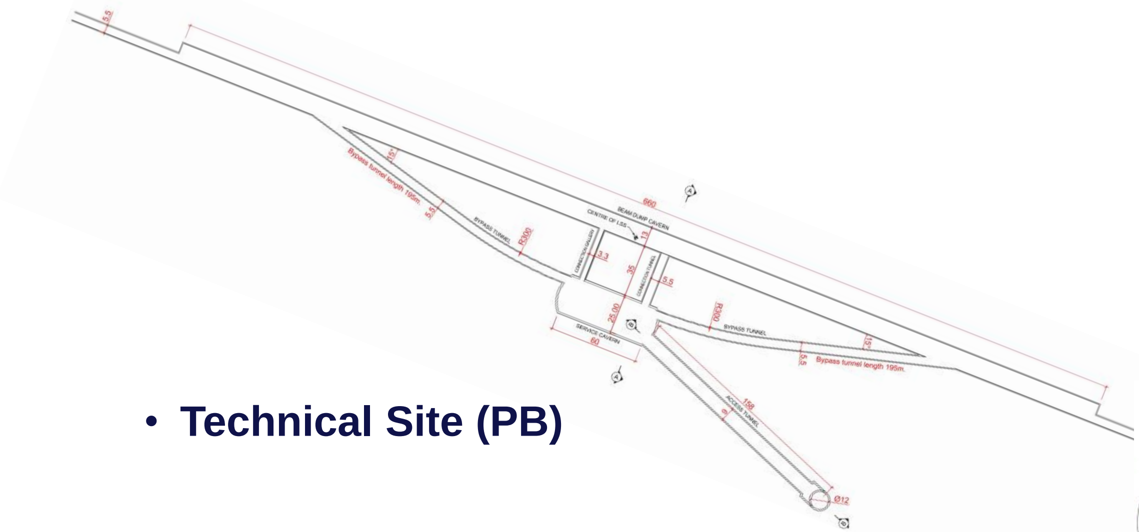


PLAN VIEW
1:1000

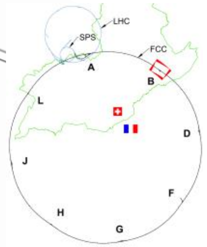


KEY PLAN





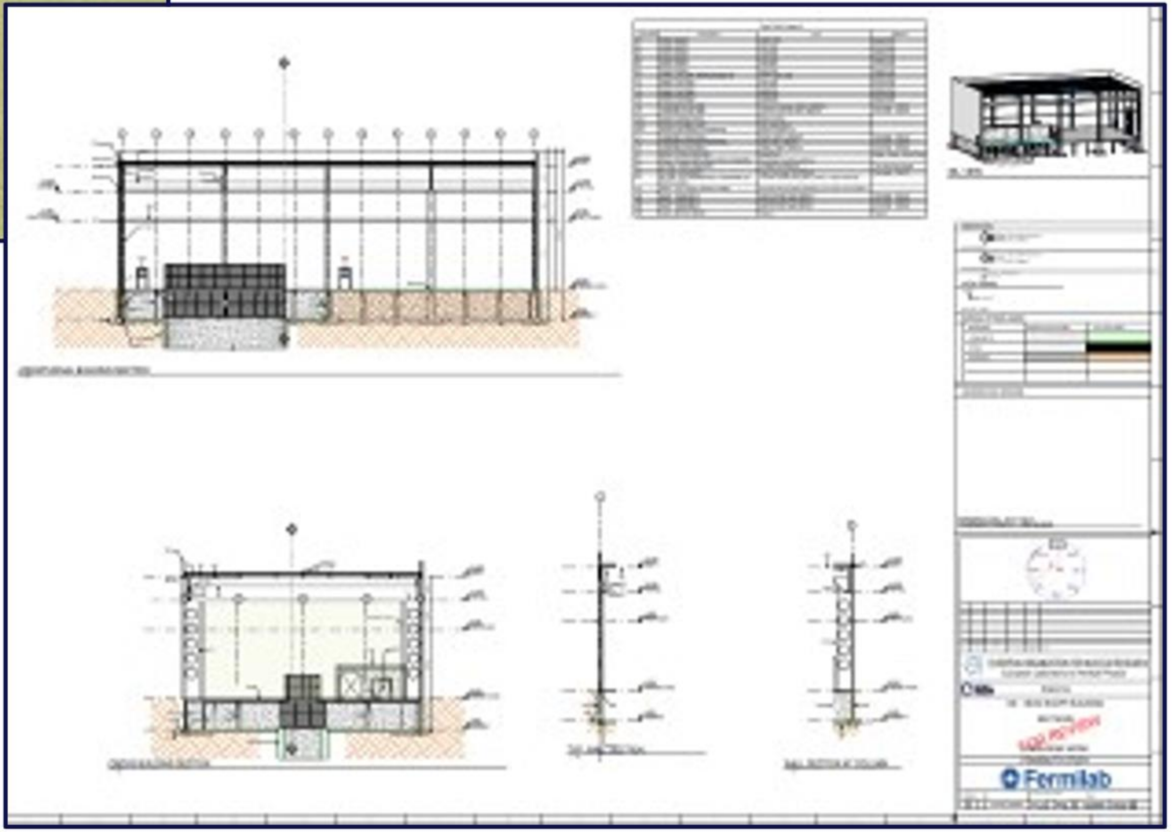
- **Technical Site (PB)**



KEY PLAN

CE surface progress

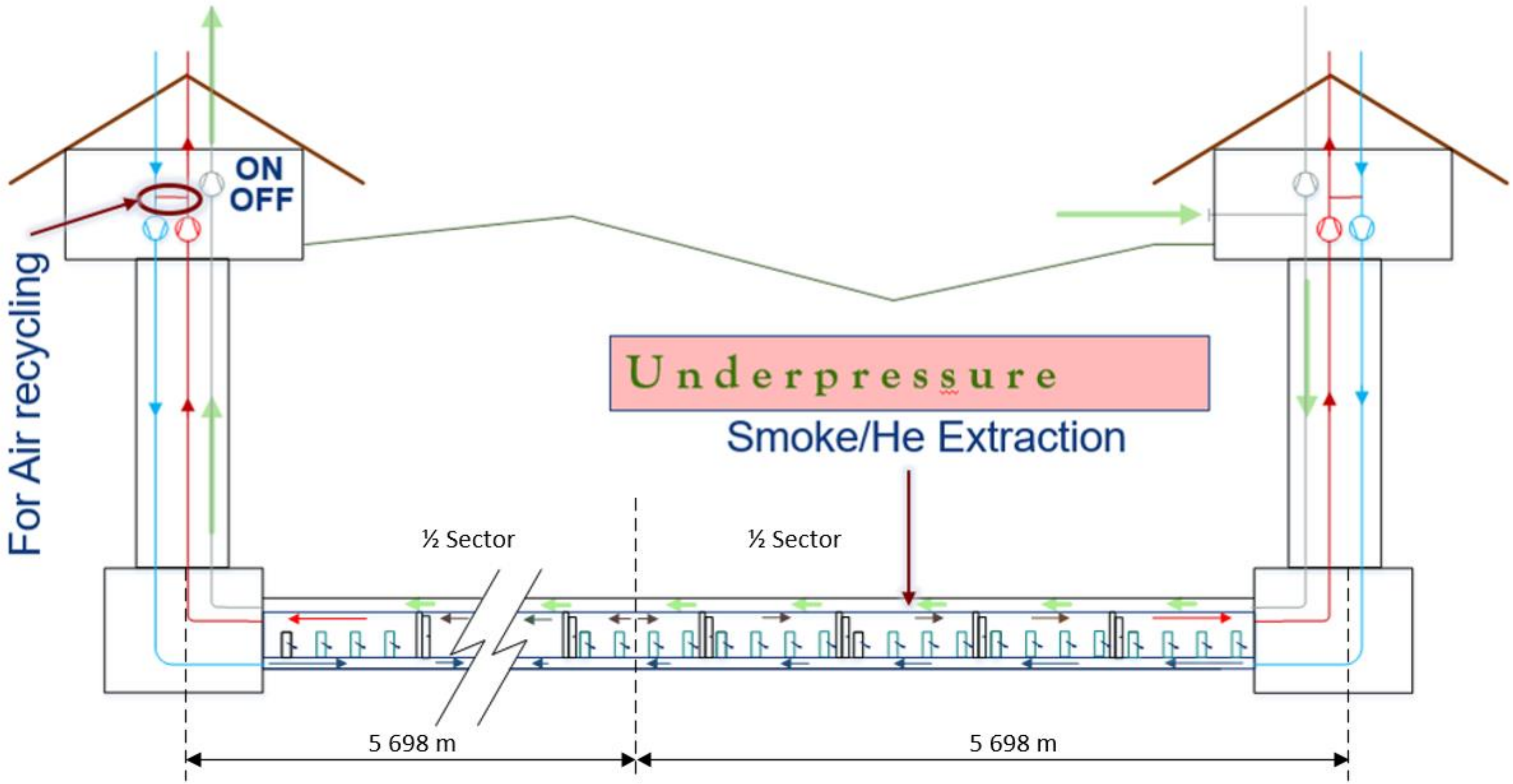
Generic study of experiment site and technical site by FNAL



Examples of Fermilab Deliverables

- bills of quantities extracted from FNAL designs
- basis for cost estimate by consultant with experience on industrial constructions in CH-FR area.

Ventilation concept



- Operation of the ventilation elements in one sector of the machine tunnel during normal operation.
- Smoke and helium extraction in green, general extraction in red and air supply in blue
- Compartmentalization via fire doors every ~400 m following arc cell structure.