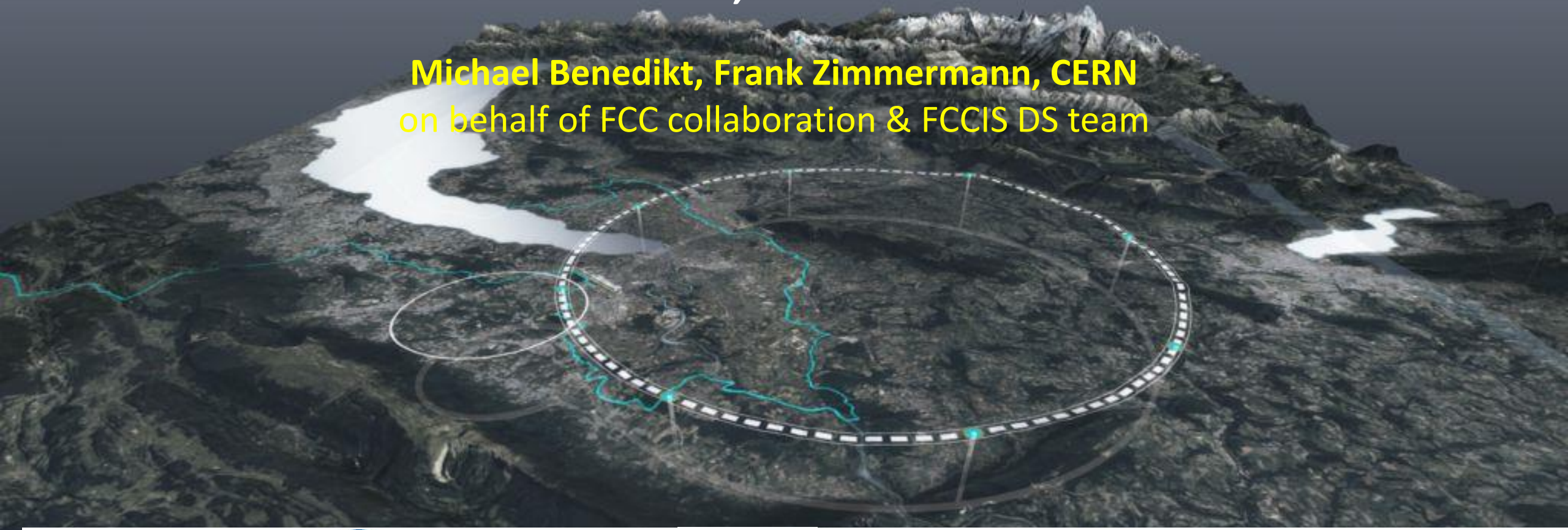
FCC Feasibility Study Status

FCC Week, 10 June 2024

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



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

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

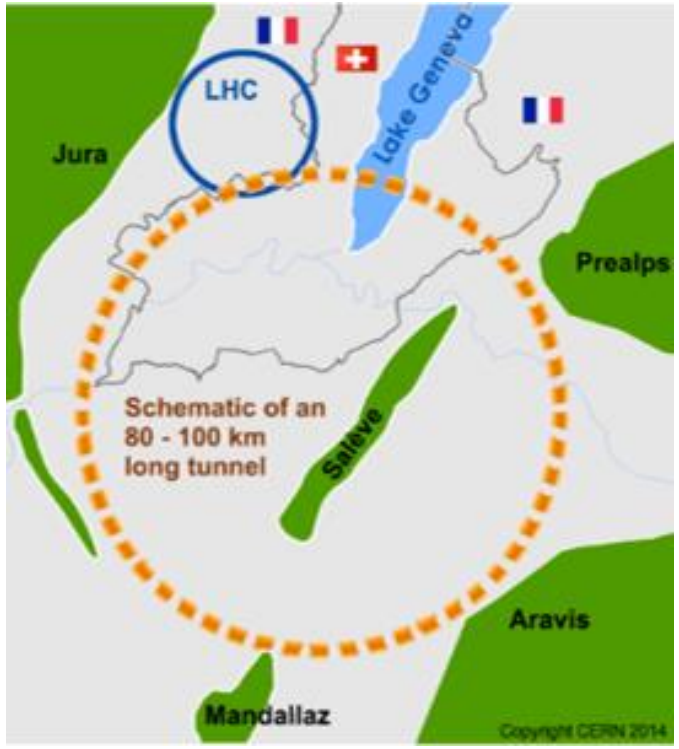
European Commission | Horizon 2020 European Union funding for Research & Innovation

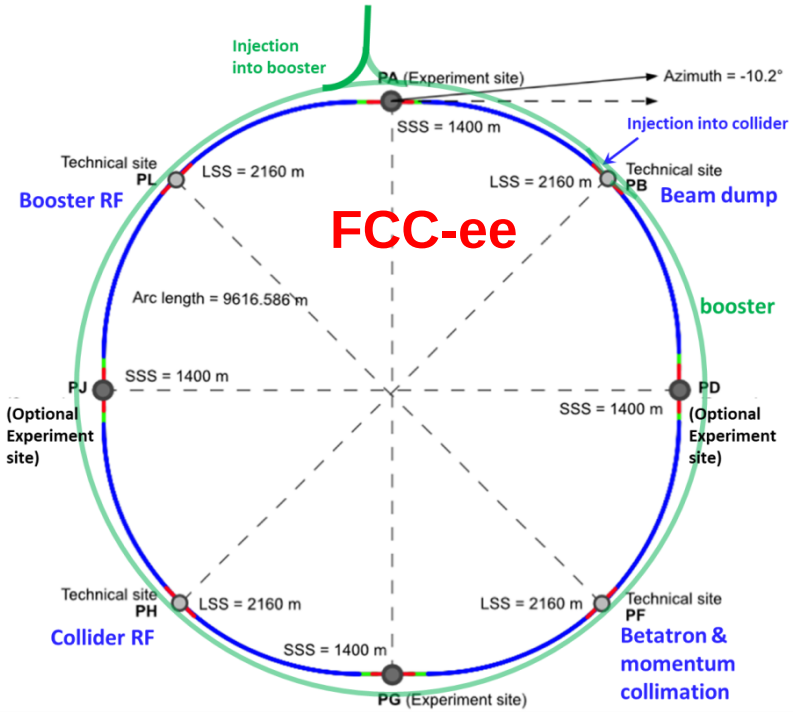
photo: J. Wenninger

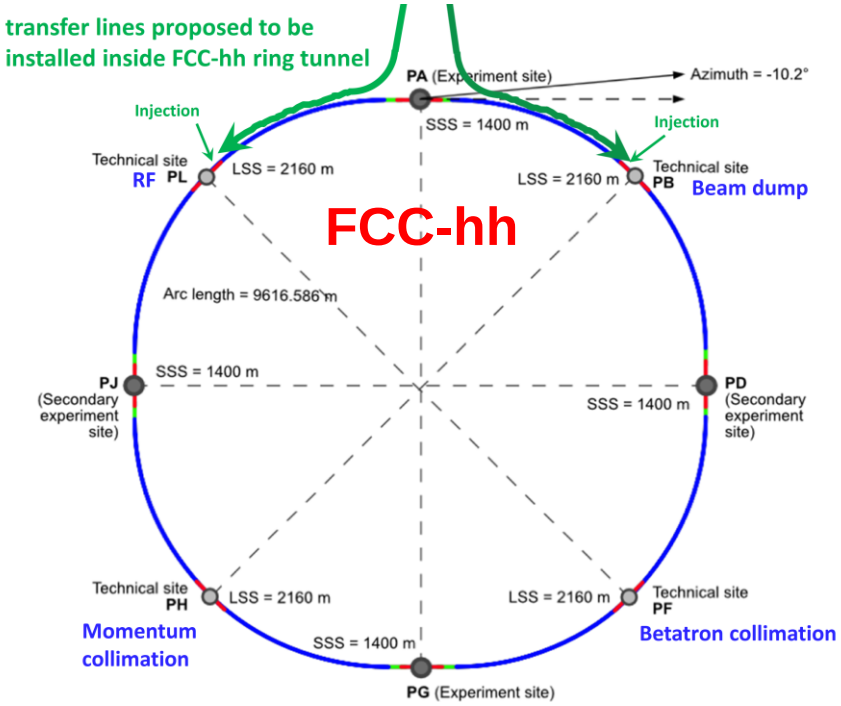
FCC integrated program

comprehensive long-term program maximizing physics opportunities

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







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 by March 2025

Feasibility Study Mid-Term Review passed !

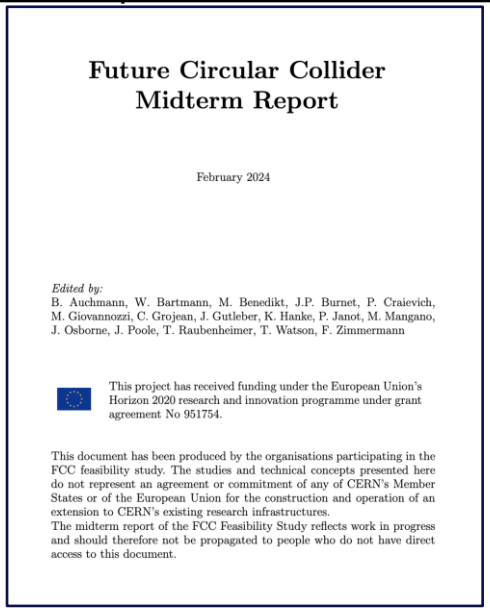
The goal of the FCC FS mid-term review is to assess the progress of the Study towards the final report.

Deliverables approved by the Council in September 2022:

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

Deliverables:

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



Future Circular Collider
Midterm Report

February 2024

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, T. Watson, F. Zimmermann

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This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

Full Report

8 Chapters/Deliverables
~ 700pp document
~ 16 editors
~ 500 contributors

Many thanks to the SAC, CRP, SPC, FC and the Council for the very useful reviews!

Documents:

- ❑ Mid-term report (all deliverables except D7)
- ❑ Executive Summary of mid-term report
- ❑ Updated cost assessment (D7)
- ❑ Funding model (D7)

Review process:

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

All deliverables met, no technical showstoppers

→70-80 recommendations

Main goals for 2024/beginning 2025

- **Completion of technical work for Feasibility Study until end 2024**
  - Implementation of recommendations of the mid-term review
  - Focus on “feasibility items” and items with important impact on cost/performance
  - Develop a risk register
  - Update cost estimate to reach cat 3 level on cost uncertainty (-20% / +30%).
  - Further develop the funding model based on discussions with CERN Council
- **Complete FS by March 2025 as input for ESPP update.**
- **In parallel, continue work with host states on project definition and responsibilities, authorization procedures, excavation material strategy and regional implementation development.**

Feasibility Study Report for March 2025

Structure: 3 Volumes

- ***Vol. 1:*** *Physics, Experiments and Detectors (~200 pages)*
- ***Vol. 2:*** *Accelerators, Technical Infrastructures, Safety Concepts (~370 pages)*
- ***Vol. 3:*** *Civil Engineering, Implementation & Sustainability (~200 pages)*
- **Input for Update of European Strategy for Particle Physics**

to be prepared with Overleaf & published by EPJ (Springer-Nature) – FCCIS members

In addition documentation on Cost Estimate – Funding Models

Pre-TDR phase from April 2025 until end 2027

Main goal is to provide all information to Council to allow taking a decision on the project **by end of 2027 or early 2028**

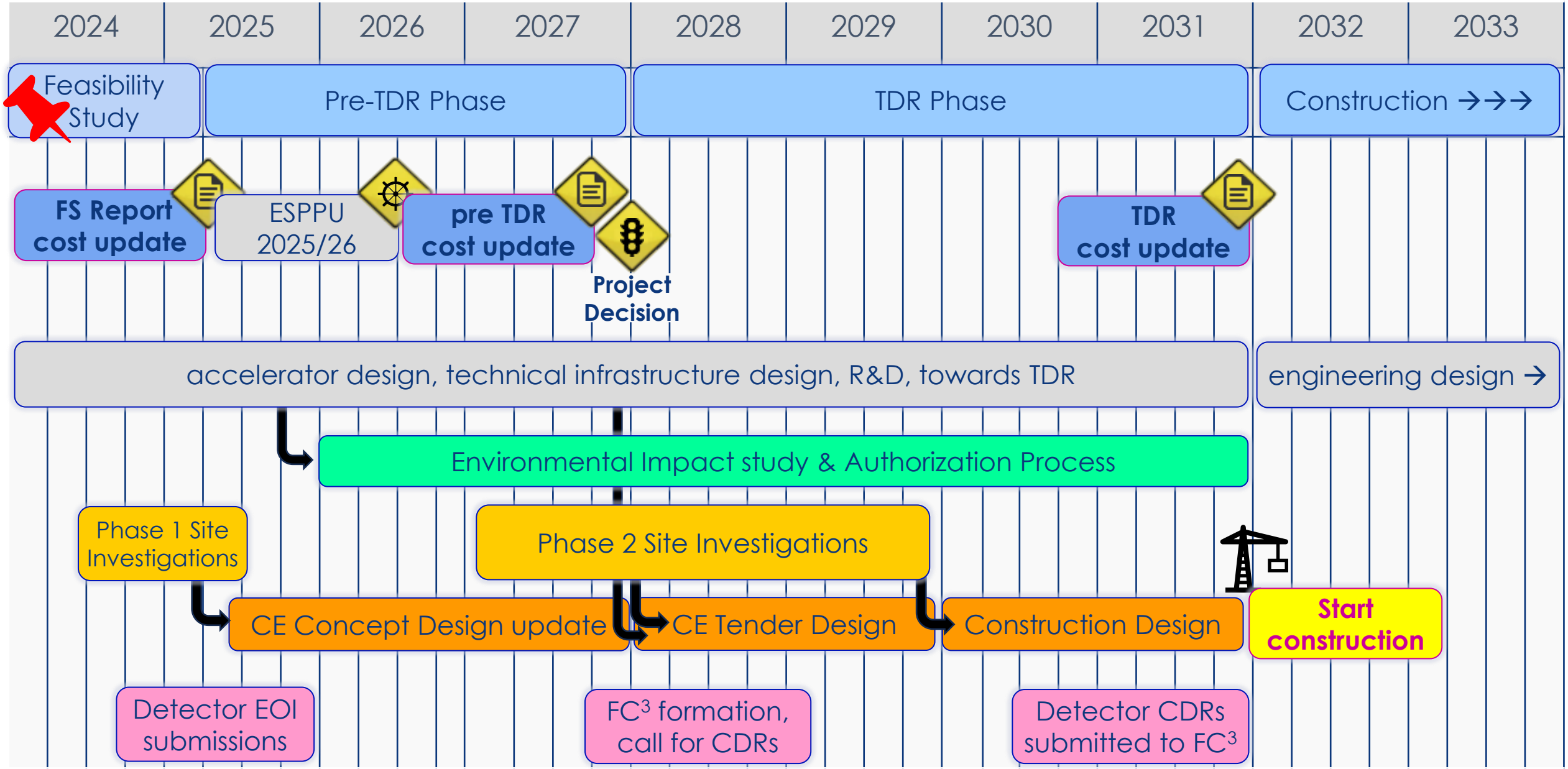
- Further develop the civil engineering and the technical design of all major systems and components, so as to provide a **more detailed cost estimate** with reduced uncertainties
- Continuation of **technical R&D activities**
- Work with host states on **regional implementation development** and **authorization process definition to enable launch of environmental impact study in 2026**
- Continuation of site investigations and perform an **overall integration study to specify requirements of technical infrastructure, accelerators and detectors**

  → **Provision of input for civil engineering design if the project goes ahead.**

→ Work with international partners to define roles and work packages

FUTURE CIRCULAR COLLIDER

Expected time line till start of construction

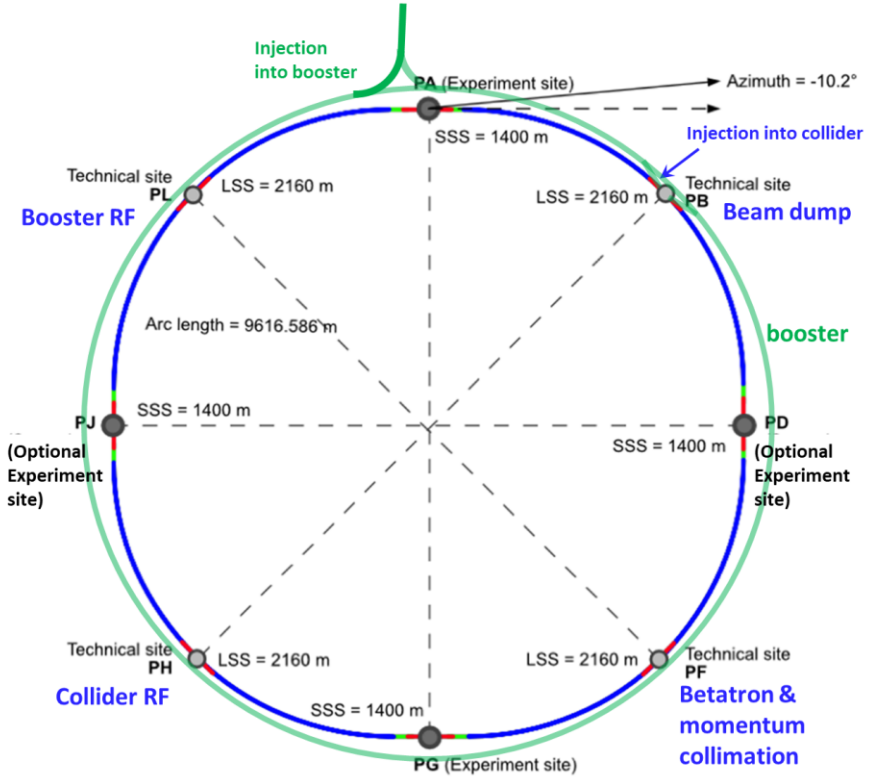


Reference layout and implementation: PA31 - 90.7 km

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, 4-fold symmetry



V. Mertens, J. Gutleber

PA: Experiment

PB: technical

PL: technical

PD: experiment

PJ: experiment

PF: technical

PH: technical

PG: experiment

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**

FUTURE CIRCULAR COLLIDER

Regional implementation activities

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

PA – Ferney Voltaire (FR) – experiment site

PB – Présinge/Choulex (CH) – technical site

PD – Nangy (FR) – experiment site

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

PG – Charvonnex/Groisy (FR) – experiment site

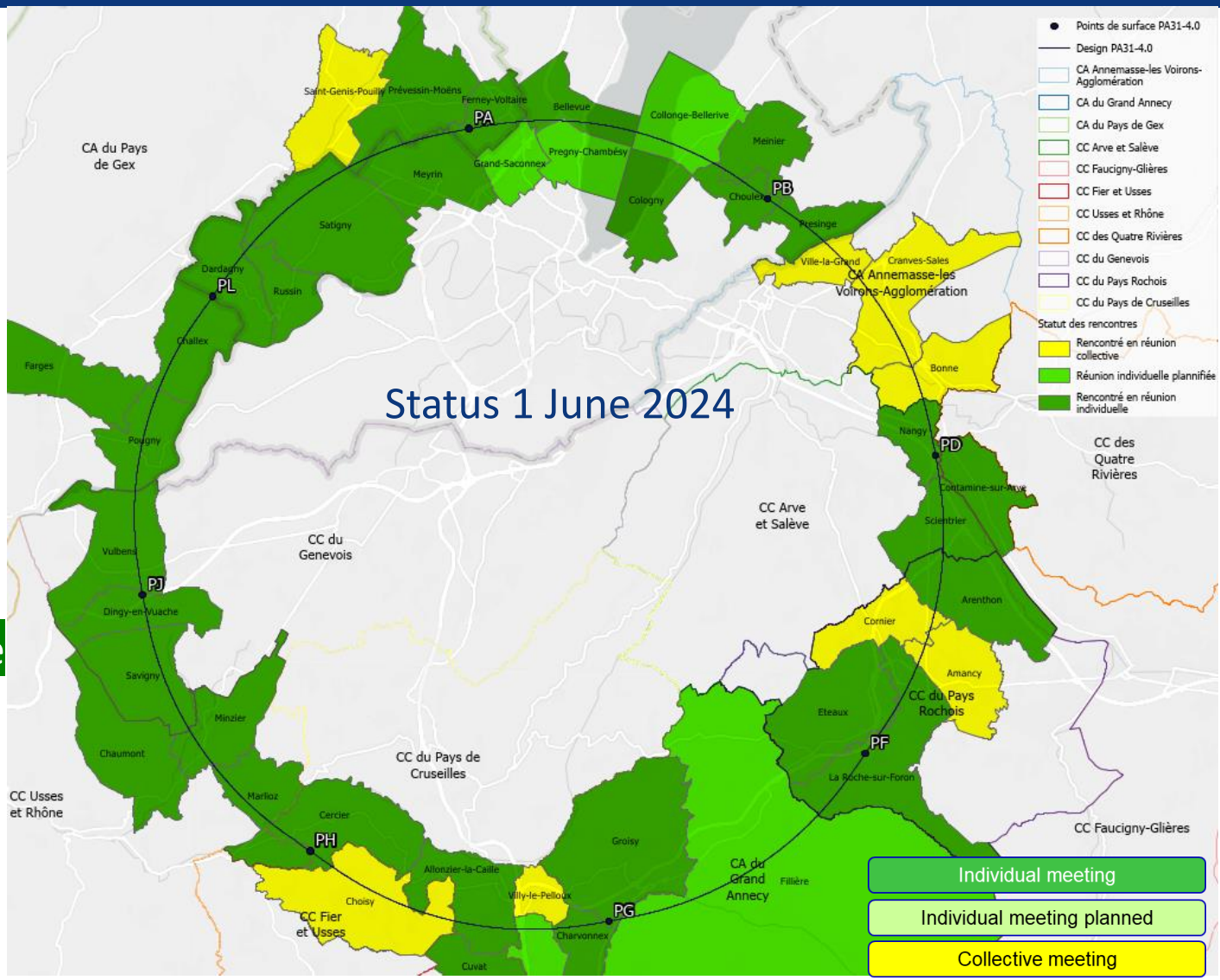
PH – Cercier (FR) – technical site

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

PL – Challex (FR) – technical site

Detailed work with municipalities and host states

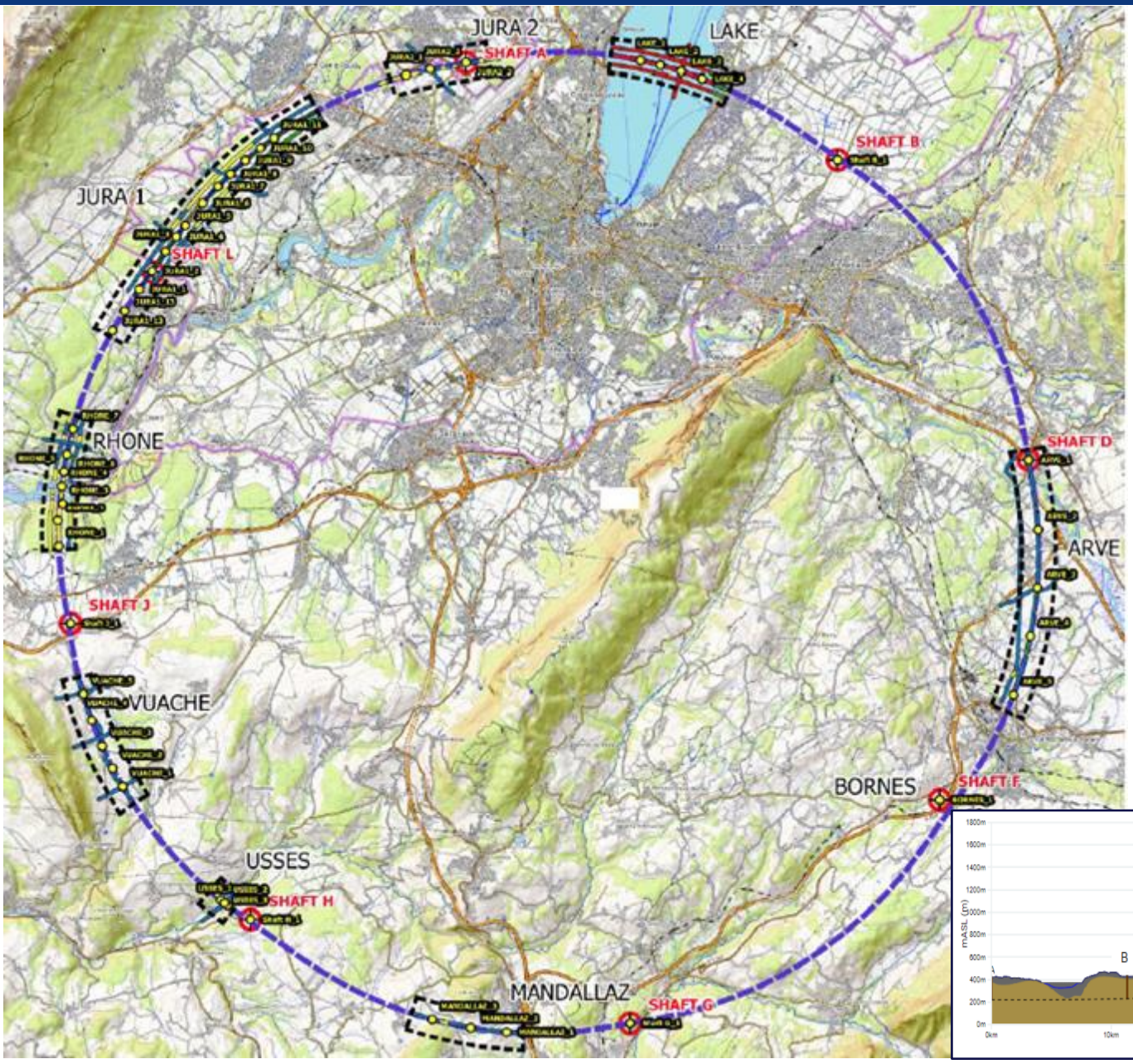
- identify land plots for surface sites
- understand specific aspects for design
- identify opportunities (waste heat, tec.)
- reserve land plots until project decision



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

FUTURE CIRCULAR COLLIDER

First series of site investigations



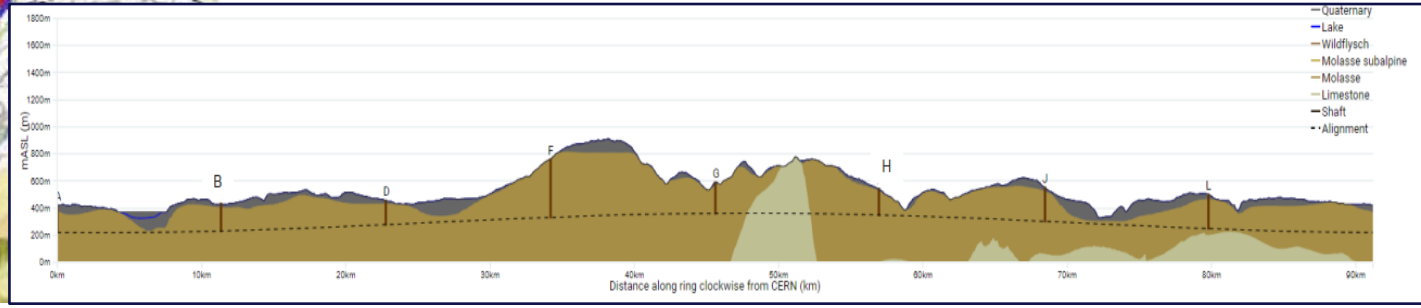
Site investigations to identify exact location of geological interfaces:

- Molasse layer vs moraines/limestone
- ~30 drillings and ~100 km seismic lines
- Start in July 2024

→ **Vertical position and inclination of tunnel**

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



Start of public information & engagement sessions

First public information and discussion meeting at the Science Gateway on the 24th April at CERN.

The meeting was organised for the local community of our Host States, France and Switzerland, in the Science Gateway. The "Progress of the feasibility study of the Future FCC circular collider" was followed by a discussion with the participants.

La Roche-sur-Foron - Haute Savoie international fare April 27 to May 6

Unveiling the science of tomorrow: FCC Study takes centre stage at La Roche-sur-Foron exhibition

The Future Circular Collider team discussed the project's status and aspirations with a large number of attendees

15 MAY, 2024 | By Zoe Nikolaidou

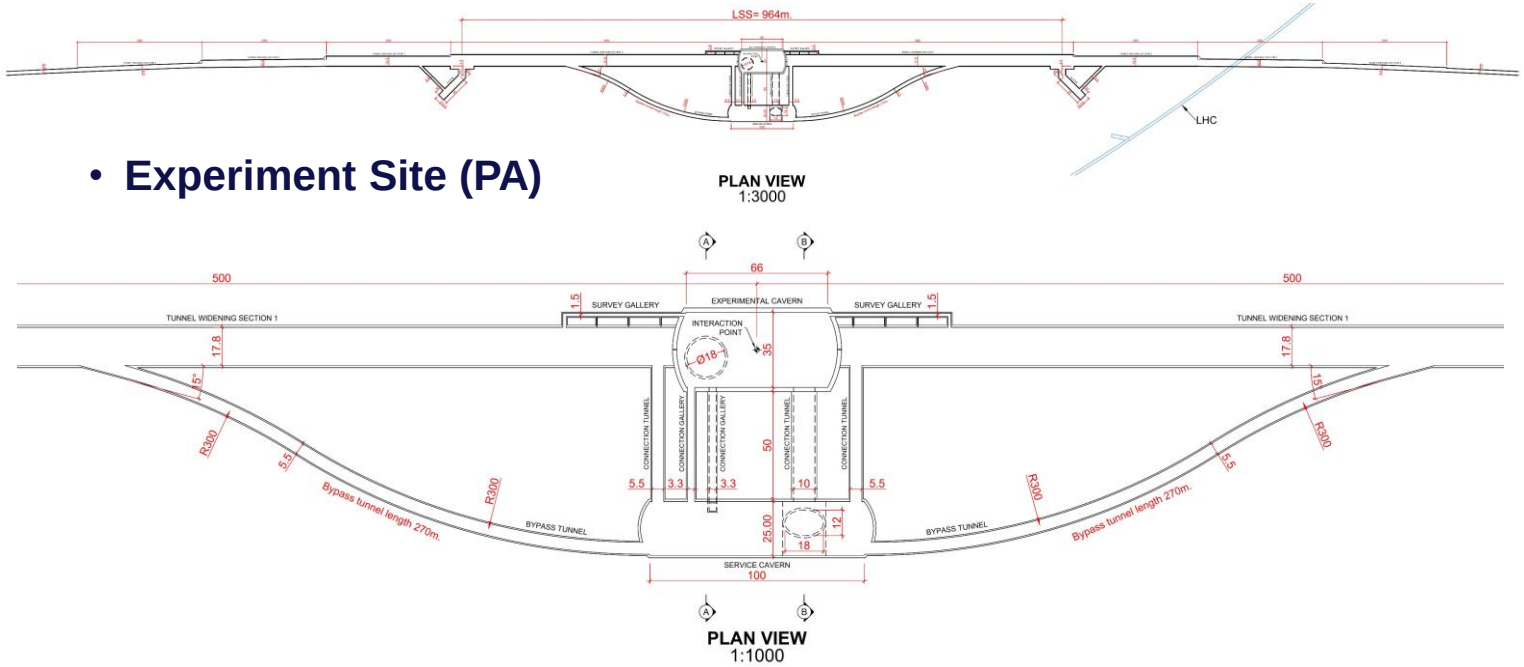
CERN's participation in the International Fair of Haute-Savoie/Mont Blanc, enhanced by the valuable help of volunteers from the FCC team, resulted in meaningful discussions with more than 2000 members of the local community on topics ranging from the required technological advancements to sustainability measures.

On 15 May, RTS (Radio Télévision Suisse) broadcasted a special program celebrating CERN's 70th anniversary and hosted at CERN's Science Gateway.

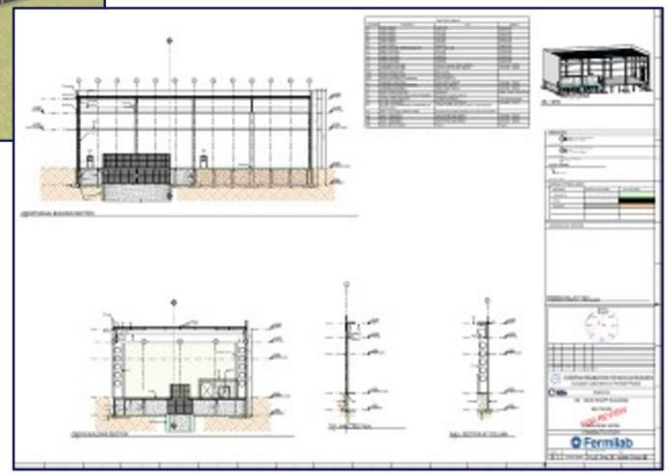
The event featured a comprehensive look at CERN's illustrious history, groundbreaking achievements, and future ambitions, including the prominently featured Future Circular Collider (FCC) project with study experts interacting with the audience.

CE underground and surface site development

- **Full 3D model of all underground structures as basis for costing and scheduling exercises with external consultant.**



- **Experiment Site (PA)**



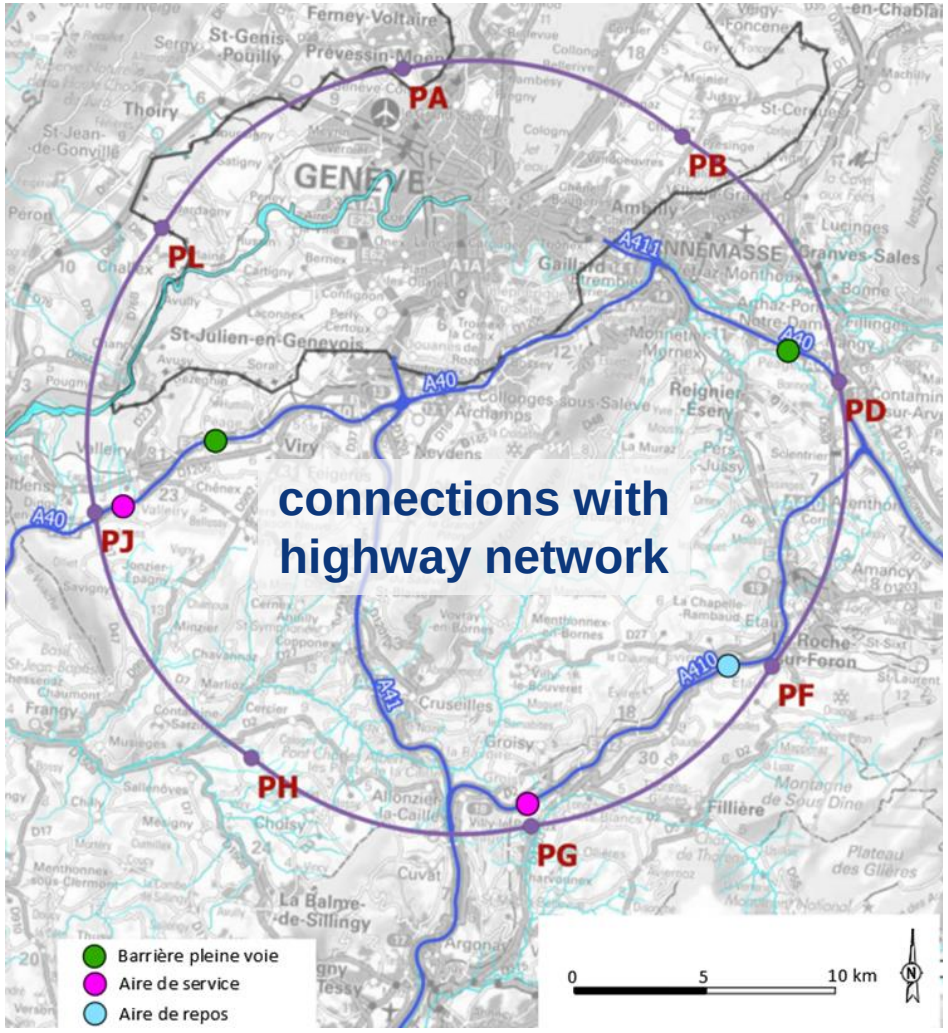
Examples of Fermilab Deliverables

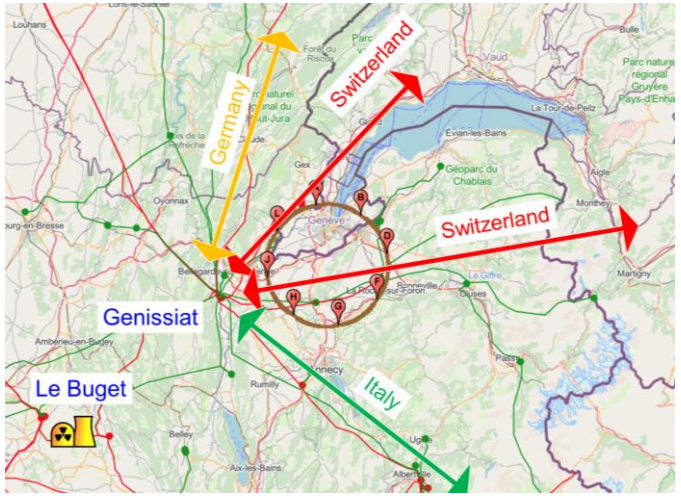
Fermilab

- **Generic study of experiment site and technical site done by FNAL**
- **Bills of quantities extracted from FNAL designs**
- **Basis for cost estimate by consultant with experience on industrial constructions in CH-FR area.**

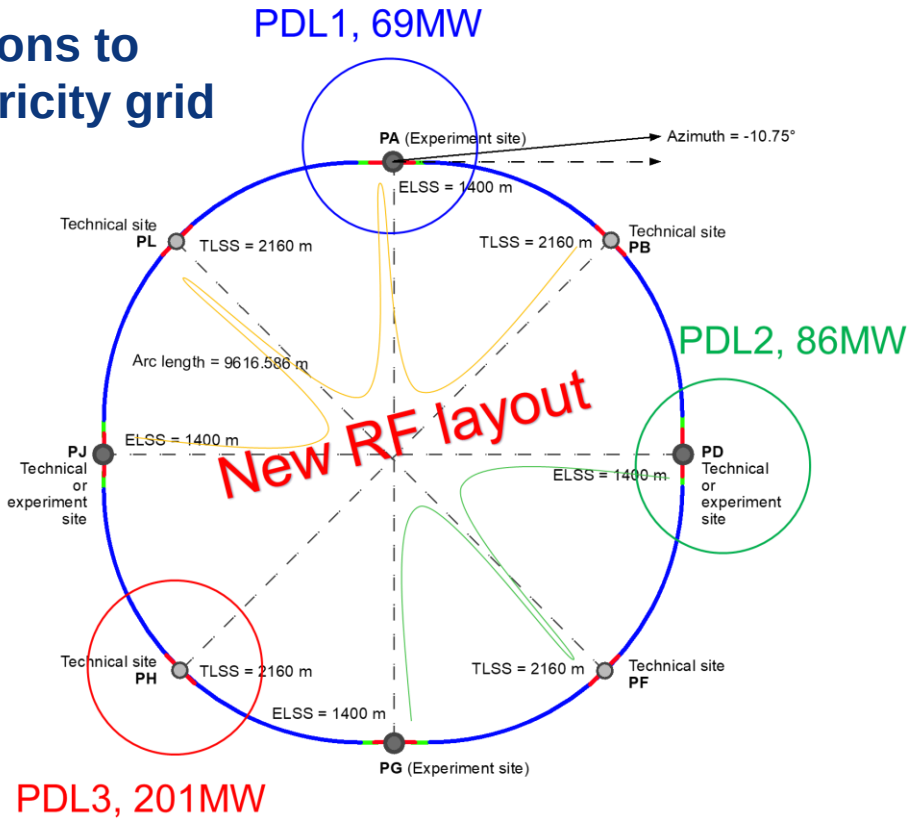
Integration with regional infrastructures

- Road accesses developed for all 8 surface sites
- Four possible highway connections defined
- Less than 4 km of new roads required





Connections to French electricity grid



- Electrical connection concept developed with RTE (French electricity grid operator)
- Three HV supply points, two new stations & CERN Prevessin
  ➔ requested loads have no significant impact on grid
- R&D efforts aiming at reduction of the energy consumption of FCC-ee and FCC-hh

FUTURE CIRCULAR COLLIDER

FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
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

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam.
- Independent vacuum systems for electrons and positrons
- full energy booster ring with top-up injection, collider permanent in collision mode

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

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

F. Gianotti

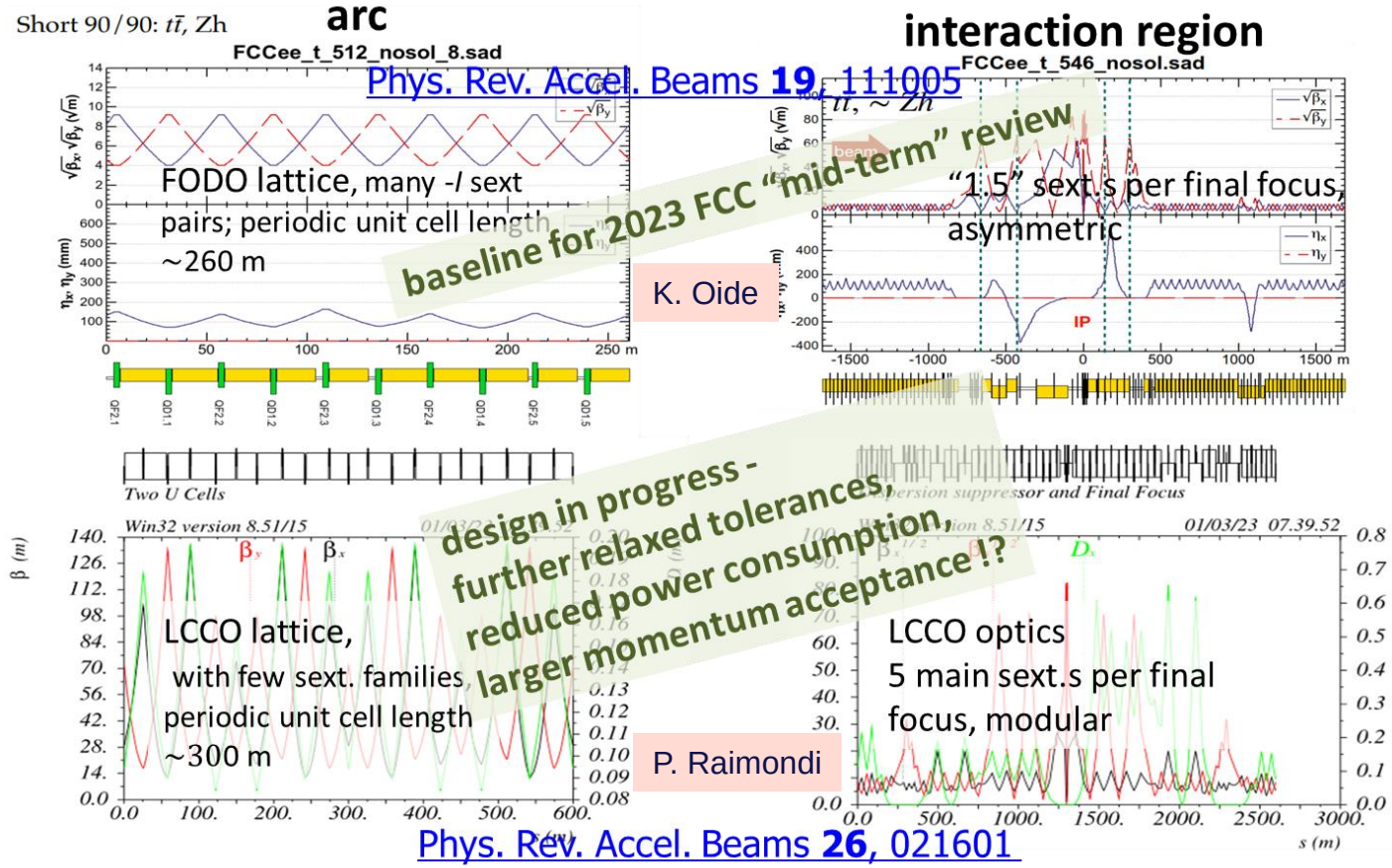
Collider and Booster design

Complete accelerator design and layout

- consolidated beam parameters throughout entire chain & different operation modes
- definitive collider and booster and optics and layout
- beam-based alignment procedures, tolerances and requirements
- complete impedance models for booster and collider rings

➔ **specifications for design of components and technical infrastructure**

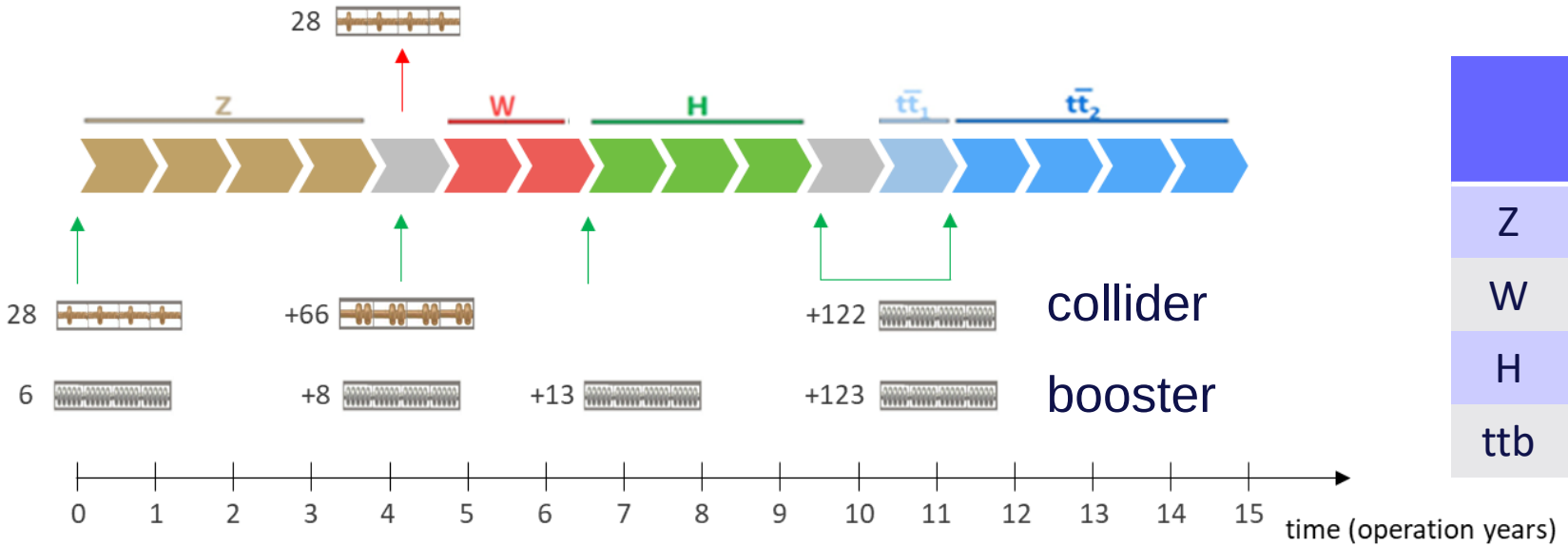
➔ **full inventory for integration studies and requirements for civil engineering**



Phys. Rev. Accel. Beams **19**, 111005

Phys. Rev. Accel. Beams **26**, 021601

FCC-ee SRF system



	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.08
W	80	135	1
H	120	26.7	2.08
ttb	182.5	5	11.67

O. Brunner. F. Peauger

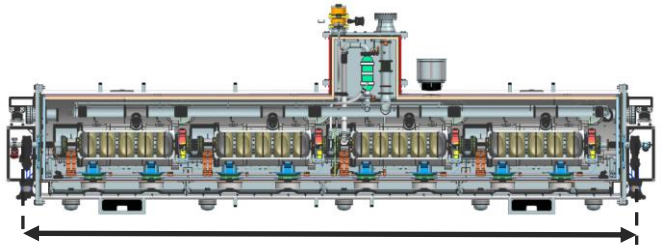
Key technologies:

- **400 MHz Nb/Cu** for collider Z, WW, (Z)H working points
- **800 MHz bulk Nb** for booster & ttbar collider
- quasi-continuous evolution of machine configurations
- long-term R&D program with international partners
  - high *Q* cavities, thin film coatings (incl. Nb_3Sn), cryomodules, efficient RF power sources

ttbar, booster

5-cell 800 MHz, bulk Nb

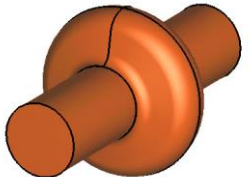
Jefferson Lab



Fermilab ~7 m

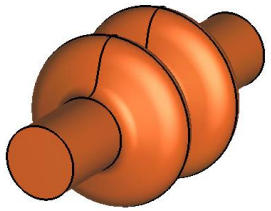
Z

1-cell 400 MHz, Nb/Cu



W, H

2-cell 400 MHz, Nb/Cu



effort to use 2-cell cavities also for Z running to raise operational efficiency

I. Karpov

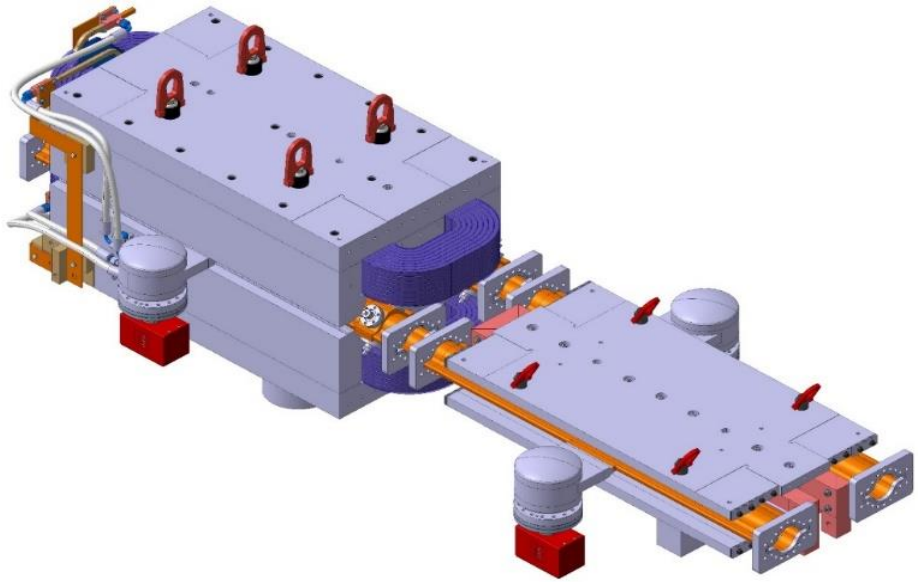
Arc layout and integration optimization

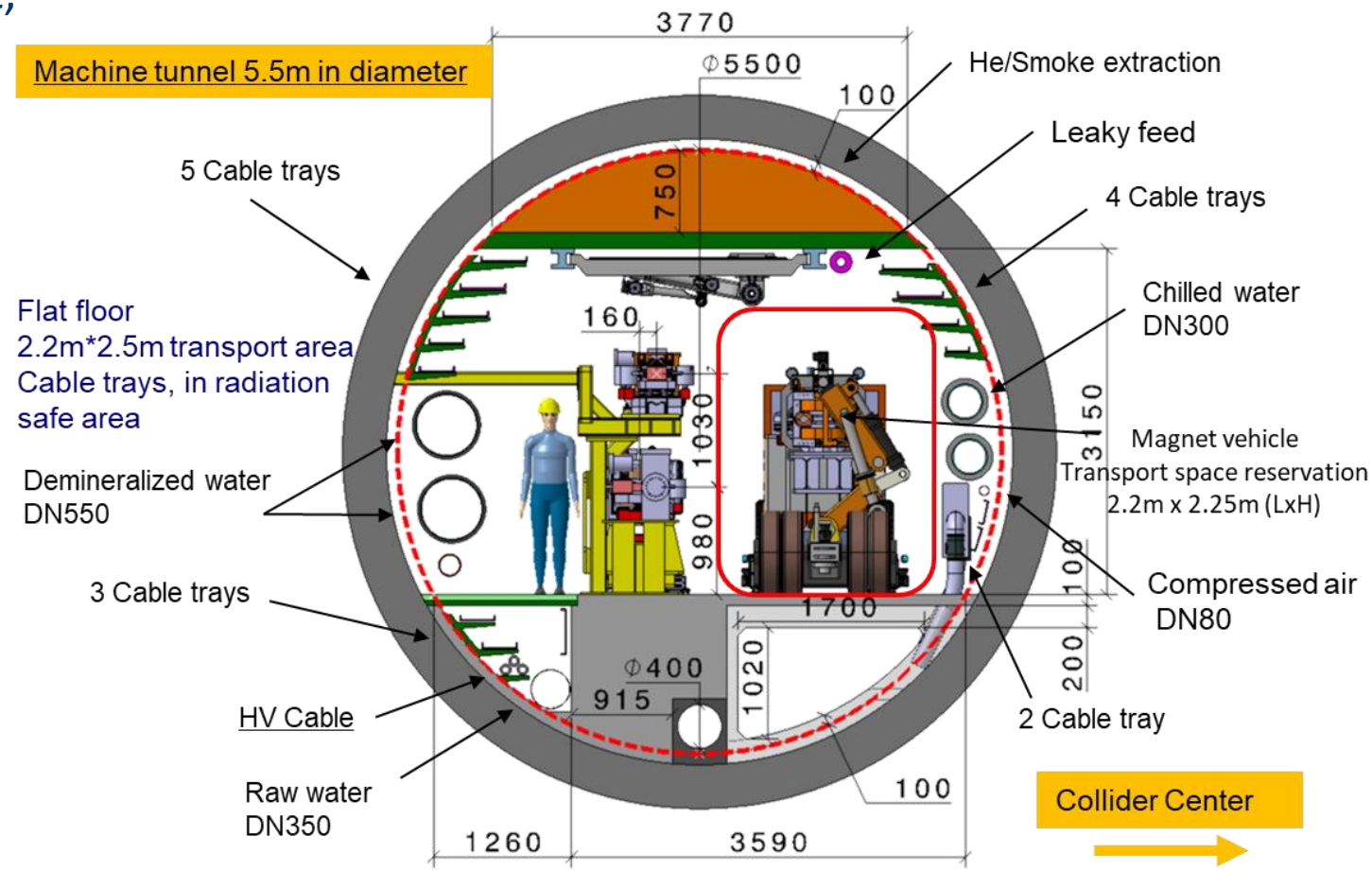
Arc cell optimisation – 80 km total length, dedicated working group active.

- Including support, girder and alignment systems, shielding systems
- vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs,
- cabling, cooling & technical infrastructure interfaces.
- Safety aspects, access and transport concept,

→ **Confirmation of tunnel diameter**

FCC-ee arc half-cell mock up





F. Carra, CERN; F. Valchkova

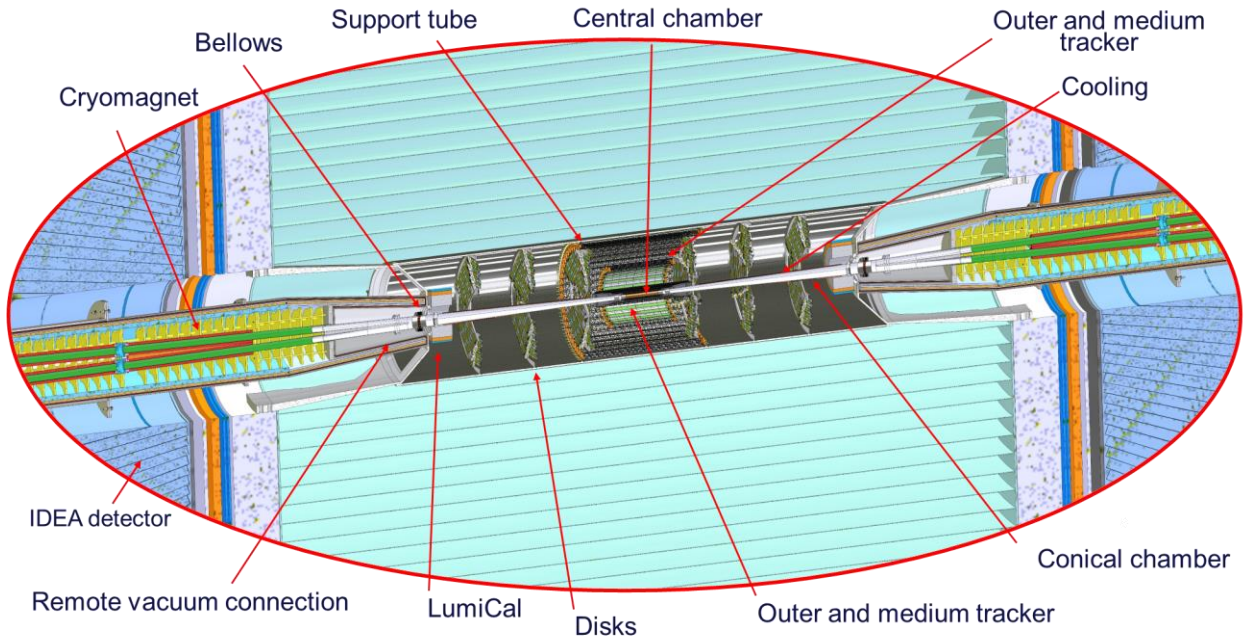
Machine detector interface

Key topics:

- SC IR magnet system &Cryostat design
- 3D integration
- IR mock-up / INFN

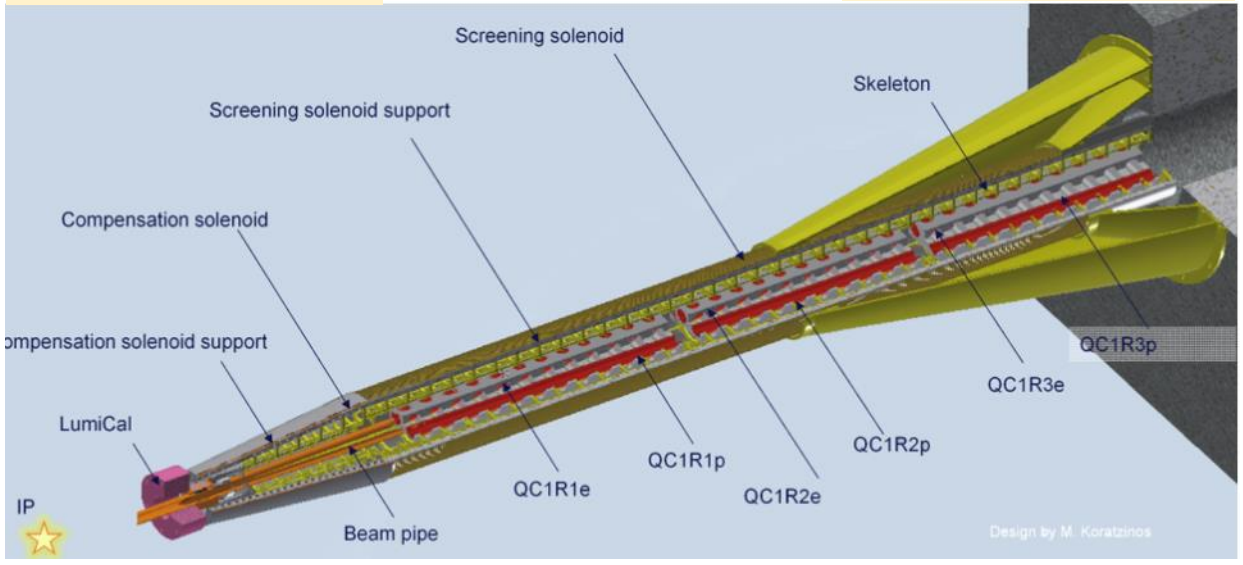
Machine		FCCee	CEPC	ILC	SuperKEKB
Crossing-angle	mrad	30	33	14	83
L*	m	2.2	1.9	3.5	0.935
Vertical β_y* at IP	mm	0.7-1.6	0.9-2.7	0.4	0.3
Detector soln field	T	2/3	3	3.5/5	1.5
Detector stay clear	mrad	100	118/141	90	350/436
Two beam ΔX at L*	mm	66	62.7	49	77.6
He temperature	K	1.9	4.2	4.5	4.5

M. Koratzinos, PSI



M. Boscolo, F. Palla, INFN

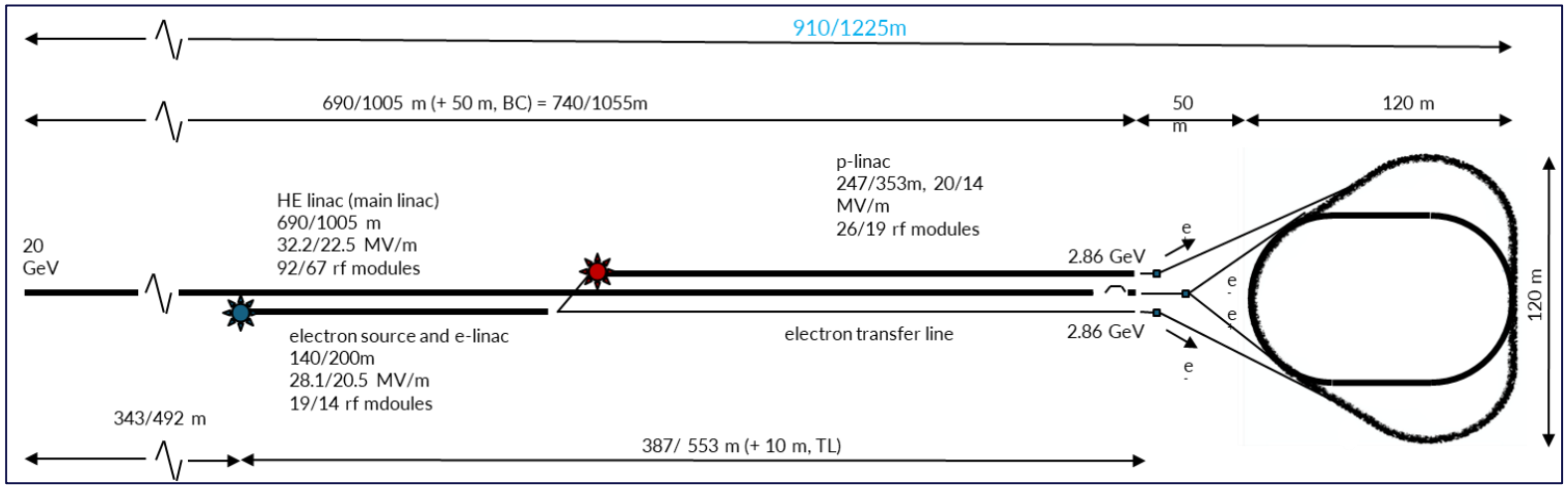
J. Seeman, SLAC
P. Tavares , CERN



FCC-ee Injector

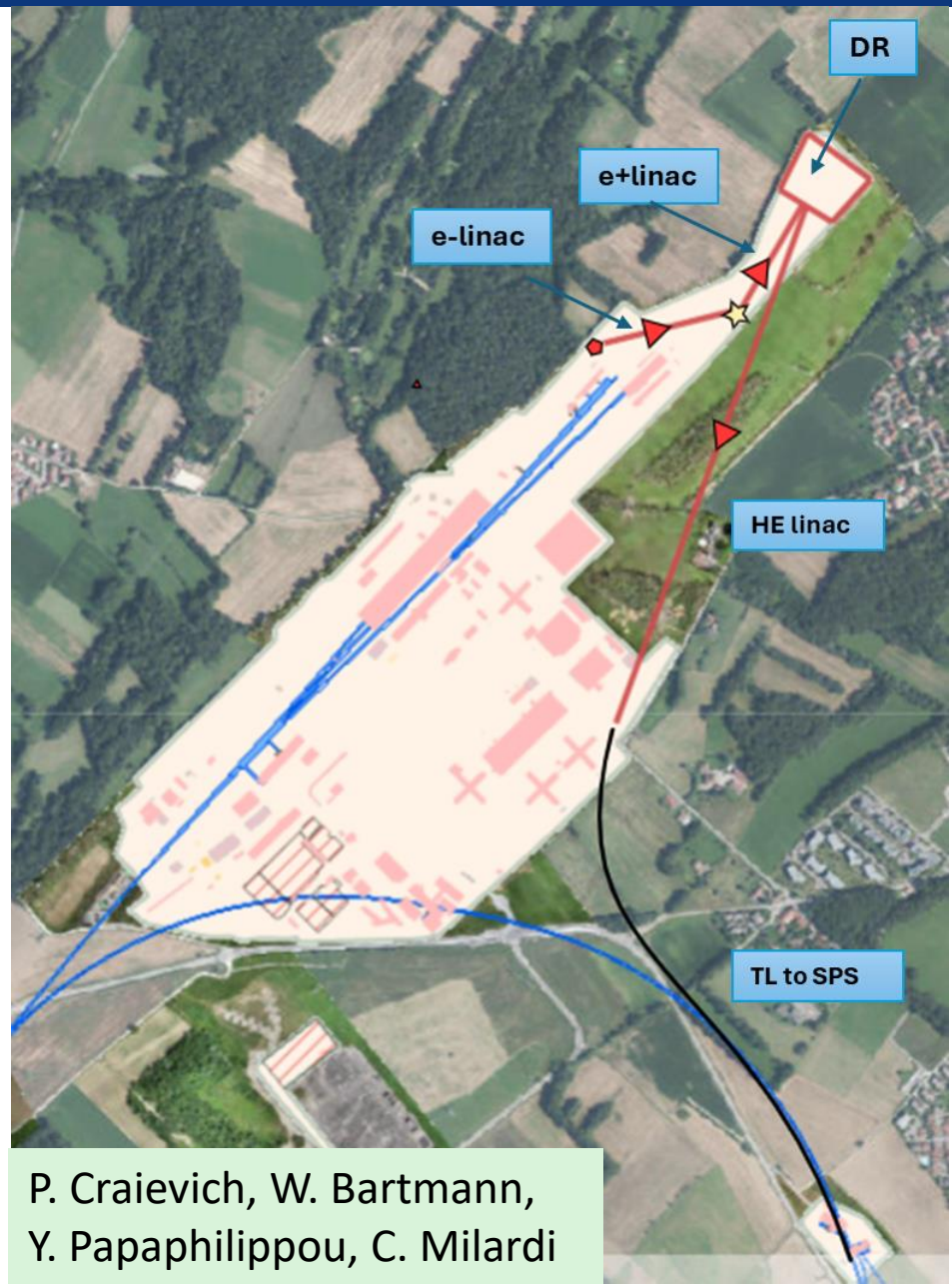
Overall injector parameter optimisation, following mid-term review recommendations

- Operation frequency, operation gradient vs number of structures/overall length
- Positron production energy, damping ring energy



Injector layout and implementation study on CERN Prevessin Site

- Technical infrastructure pre-design & integration with services at Prevessin site
- Injector cost estimate update



P. Craievich, W. Bartmann, Y. Papaphilippou, C. Milardi

FUTURE CIRCULAR COLLIDER

FCC-hh main machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significant amount of time for high-field magnet R&D, aiming at highest possible collision energies

- Target field range for cryo-magnet R&D

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
- ❑ optimization of energy consumption: → R&D on cryo, HTS, beam current, …

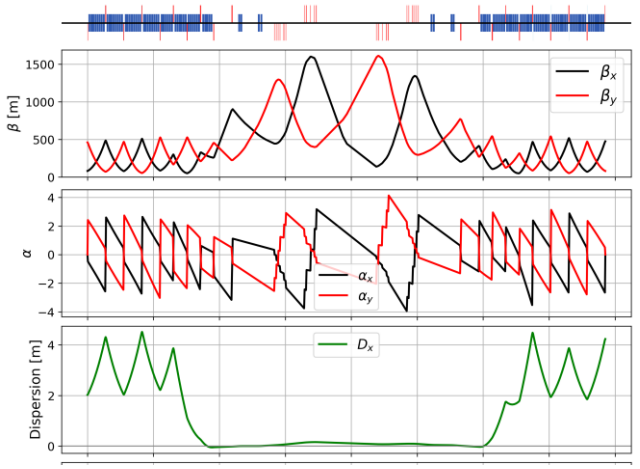
Formidable physics reach, including:

- ❑ 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

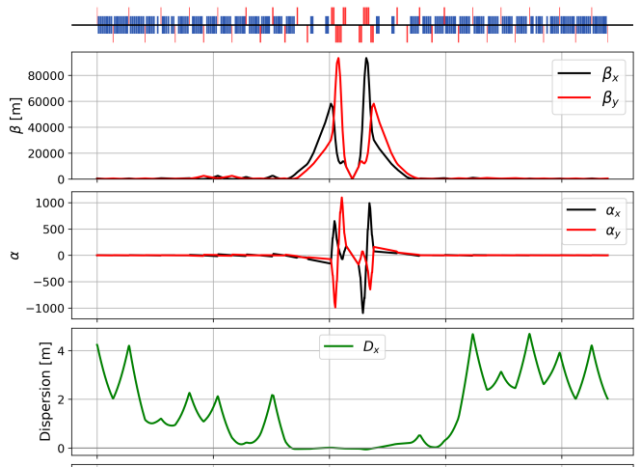
Key activities on FCC-hh: cryo magnet system, optics design

Optics design activities:

- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)

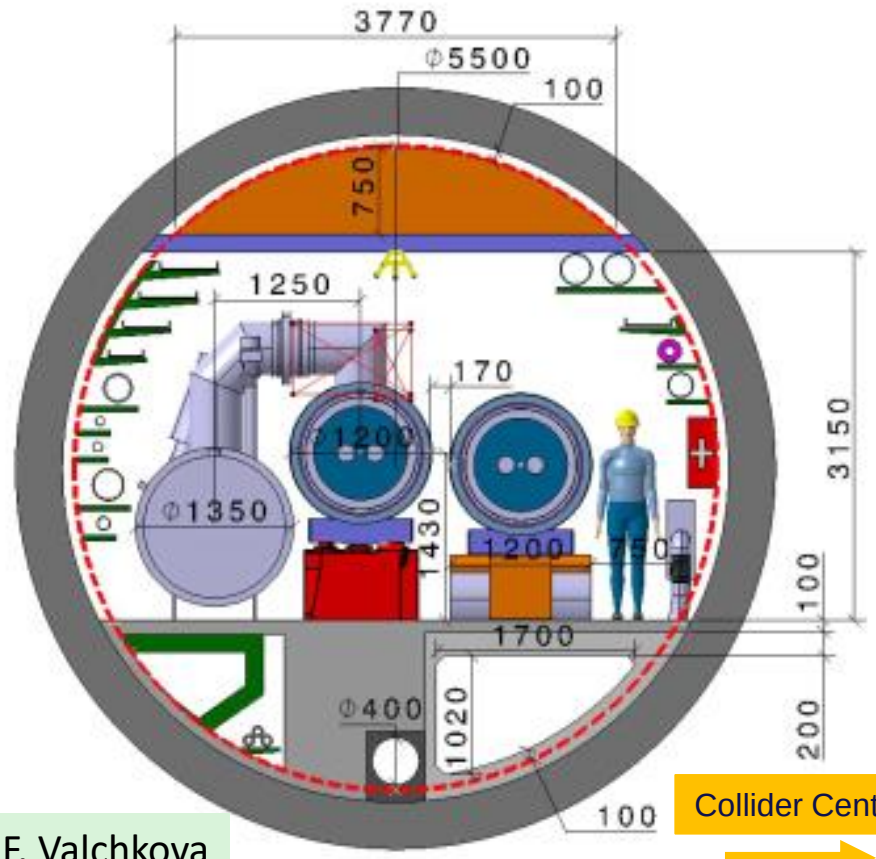


betatron collimation straight



experimental straight

M. Giovannozzi. G. Perez, T. Risselada



F. Valchkova

High-field cryo-magnet system design

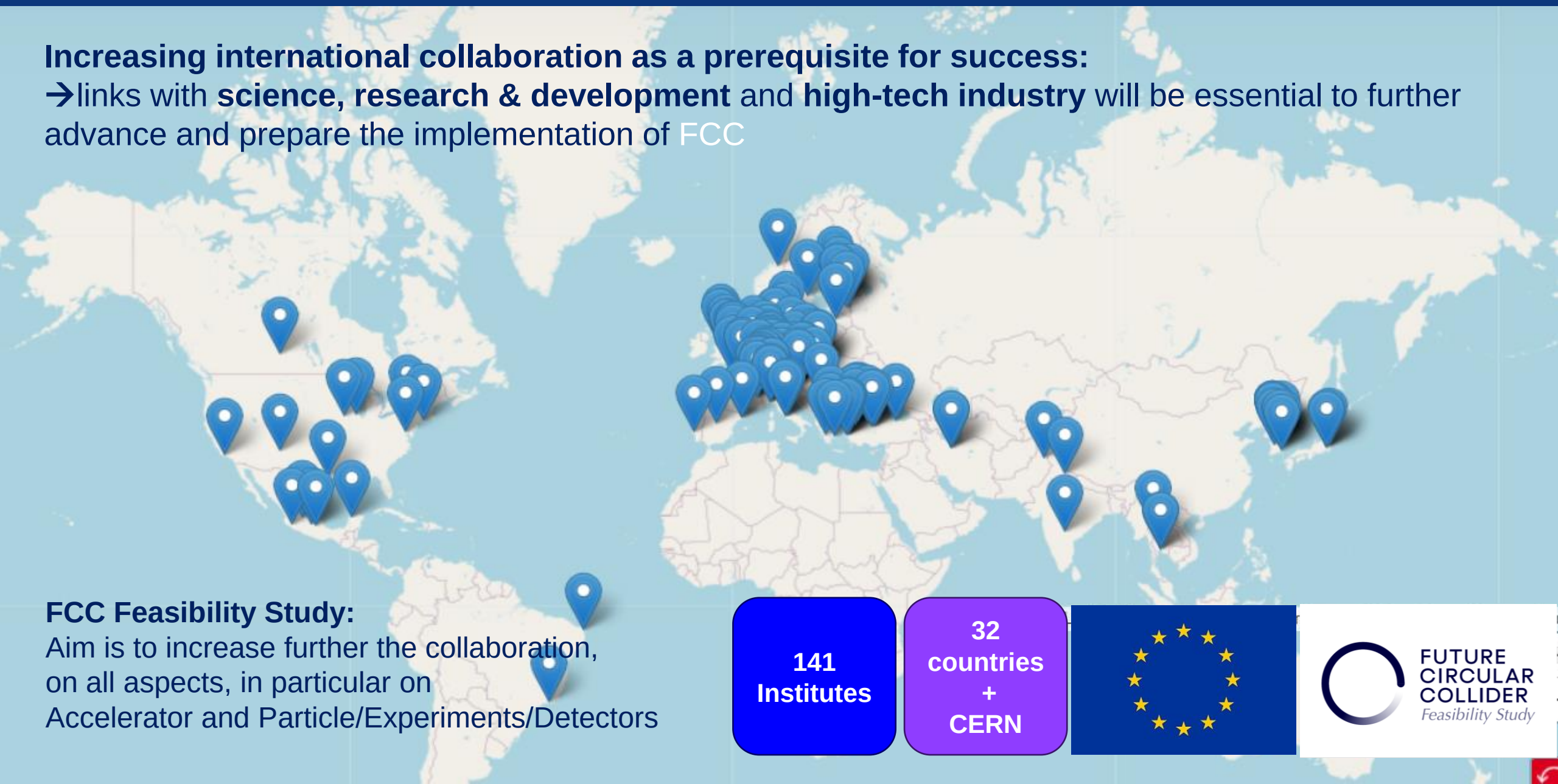
- Conceptual study of cryogenics concept and temperature layout for LTS and HTS based magnets, in view of electrical consumption.
- Update of integration study for the ongoing HFM designs and scaling to preliminary HTS design.

  → **Confirmation of tunnel diameter!**
- HFM R&D (LTS and HTS) on technology and magnet design, aiming also at bridging the TRL gap between HTS and Nb_3Sn.

FUTURE CIRCULAR COLLIDER

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



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

141 Institutes

32 countries + CERN

FUTURE CIRCULAR COLLIDER
Feasibility Study

FUTURE CIRCULAR COLLIDER

FCC Main Goals for Coming Years

- **The first part of the FCC Feasibility Study has been concluded with the mid-term review**
- **Next milestone: completion of the FCC Feasibility Study by March 2025**
- **By 2027-2028, possible FCC project approval, start of CE design contract:**
  - specifications to enable CE tender design by 2028
  - refined input for environmental evaluation and project authorisation process
  - requires overall integration study and designs based on technical pre-design of accelerators, technical infrastructure and detectors
- **By 2031-32, possible start of CE construction:**
  - CE groundbreaking
  - TDR to enable prototyping, industrialization towards component production
- **Strong collaboration with US and further international partners is essential for success!**

FCC Week 2024

- **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!**

- **Many thanks to all participants and committee members for joining, I wish everybody a productive and fruitful week with lots of progress towards completing the FCC Feasibility Study.**