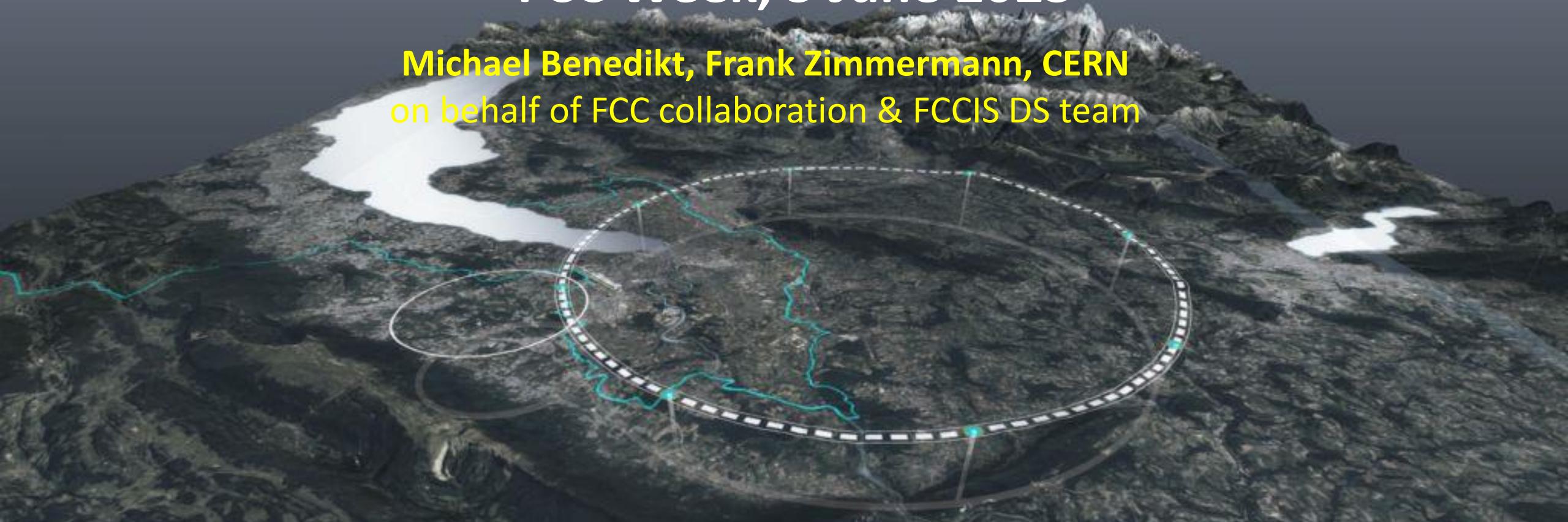


# FCC Feasibility Study Status

FCC Week, 5 June 2023

Michael Benedikt, Frank Zimmermann, CERN  
on behalf of FCC collaboration & FCCIS DS team



Swiss Accelerator  
Research and  
Technology

<http://cern.ch/fcc>



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



Horizon 2020  
European Union funding  
for Research & Innovation

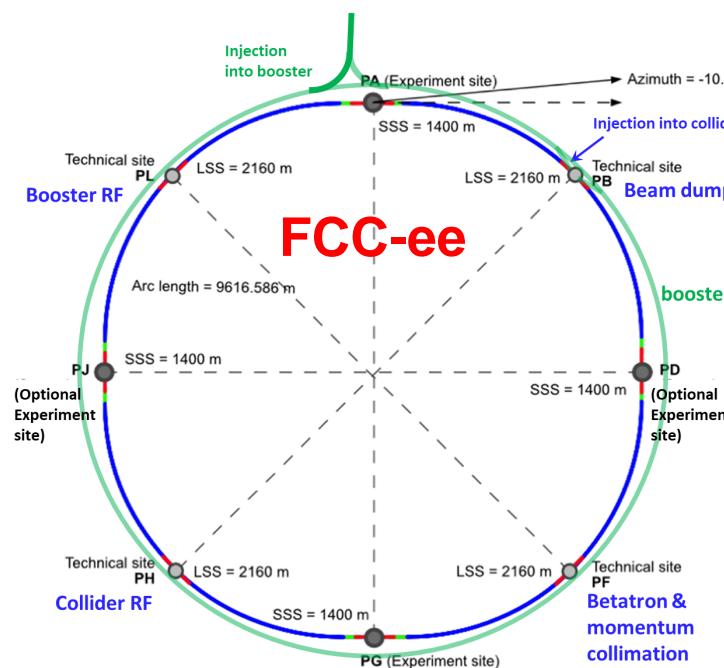
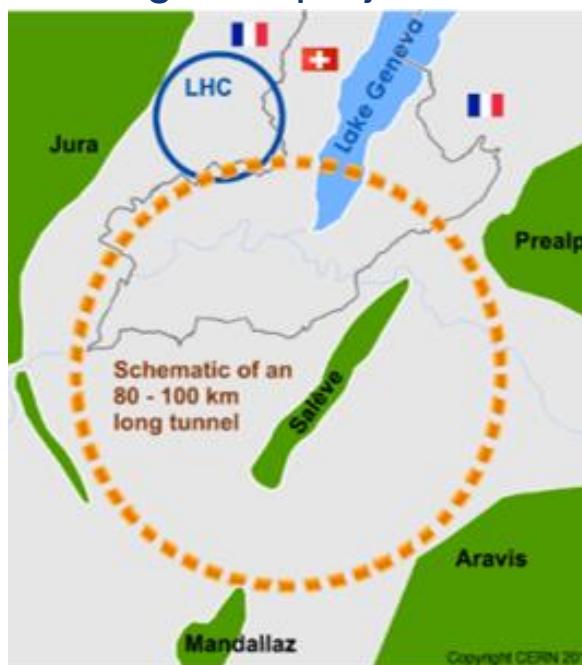
photo: J. Wermuth



# FCC integrated program

## comprehensive long-term program maximizing physics opportunities

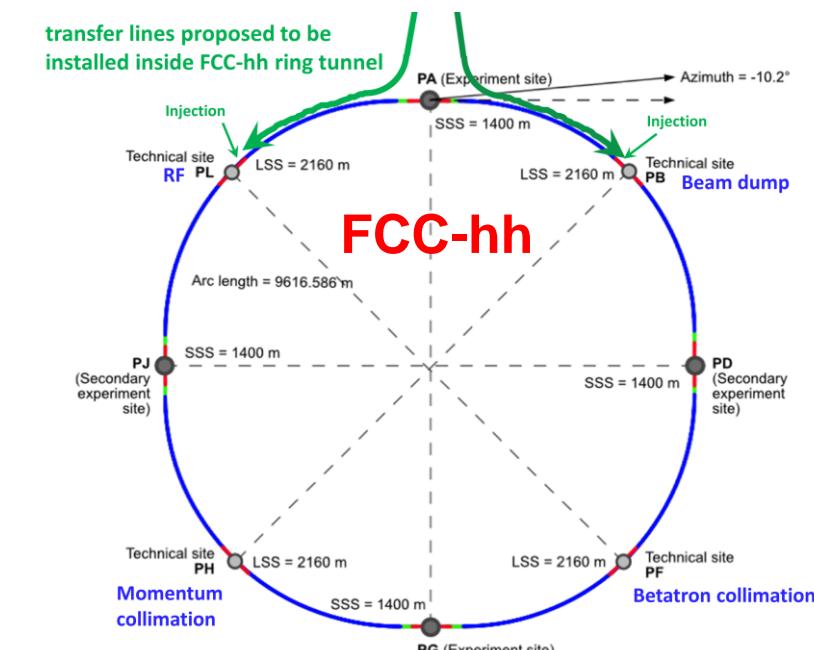
- stage 1: FCC-ee ( $Z$ ,  $W$ ,  $H$ ,  $t\bar{t}$ ) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh ( $\sim 100$  TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- highly synergetic and complementary programme boosting the physics 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



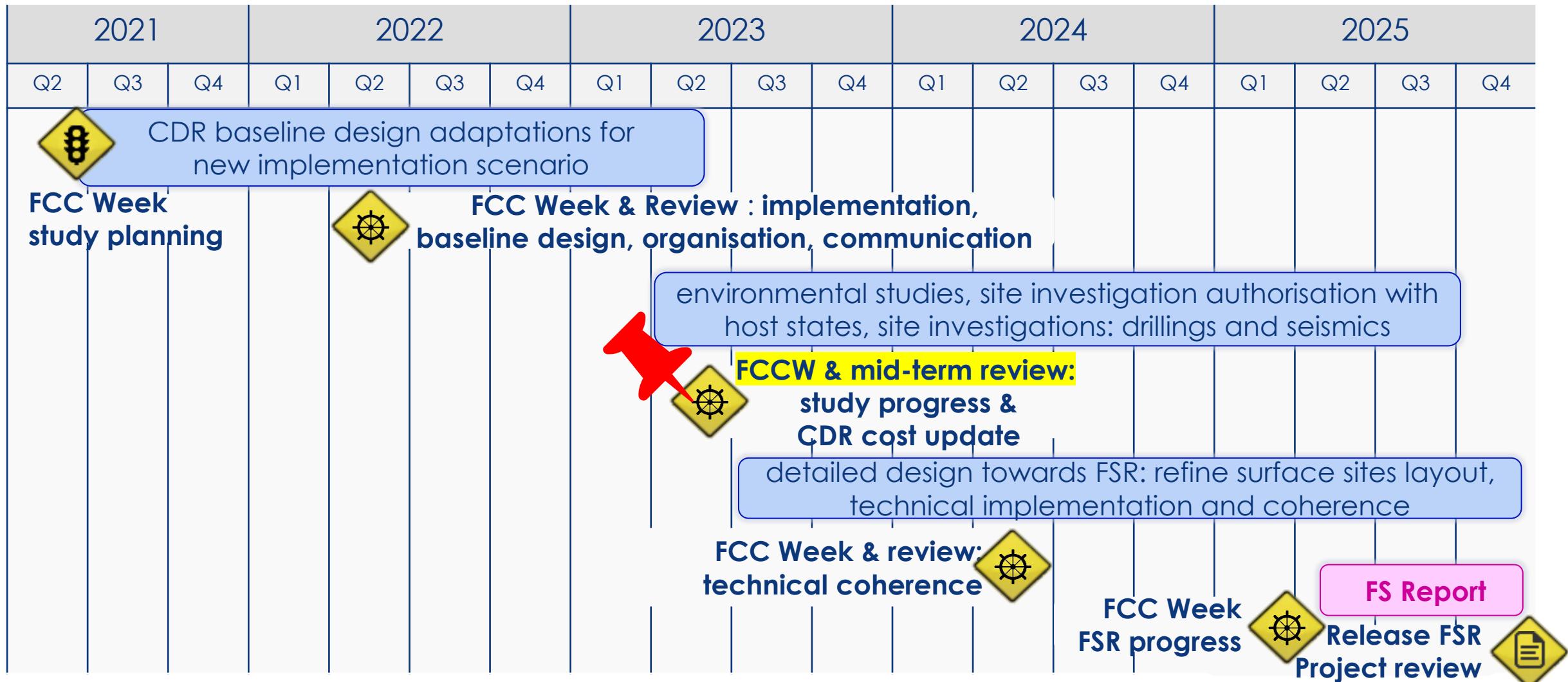
2020 - 2040

2045 - 2063

2070 - 2095



# Feasibility Study Timeline and main activities/milestones





# Optimized placement and layout for feasibility study

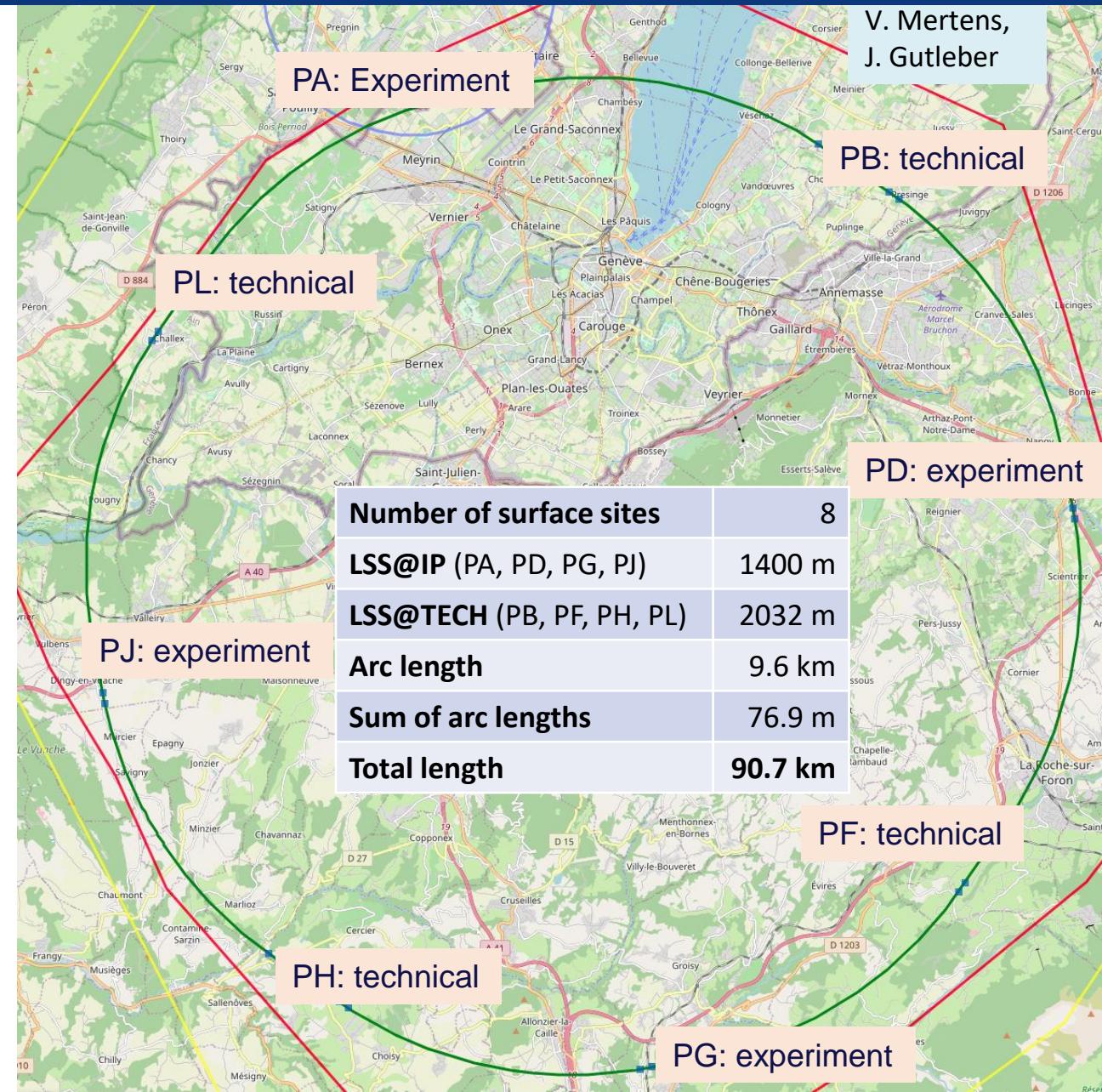
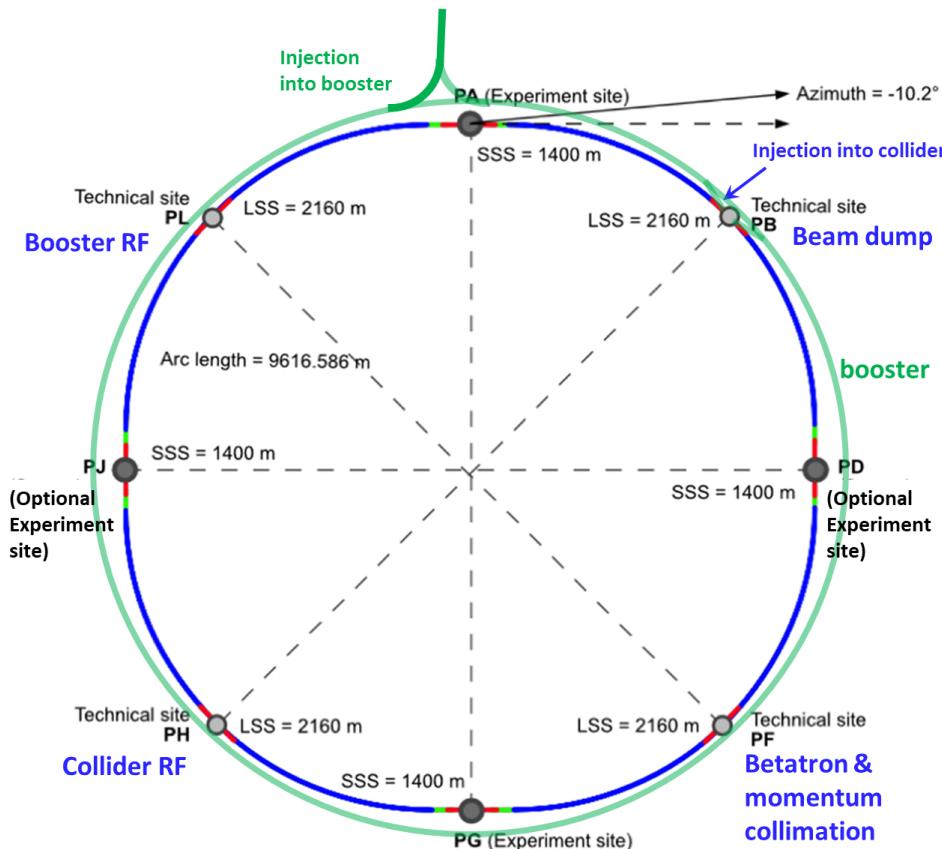
## Major achievement: optimization of the ring placement

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), etc.

“Éviter, reduire, compenser” principle of EU and French regulations

**Lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold superperiodicity, possibility of 2 or 4 IPs**

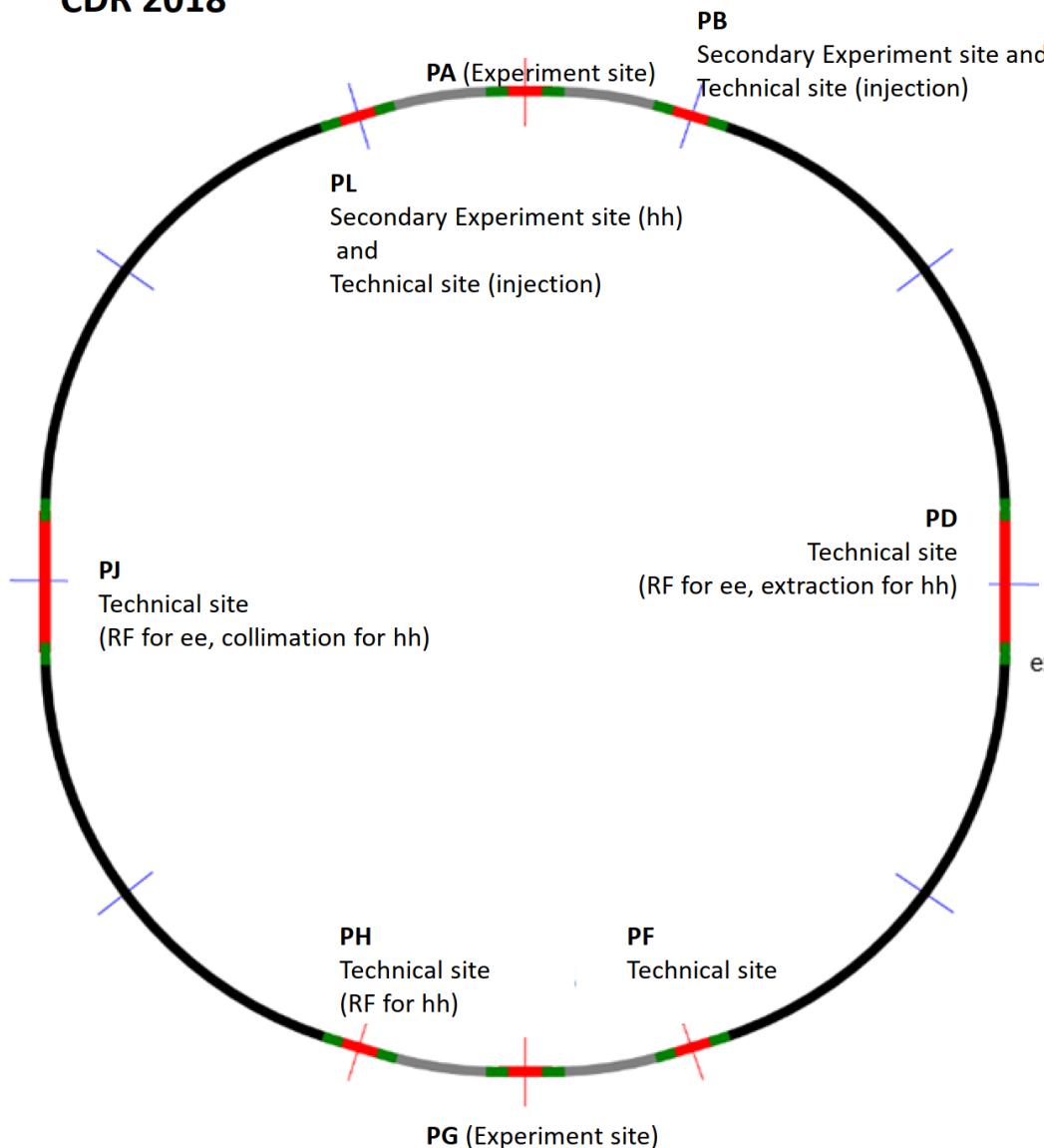
Whole project now adapted to this placement



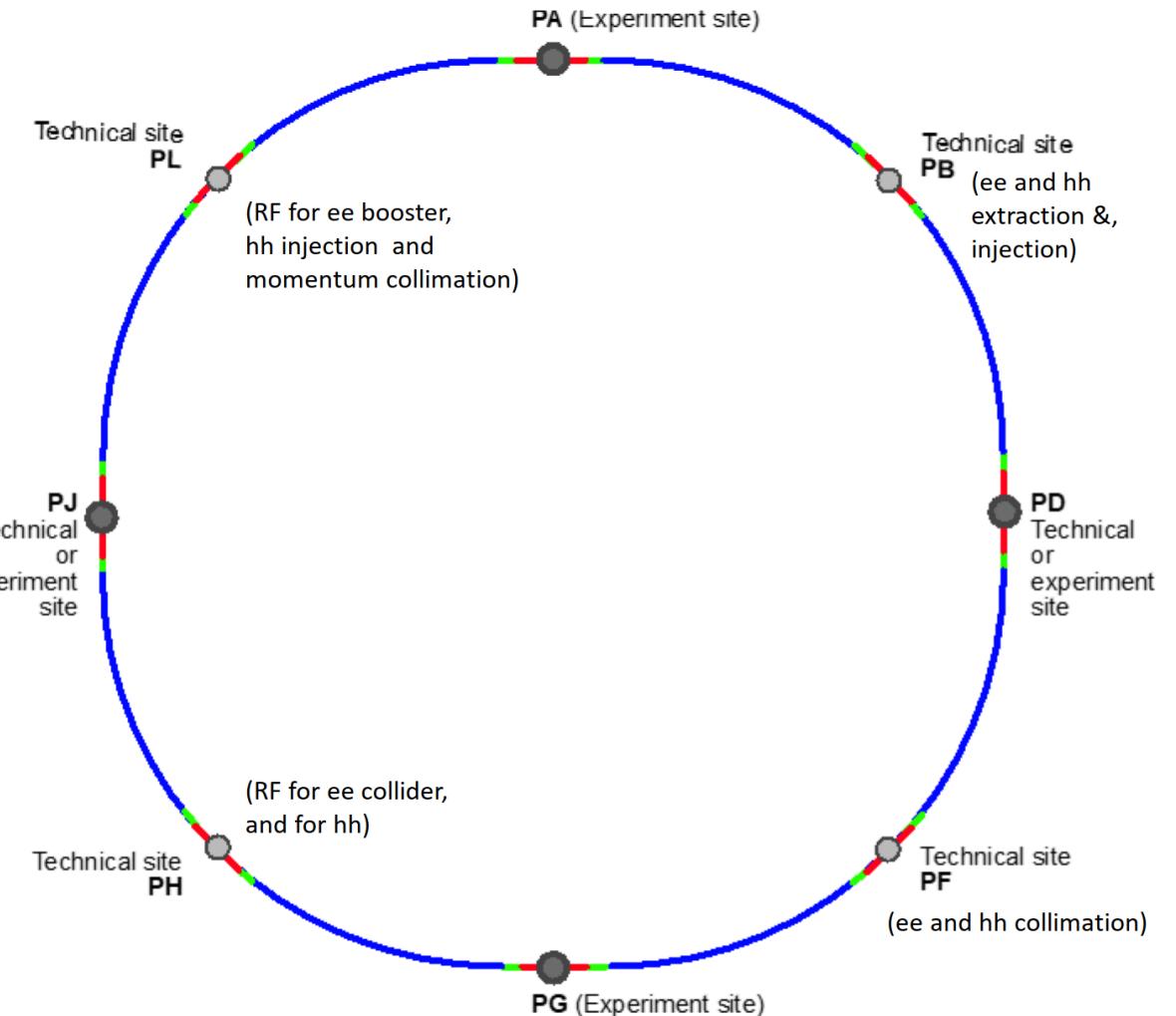


# Revised layout and geometry

CDR 2018



"Optimised" Midterm 2023





# 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



# 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 technique et 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 technique et experimental**

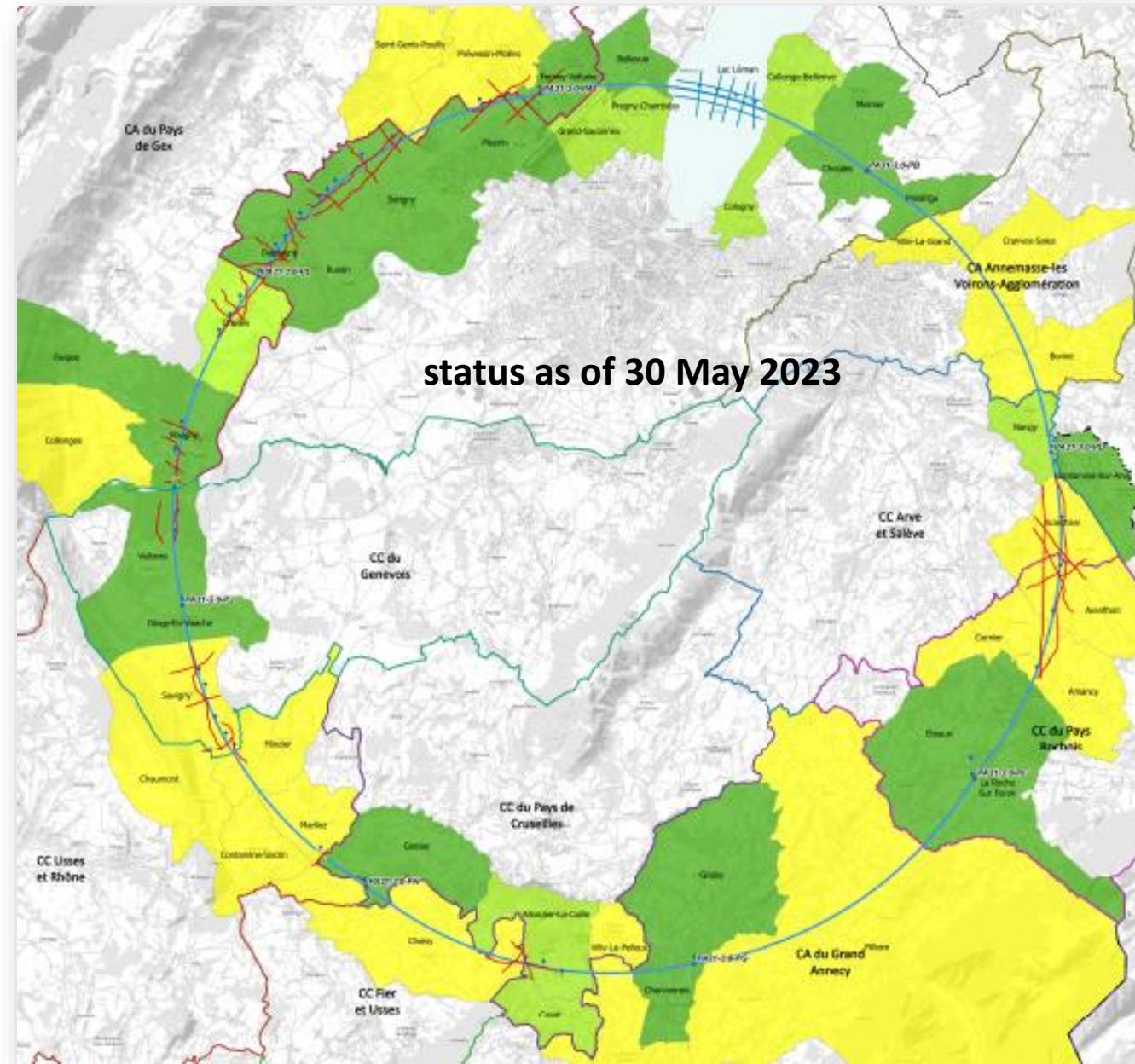
**PL – Challex (FR) – site technique**

Rencontre individuellement

Rendez-vous proposé / programmé

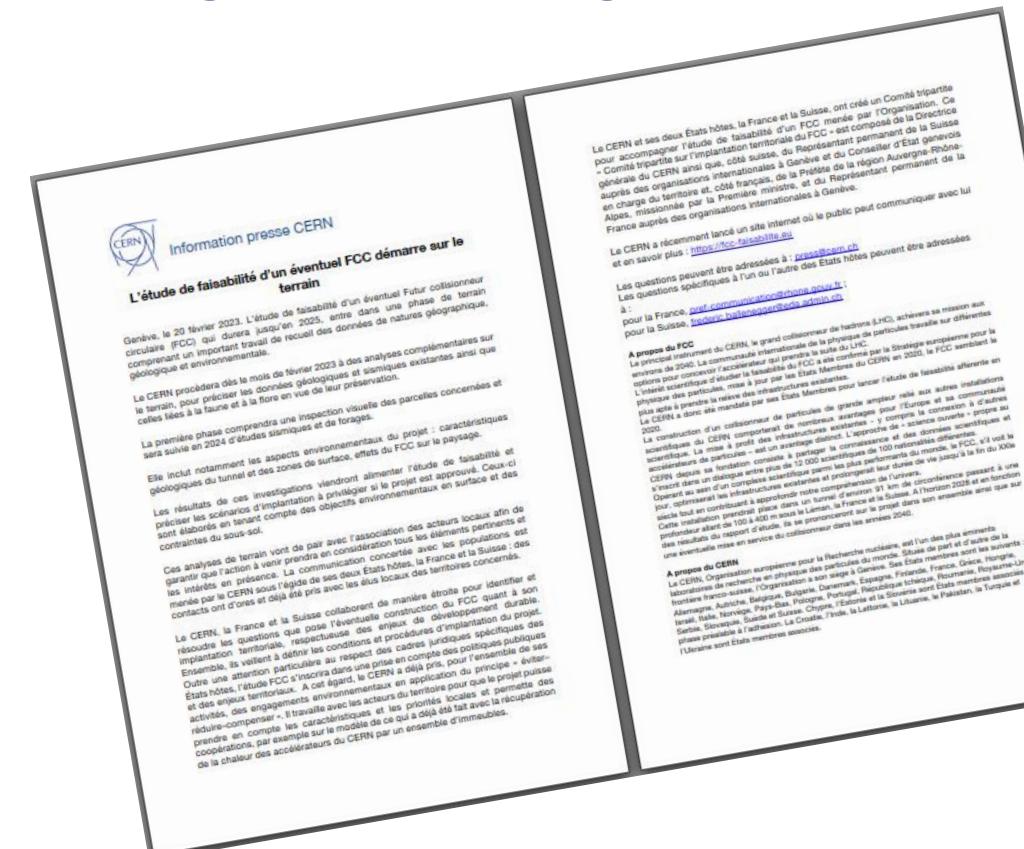
Rencontre collective

**Environmental studies and preparation of geological investigations (drillings and seismics) ongoing since February 2023**



# Communication aspects

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



- 11 journalistes
- 90 press clippings
- 31 countries



Le Cern fait un petit pas vers un plus grand accélérateur de particules

particular

**G**enève, 19 avr 2023 (AFP) - Environnement, sismologie, géologie... L'Organisation européenne pour la recherche nucléaire (Cern) a lancé ses premières analyses sur le terrain pour construire un accélérateur de particules trois fois plus long que l'installation actuelle qui arrivera à son terme en 2040.

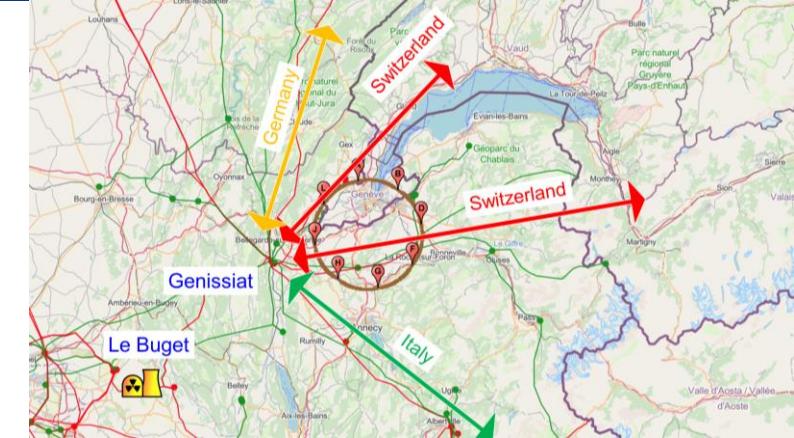
S'il voit le jour, le Futur Collisionneur Circulaire (FCC) formera sous la frontière franco-suisse un tunnel circulaire de 91 km de long et d'environ 5 mètres de diamètre, entre 100 et 300 mètres sous terre. Son tracé passerait sous Genève, le lac Léman et s'étendrait jusque dans les environs d'Annecy.

Huit lieux pourraient accueillir les sites de surface technique et scientifique, dont cinq en Haute-Savoie, deux dans l'Ain et un à Genève. Meaux, ingénieur au Cern, lors d'une vi-

# Connections to electrical grid infrastructure

## Updated FCC-ee energy consumption

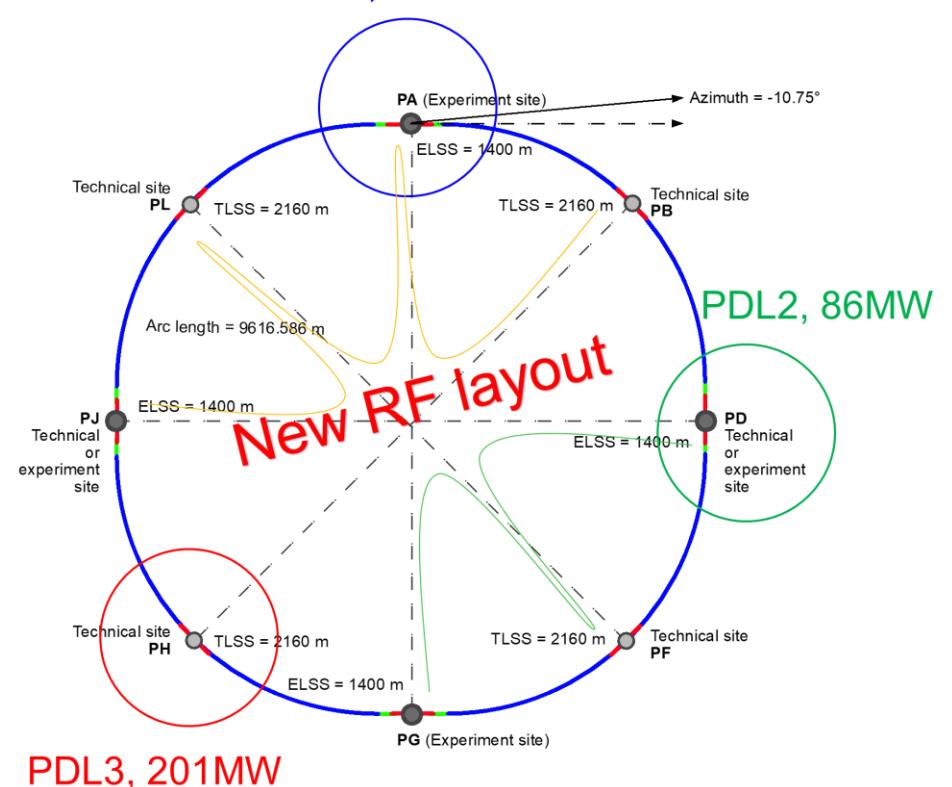
	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. power during beam operation (MW)	<b>222</b>	<b>247</b>	<b>273</b>	<b>357</b>
Average power / year (MW)	122	138	152	202
<b>Total yearly consumption (TWh)</b>	<b>1.07</b>	<b>1.21</b>	<b>1.33</b>	<b>1.77</b>



## 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):

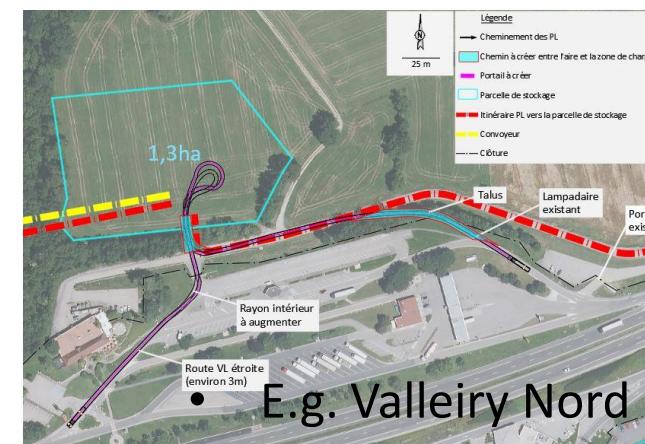
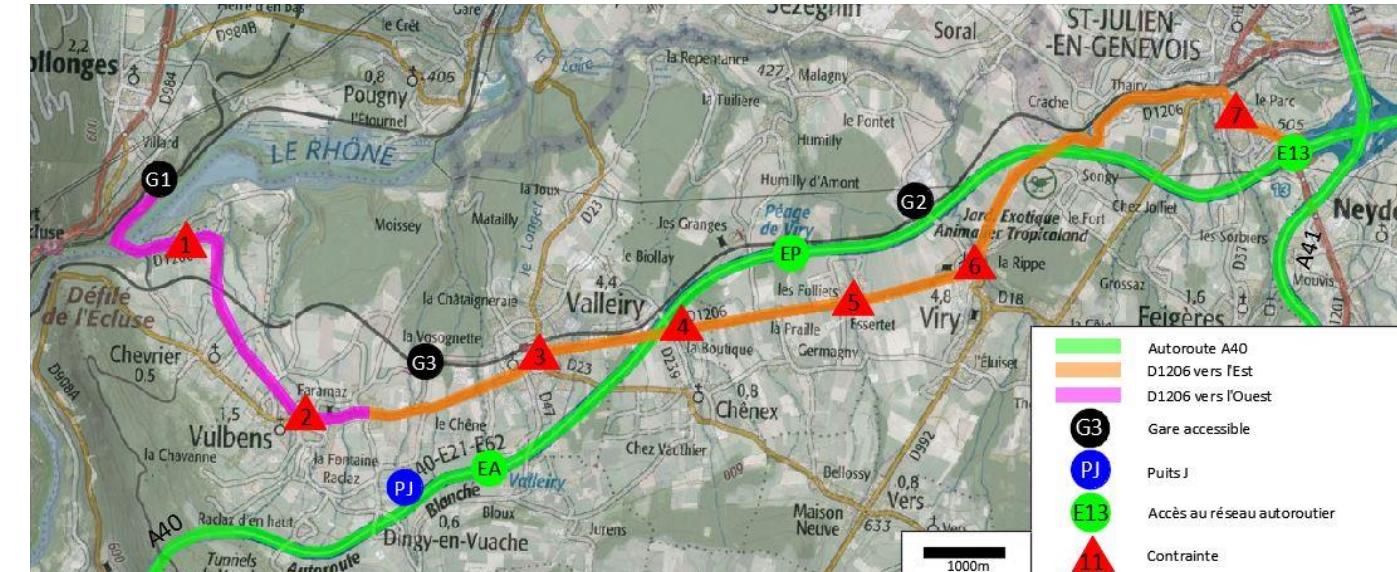
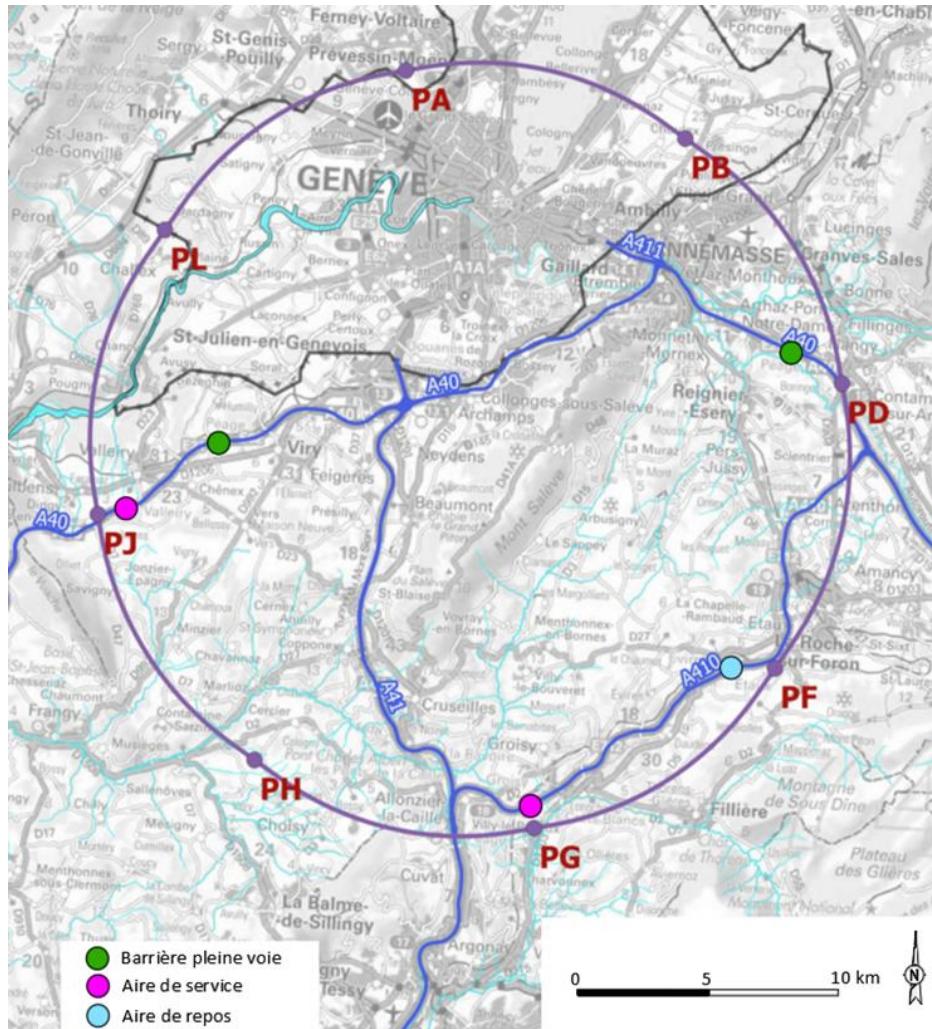
- **Point D, with a new sub-station covering PB – PD – PF – PG**
- **Point H with a new dedicated sub-station for collider RF**
- Point L, with a sub-station covering PJ – PL – PA
- → Alternative to new sub-station at Point L is **reusing the existing CERN Precession station to PA**
- **All options pursued with RTE**
- **Powering concept and max. power rating of the three sub-stations compatible FCC-hh.**





# Connections to transport infrastructure

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

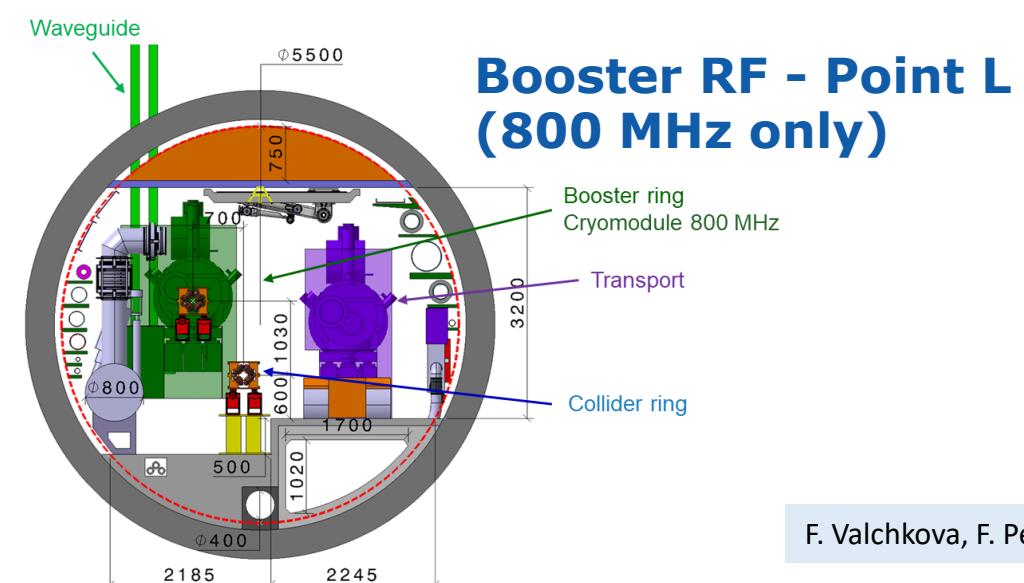
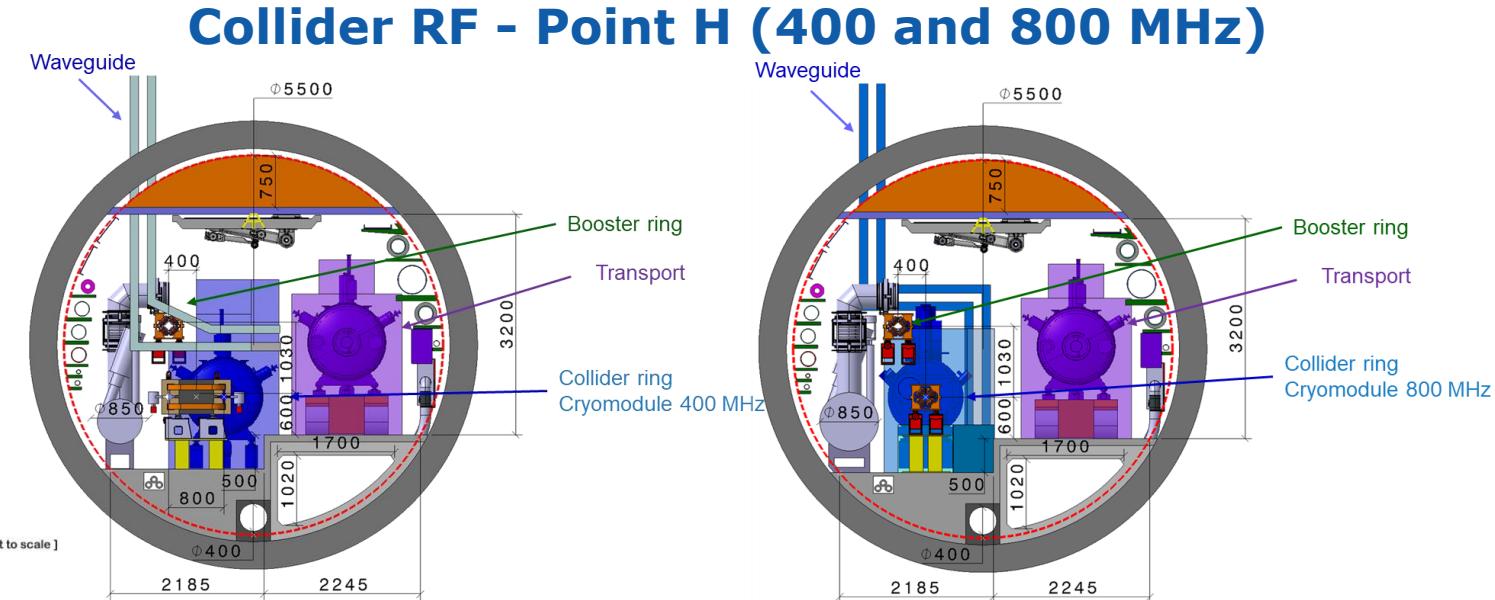
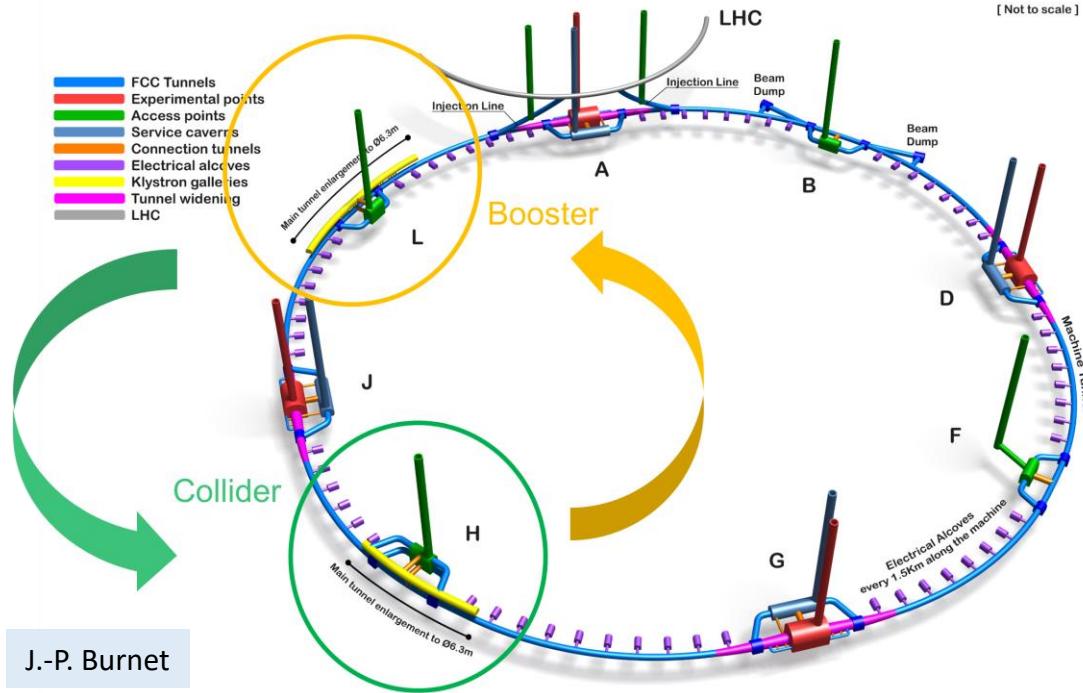


Detailed road access scenarios & highway access creation study carried out by Cerema including regulatory requirements in France



# 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.

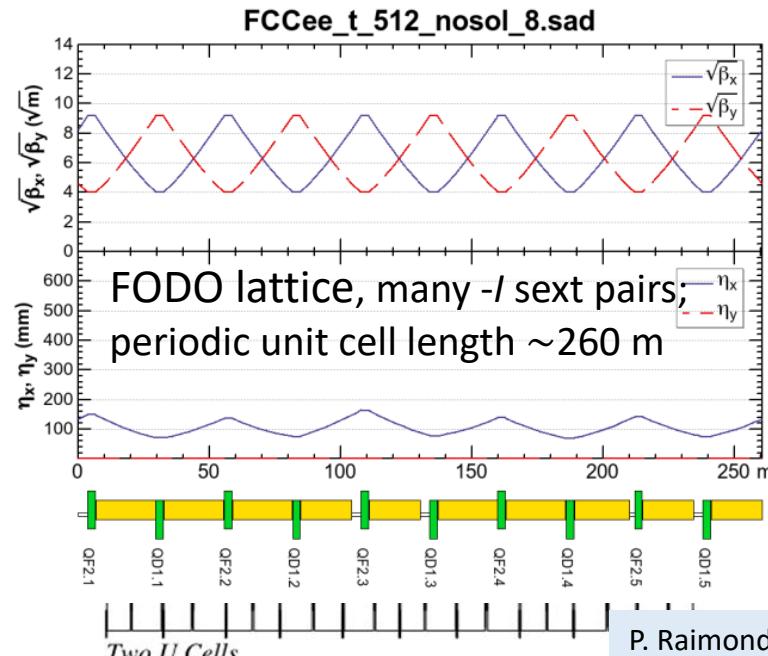




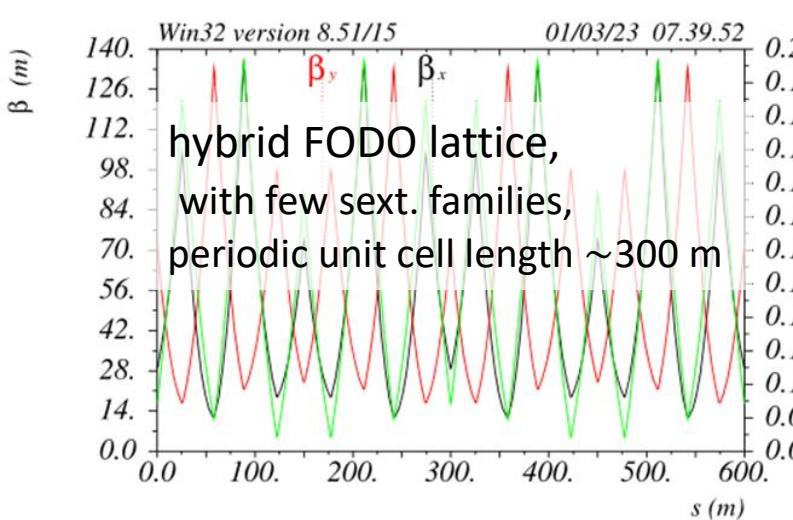
# FCC-ee optics baseline & further evolution(s)

Short 90/90:  $t\bar{t}$ , Zh **regular arc**

K. Oide

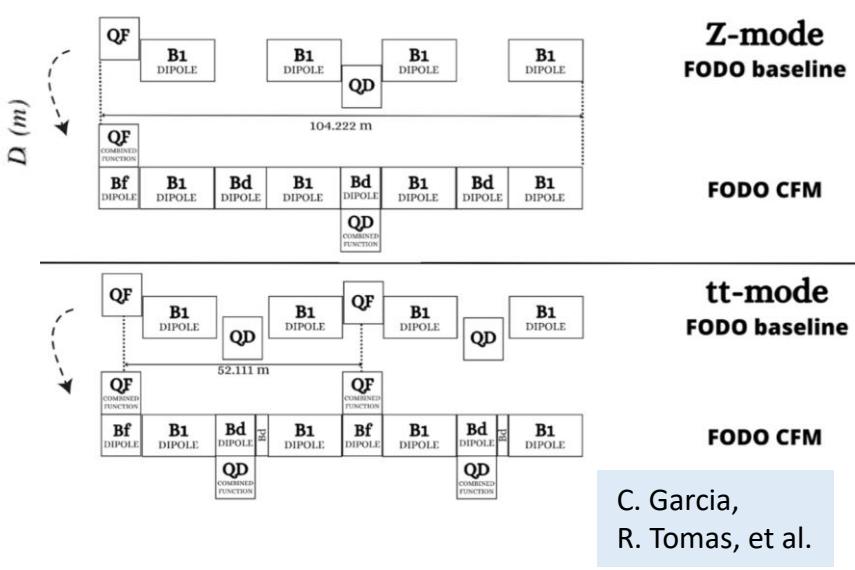


P. Raimondi



## optimisation goals:

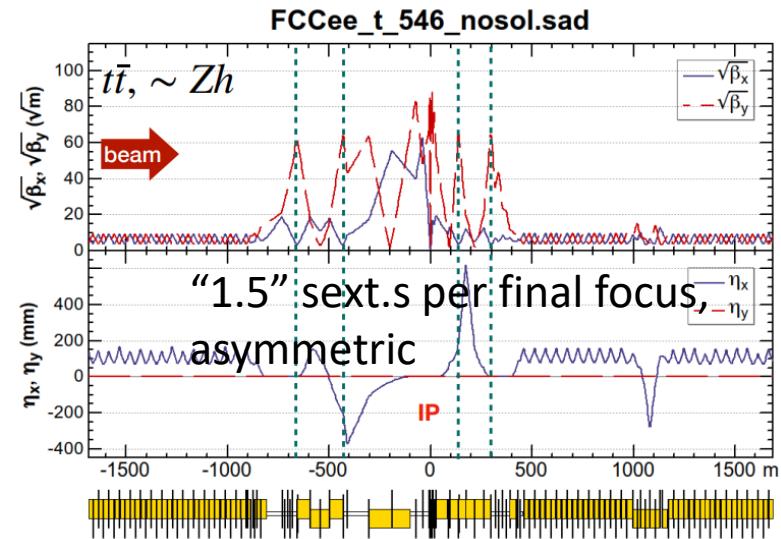
- reduced power consumption
- lower SR energy loss
- increased momentum acceptance
- relaxed tolerances
- larger dynamic aperture
- simplified powering schemes



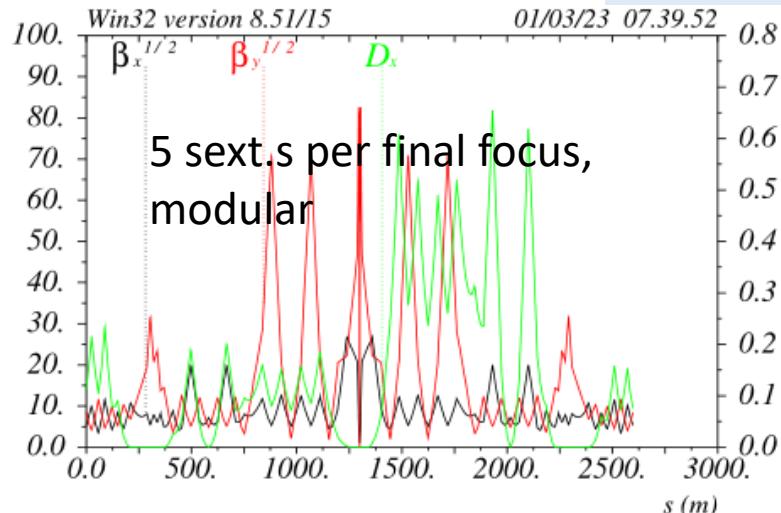
C. Garcia,  
R. Tomas, et al.

**interaction region**

K. Oide



P. Raimondi



s (m)

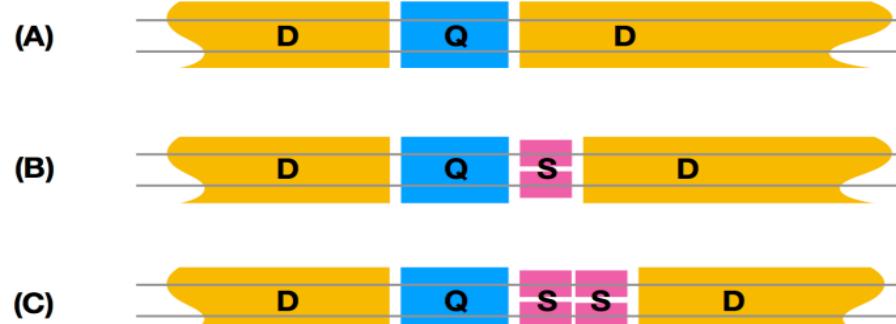


# R&D on HTS option for FCC-ee arc quads and sextupoles

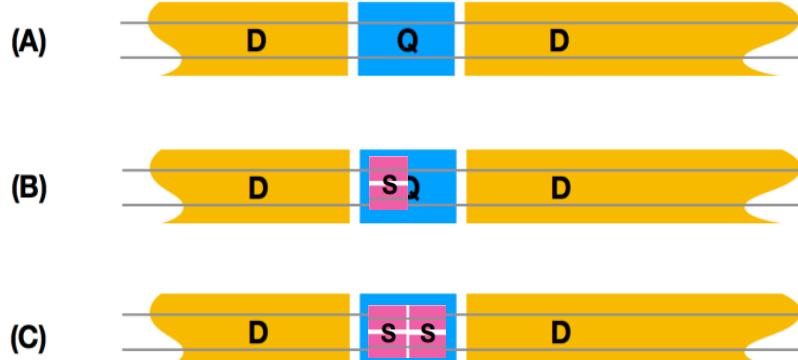
## CDR: 2900 quads & 4700 sextupoles

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

CDR arc lattice

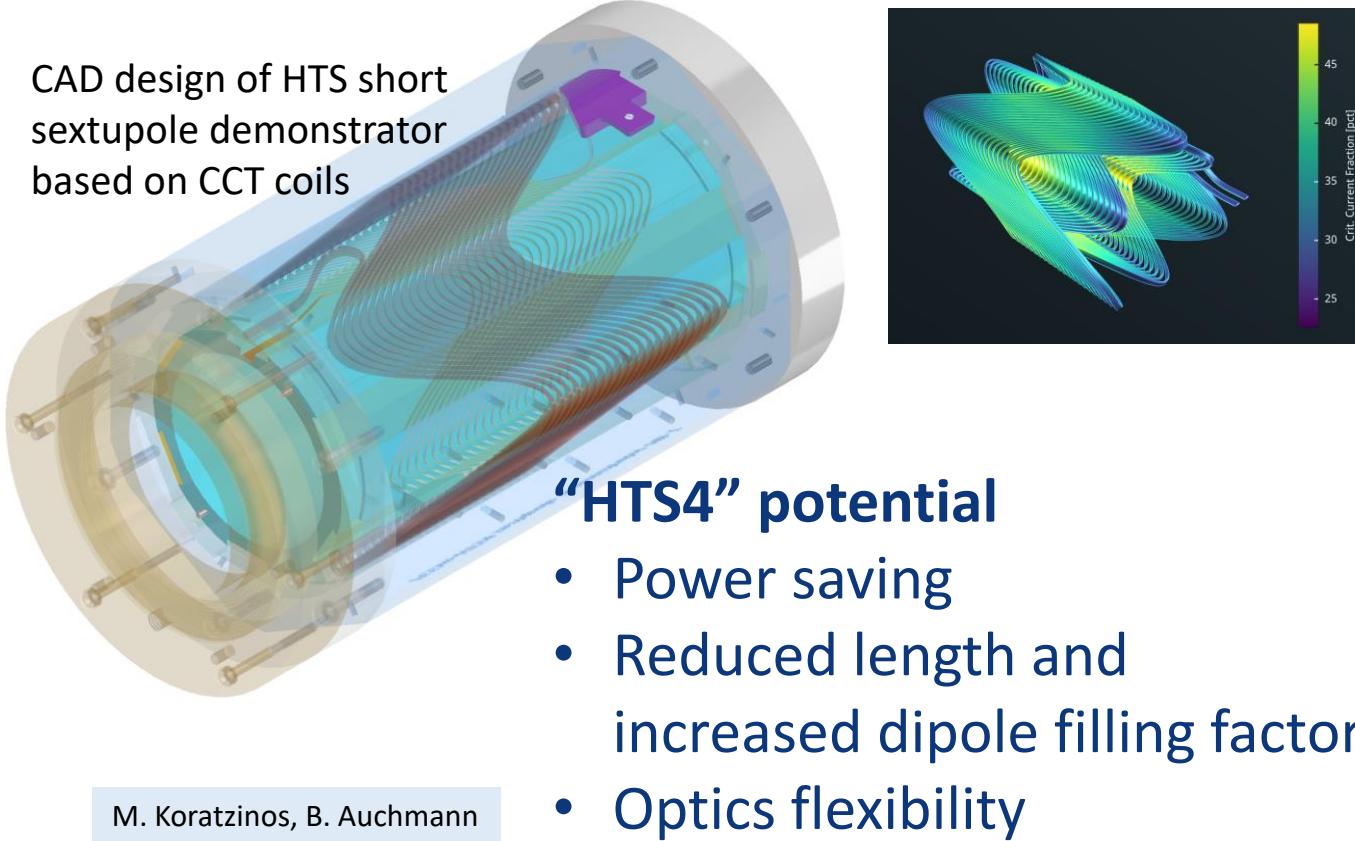


HTS option



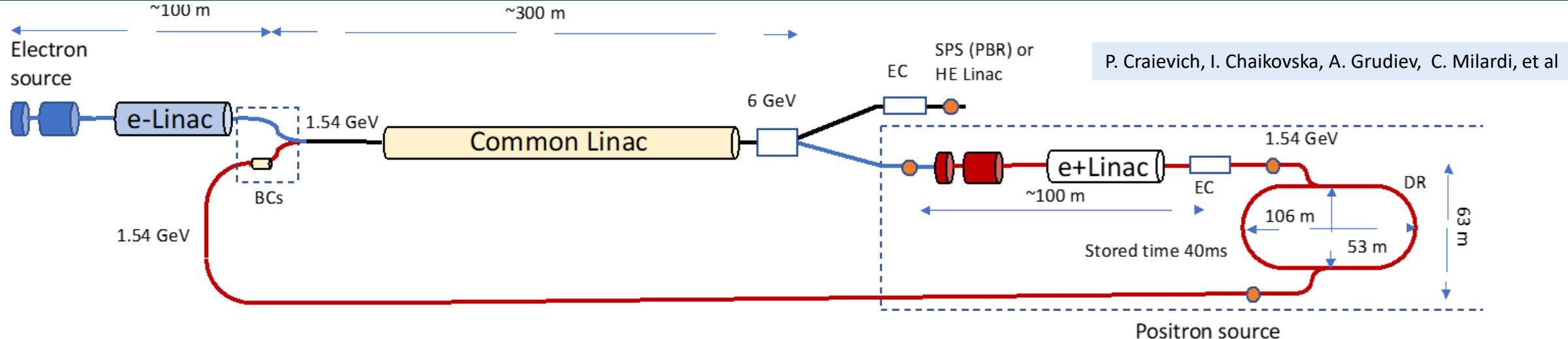
## "HTS4" project within CHART collaboration

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

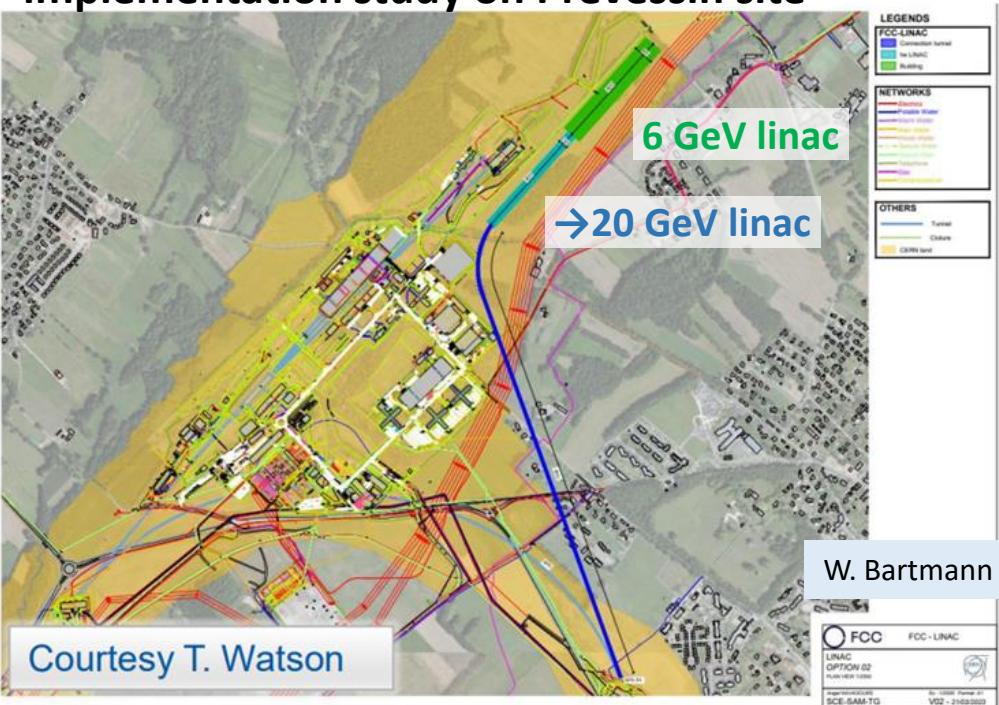




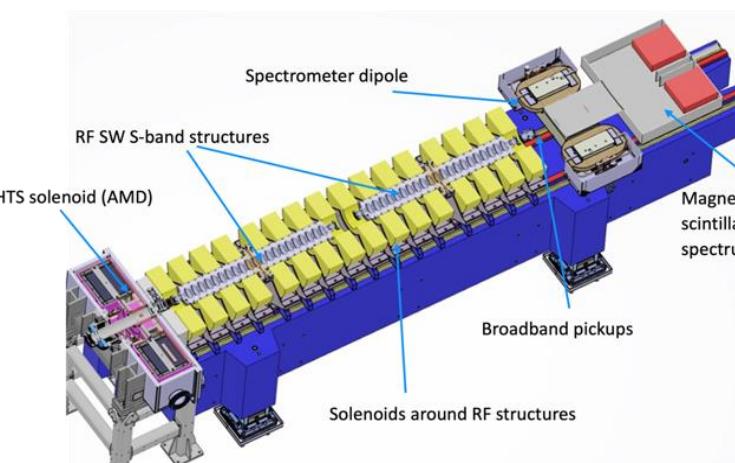
# new FCC-ee injector layout & implementation



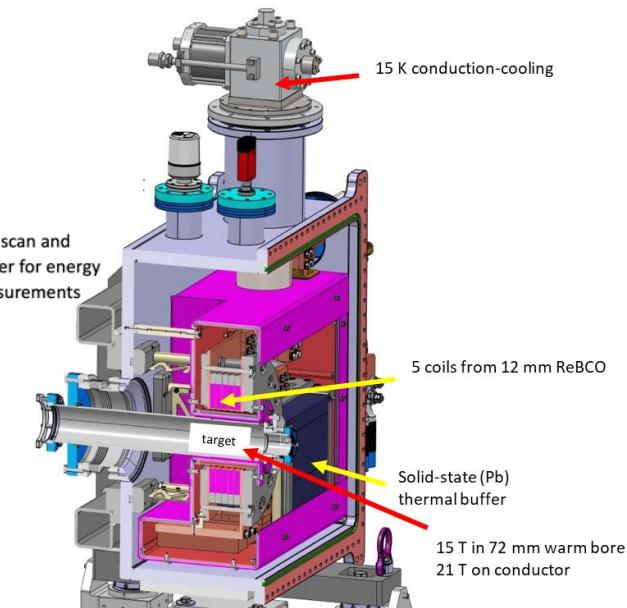
## implementation study on Prevessin site



“Positron production experiment” at PSI’s SwissFEL,  
beam tests from 2025/26



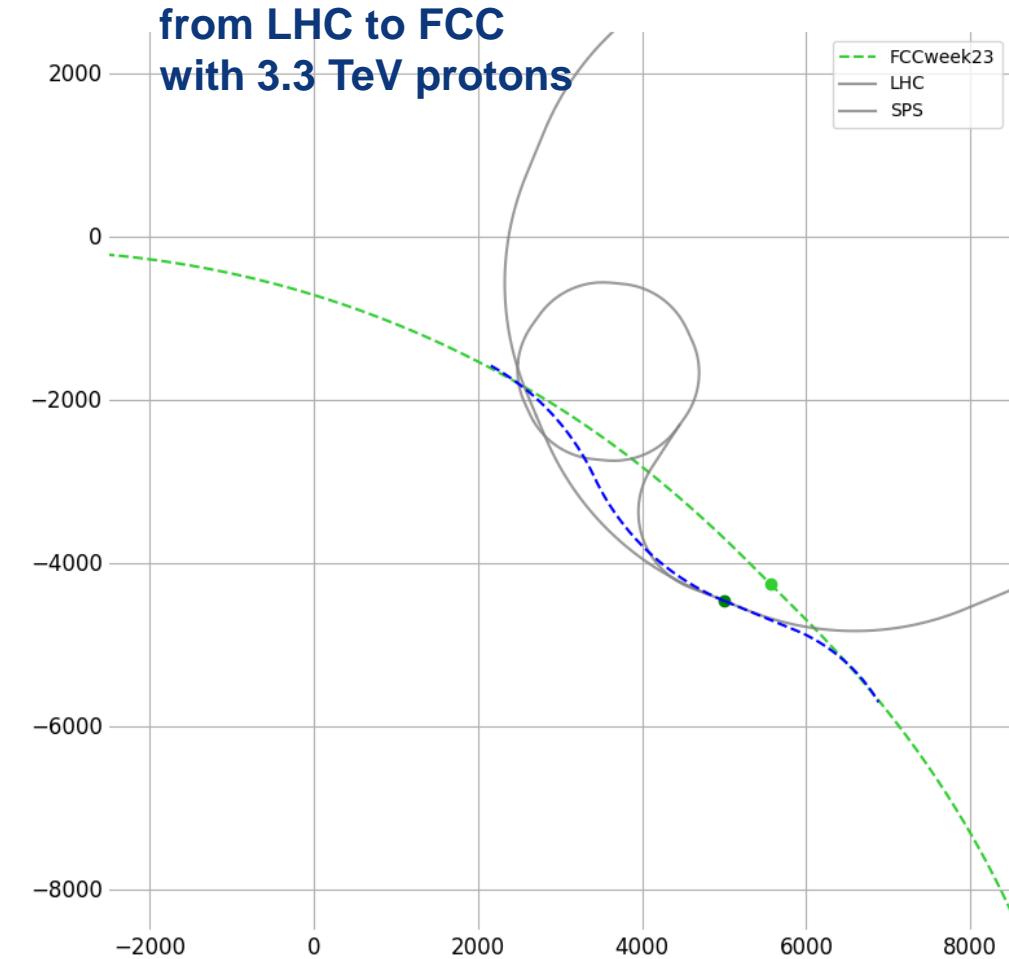
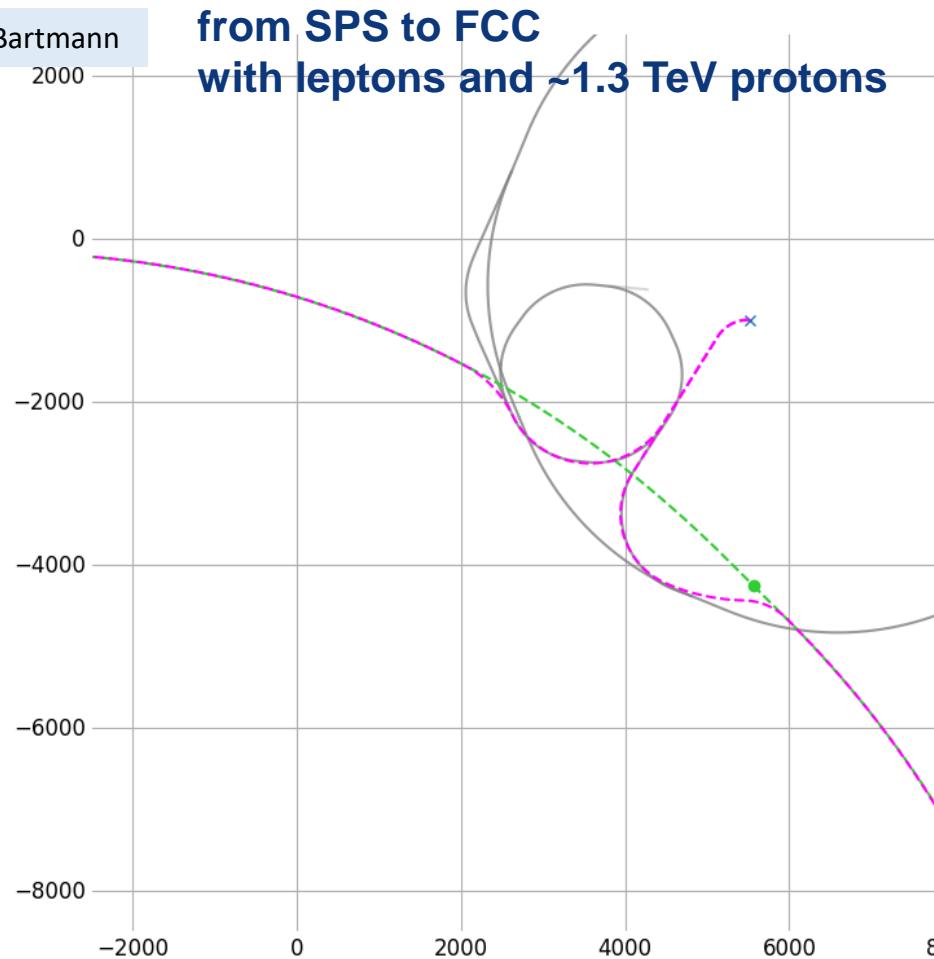
HTS NI target solenoid  
J. Kosse, T. Michlmayr, H. Rodrigues





## transfer lines for ee &amp; hh

W. Bartmann

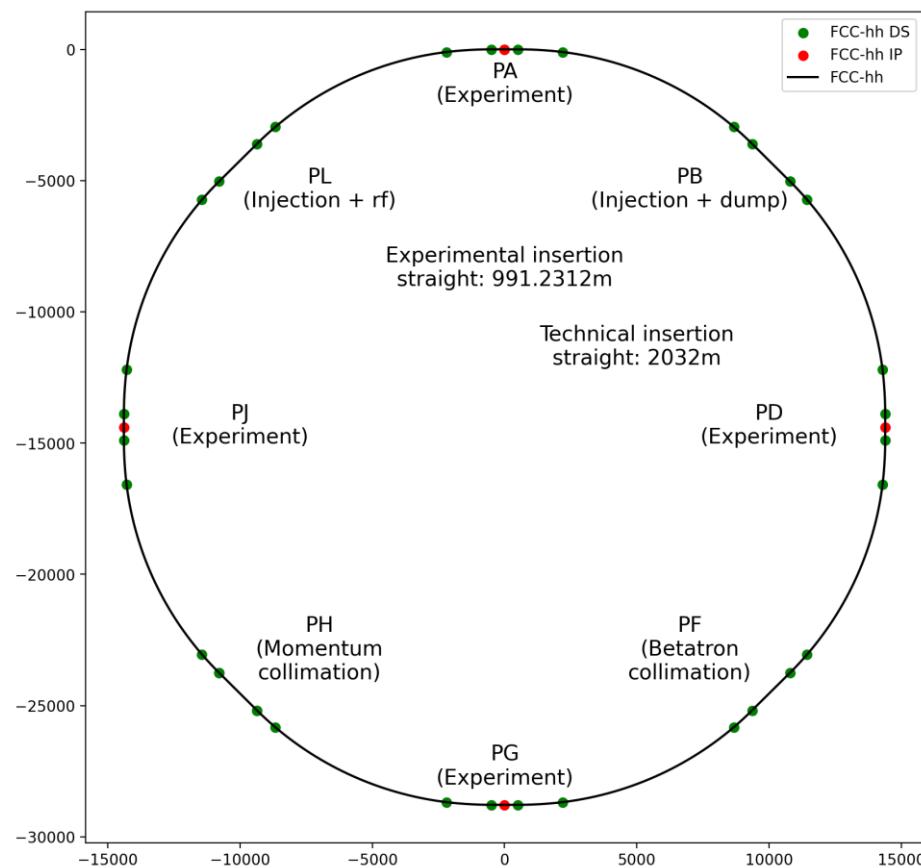


From 6 or 20 GeV Linac on Prevessin site, 1.7 km tunnel down to SPS LSS4, both particle species; then beam separation: (1) one beam into TI 8 tunnel and at LHC level a new tunnel of 1.8 km to connect to the FCC collider, (2) other beam fed through the SPS tunnel, extracting at LSS6 followed by short 800 m tunnel to connect to FCC; all lines from SPS level onwards compatible with 1.3 TeV protons; options also compatible with SPS as lepton pre-booster if 6 GeV linac.

blue lines are compatible with 3.3 TeV hadrons and would need new tunnels; leptons could be fed down as for the SPS option via TI8 and then one beam just continue in the same direction, the other beam would need a small u-turn around LHC P8 to use the same line as hadrons, or a u-turn to the collider tunnel or come directly via the SPS and a small connection tunnel as in the SPS option

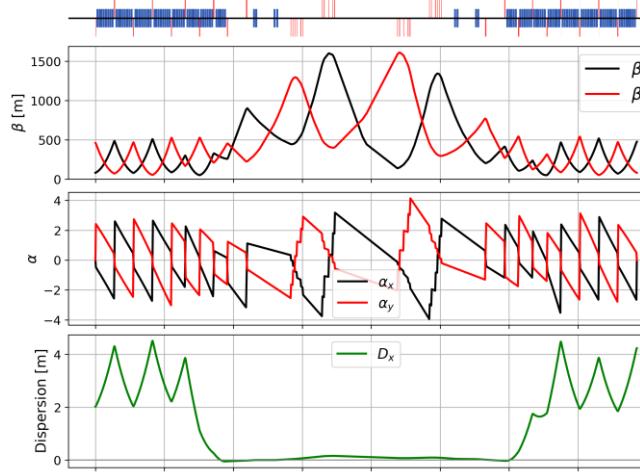


# FCC-hh layout, optics work, geom. integration

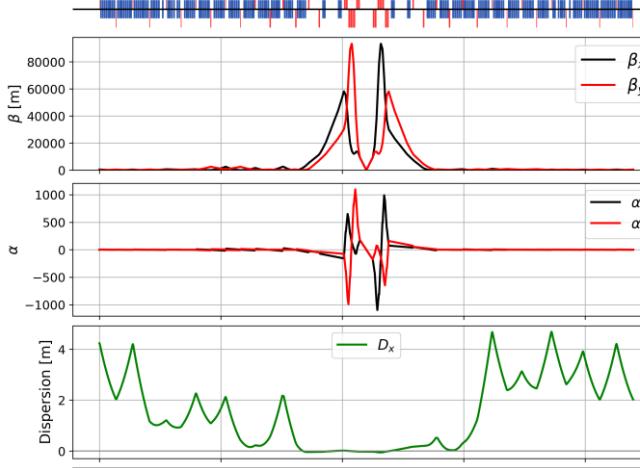


- adaptation to new layout and geometry
- shrink  $\beta$  collimation & extraction by ~30%
- optics optimisation (filling factor etc.)
- move hh IPs on top of ee IP to optimise tunnel and cavern widths.

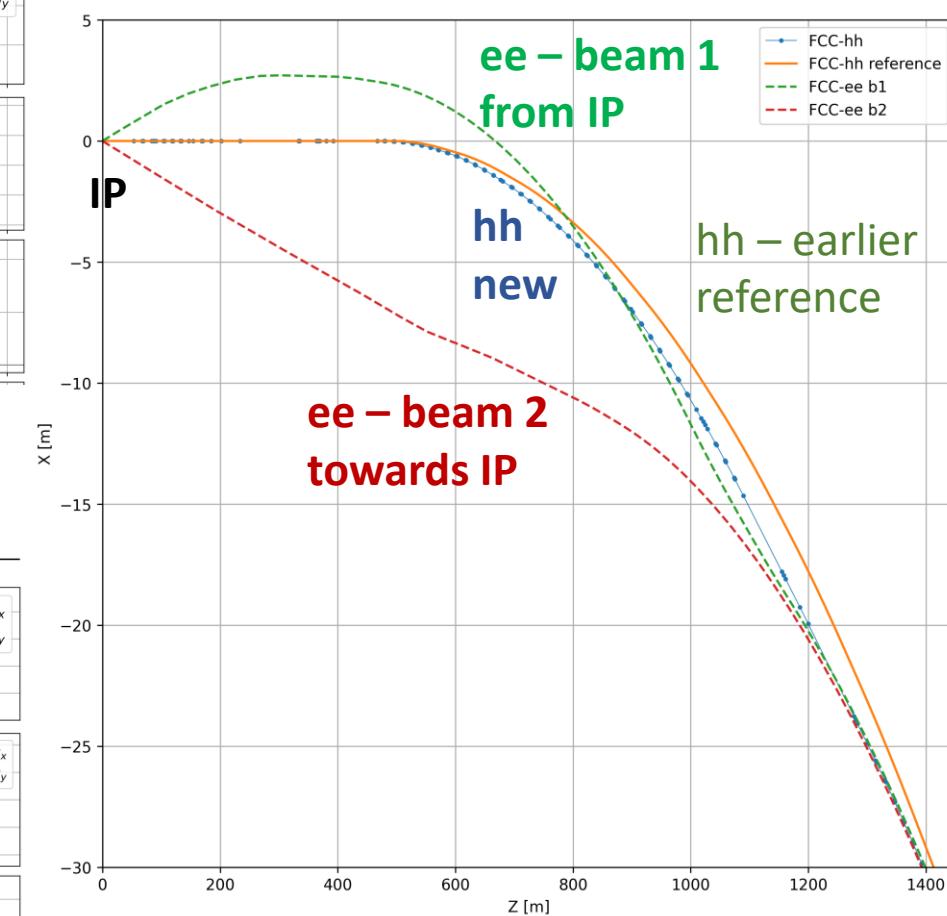
## betatron collimation straight



## experimental straight

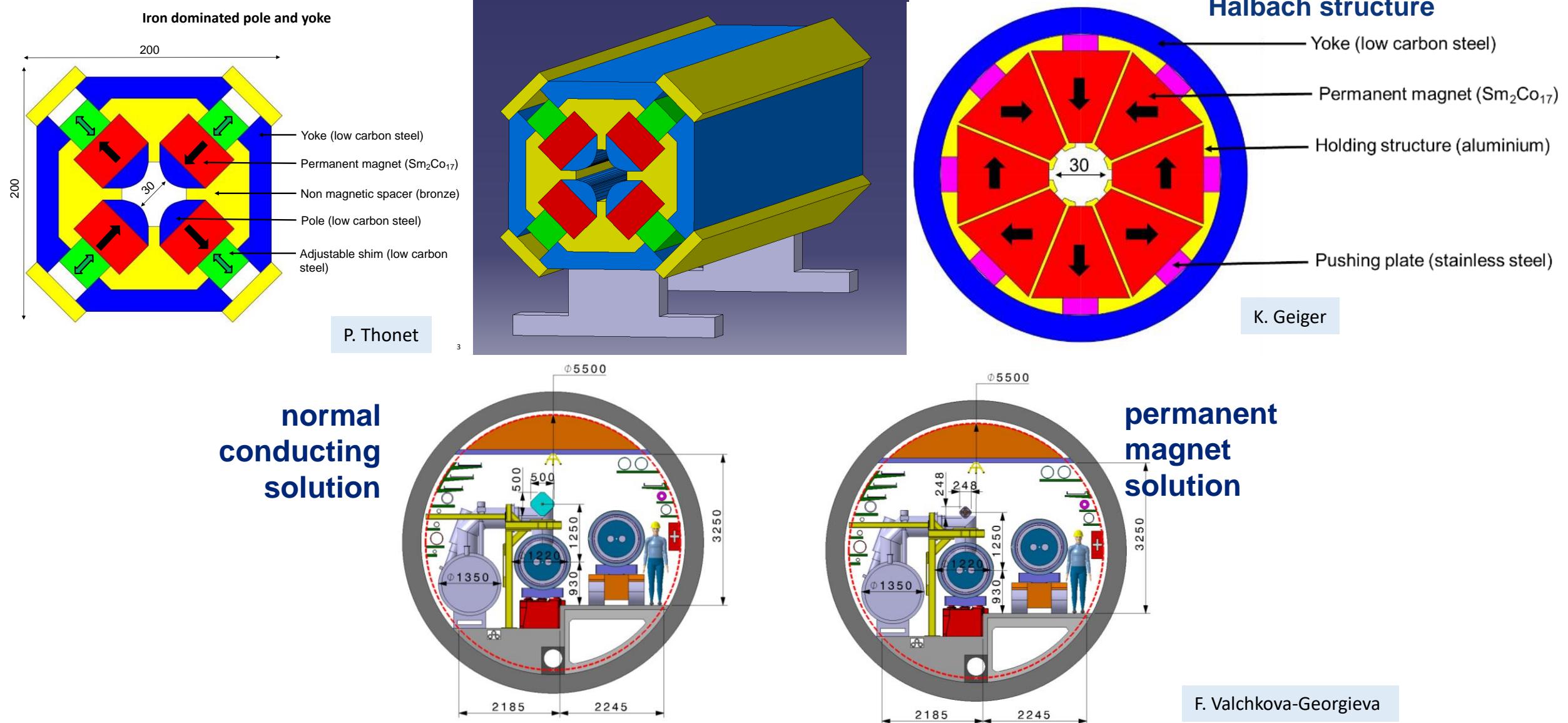


## 3 - beam footprint at interaction point



# hh transfer line continuation in main tunnel

dipoles: about 1.1-1.2 T; quadrupoles: about 40 T/m; two options: normal conducting or permanent magnets



# FCC-ee: main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [ $10^{11}$ ]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [ $\mu\text{m}$ ]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	182	19.4	7.3	1.33
total integrated luminosity / year [ab $^{-1}$ /yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10
	4 years $5 \times 10^{12} Z$ LEP $\times 10^5$	2 years $> 10^8 WW$ LEP $\times 10^4$	3 years $2 \times 10^6 H$	5 years $2 \times 10^6 tt$ pairs

Currently assessing  
technical feasibility  
of changing operation  
sequence  
(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,  $\tau$
- indirect discovery potential up to  $\sim 70$  TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points  $\rightarrow$  robustness,  
statistics, possibility of specialised detectors  
to maximise physics output



# FCC-hh: main machine parameters

Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb <sub>3</sub> Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10 <sup>11</sup> ]	1	1	2.2	1.15
bunch spacing [ns]	25	25	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	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [ $\mu\text{m}$ ]	2.2		2.5	3.75
peak luminosity [10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	6.1-8.9		0.7	0.36
integrated luminosity [fb <sup>-1</sup> ]	20000		3000	300

If 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



# mid-term review: deliverables and planning

## Mid-term review deliverables as defined in CERN/3654/Rev.2, September 2022

### Infrastructure & placement

- Preferred placement and progress with host states (territorial matters, initial states, dialogue, etc.)
- Updated civil engineering design (layout, cost, excavation)
- Preparations for site investigations

### Technical Infrastructure

- Requirements on large technical infrastructure systems
- System designs, layouts, resource needs, cost estimates

### Accelerator design FCC-ee and FCC-hh

- FCC-ee overall layout with injector
- Impact of operation sequence: Z, W, ZH,  $t\bar{t}$  vs start at ZH
- Comparison of the SPS as pre-booster with 10-20 GeV linac
- Key technologies and status of technology R&D program
- FCC-hh overall layout & injection lines from LHC and SC-SPS

### Planning

- **FCC Week 2023:** presentations of most technical deliverables, closed SAC meeting on Thursday 8 June 2023 afternoon
- **16 – 17 (18) October 2023: SAC mid-term review meeting** with all deliverables, **CRP cost review meeting**
- **End October 2023:** SAC and CRP reports available to SPC and FC
- **20 – 22 November 2023: SPC and FC review meetings** on mid-term review
- **2 February 2024:** Council meeting on mid-term review

**Results of both general mid-term review and the cost review should indicate the areas of attention for the second part of the Feasibility Study**

### Physics, experiments, detectors:

- Documentation of FCC-ee and FCC-hh physics cases
- Plans for improved theoretical calculations to reduce theoretical uncertainties towards matching FCC-ee statistical precision for the most important measurements.
- First documentation of main detector requirements to fully exploit the FCC-ee physics opportunities

### Organisation and financing:

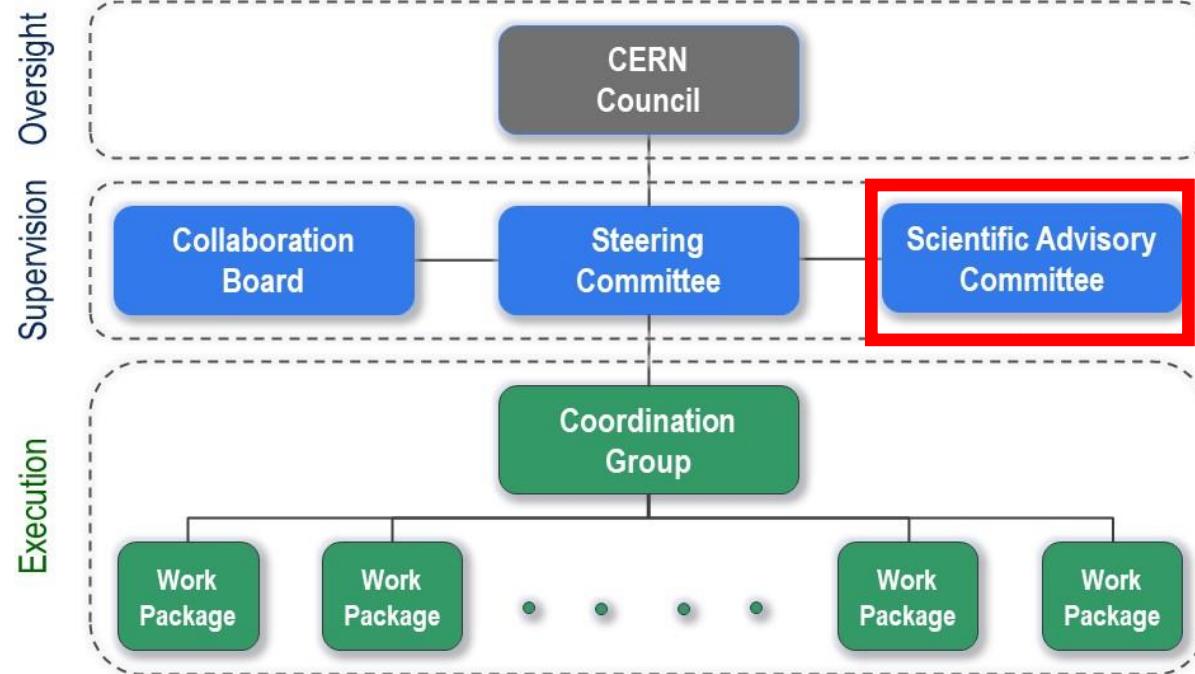
- Overall cost estimate & spending profile for stage 1 project

### Environmental impact, socio-economic impact:

- Initial state analysis, carbon footprint, management of excavated materials, etc.
- Socio-economic impact and sustainability studies



# mid-term technical review – Scientific Advisory Committee



SAC follows and reviews the implementation of the Feasibility Study, giving scientific and technical advice to FCC SC and to Coordination Group, providing guidance to facilitate major technical decisions.

**Members:** 16 international experts not directly involved in the Feasibility Study with renowned expertise in one or more scientific and technical domains relevant to the Study (accelerators, technical infrastructure, key technologies, physics, detectors, etc.). Members and Chair appointed by SC.

## SAC members:

Riccardo Bartolini (DESY), Alain Chabert (SFTRF), Brigitte Fargevieille (EDF), Belen Gavela Legazpi (UAM), Katri Huiti (Helsinki), Srinivas Krishnagopal (BARC), Peter Krizan (Ljubljana), Philippe Lebrun (CERN, ret.), Peter McIntosh (STFC), Michiko Minty (BNL), Andrew Parker, chair (Cambridge), Kyo Shibata (KEK), Roberto Tenchini (Pisa)



# mid-term cost review – Cost Review Panel (CRP)

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

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

Action to be taken	Voting Procedure
For recommendation	SCIENTIFIC POLICY COMMITTEE 330 <sup>th</sup> Meeting 25–26 September 2022
For decision	RESTRICTED COUNCIL 20 <sup>th</sup> 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.

## The CRP will

- 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, and
- advise the FCC study team on matters of cost estimation in view of preparation of the final Feasibility Study Report for end 2025.

**Members:** The CRP consists of around 10 international experts, not directly involved in the Feasibility Study, with renowned expertise in costing and project management aspects related to the scientific and technical domains relevant to the Study (accelerators, technical infrastructure, civil engineering, detectors, etc.). Members and Chair appointed by SC.

## CRP members:

Carlos Alejaldre (F4E), Austin Ball (CERN, ret.), Umberto Dosselli (INFN), Vincent Gorgues (CEA),  
Norbert Holtkamp, chair (Stanford U.), Christa Laurila (VTV), Ursula Weyrich (DKFZ), Jim Yeck (BNL),  
Thomas Zurbuchen (ETH Zürich)



# Enlarging the Collaboration - setup

## FCC Global Collaboration Working Group (FGC)

Two approaches, one globally-oriented (FGC), the other more PED oriented (IFNC), both to engage with countries with **mature communities**, a **long-standing participation** in CERN's programmes and the **potential to contribute substantially** to the Organization's long-term scientific objectives, to facilitate opportunities for national participation in the Feasibility Study

- **Work with national laboratories, institutes and universities as well as industry to :**
  - Encourage an expanded membership.
  - **Explore opportunities for future prospective participants, in particular on the Accelerator side**
  - Support new participants in application process.
  - Assist the new participants in **defining areas of collaboration** and conclude relevant agreements.
  - Facilitate the integration process.
  - **Facilitate interest in CERN non-core areas –e.g. geology, geodesy, logistics, materials science.**
  - Prepare the foundations for research and contributions by industry.
  - Liaise with National Contact persons

Convened by Emmanuel Tsesmelis (CERN international relations)

## International Forum of National Contacts (IFNC)

- **Contact directly Physics groups in a country**, typically from LHC or Future Colliders groups to ask them **to join as new institution**
  - Discuss the physics case and the opportunities
    - To study **R&D/ Detector concepts** for FCC
    - To expand the FCC Physics scope via the study of **physics case studies**
    - To improve the **theoretical calculations** to exploit the FCC physics potential
  - Help **forming a national FCC group**, with strong PED component, which can hold its national FCC meetings, including the Accelerator community when possible
  - Identify at least one **National Contact** to exchange information between country situation and FCC management, and to strengthen the national community
  - Exchange experience across countries (**IFNC meetings**)

Convened by Gregorio Bernardi and Tadeusz Lesziak (National Contacts)



# Enlarging the Collaboration - actions

## FGC: FCC Engagement Meetings

- **Overview**
  - Extended forums with interested countries to discuss collaboration with FCC on all topics
  - Topics:
    - Introduction to FCC Feasibility Study.
    - Presentation of FCC physics, experiment, detector, accelerator and global collaboration.
    - Presentations from the country scientific community.

### Recent Meetings

- Mexico (mini meeting on accelerator), June 2021
- Republic of Korea, September 2021
- Pakistan, September 2021
- Portugal, November 2021
- Estonia, March 2022
- Greece, January 2023

### Several other initiatives, such as

- First annual US-FCC workshop at BNL in April 2023 [US FCC Workshop \(24-26 April 2023\)](#)
- Joint FCC France-Italy workshop in Lyon in November 2022 [Joint FCC-France & Italy Workshop in Lyon](#)

## IFNC: FCC PED kick-off Meetings

- **Overview**
  - Forums with interested countries to discuss collaboration with FCC on PED topics
  - Topics:
    - Introduction to FCC Feasibility Study.
    - Detailed presentations of FCC physics, experiment, detector.
    - More general on accelerator and global collaboration.

### Recent Meetings (examples)

- Nordic Countries (Denmark, Norway, Sweden, Finland), March 2021
- India, November 2022
- Brazil, March 2023

# Status of FCC global collaboration

**Increasing international collaboration as a prerequisite for success:**  
→ links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

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).

## FCC-ee physics run

Start accelerator commissioning

2047  
2046  
2045  
2044  
2043  
2042

End of HL-LHC operation

2041  
2040

Start accelerator installation

2039  
2038  
2037

Start accelerator component production  
Technical design & prototyping completed

2036  
2035  
2034  
2033

Ground-breaking and start civil engineering

2032  
2031  
2030

Start engineering design

Completion of HL-LHC: more ATS personnel available

2029  
2028  
2027

FCC Approval, R&D, start prototyping

European Strategy Update

2026  
2025

FCC Feasibility Study Report

Start detector commissioning

2047  
2046  
2045  
2044  
2043  
2042

Start detector installation

2041  
2040  
2039  
2038  
2037

Start detector component production  
Four detector TDRs completed

2036  
2035  
2034  
2033  
2032

Detector CDRs (>4) submitted to FC<sup>3</sup>

2031  
2030

Completion of HL-LHC upgrade: more detector experts available

2029  
2028  
2027

FC<sup>3</sup> formation, call for CDRs, collaboration forming

European Strategy Update

2026  
2025

Detector EoI submission by the community

FCC-ee Accelerator

Key dates

FCC-ee Detectors

# Conclusions and outlook

The first half of the FCC Feasibility Study will soon be completed with the mid-term review.

Main focal points were identifying the best placement and layout and adapting the entire project parameters to the new placement.

This was achieved in a very fruitful collaboration between all scientific and technical actors in the feasibility study and in close cooperation with the host state services concerned.

Many thanks to all participants and committee members for joining, I wish everybody a productive and fruitful week with lots of progress towards finalizing preparations for the mid-term review.

Big thanks to all persons that helped preparing this FCC Week, in particular to the local organizing team and to the FCC administrative support team!