FCC

Future Circular Collider (FCC) - Feasibility Study Status

SY FCC Workshop, 4 October 2024

Michael Benedikt, CERN
on behalf of FCC collaboration & FCCIS DS team
with particular thanks to the FCC Coordination Group

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 | FUTURE CIRCULAR COLLIDER | FCC hh ee he

*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

Intended contents

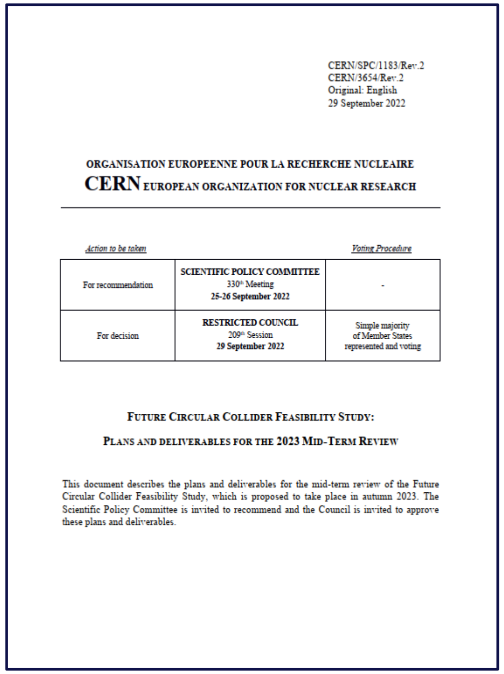
- FCC timeline and progress with mid-term review recommendations
- Present baseline, machine parameters and optics; is a major evolution needed/expected in the pre-TDR phase?
- Expectations and priorities for the pre-TDR phase in terms of machine design, equipment design, and R&D for SY systems; in particular, which level of detail is expected for system/equipment design?
- Strategy for the project work organisation, interfaces, processes and WBS for the pre-TDR phase (2025-2027) and afterwards (from 2028), in particular: how are equipment groups/specific study groups present/represented in the overall structure? formalization of work packages? is a second-layer management below the pillar management needed/foreseen?
- Technical baseline and change management process: how is all the information collected across equipment groups/study groups? which bodies take decisions? how are decisions documented and communicated to equipment/study groups? Interplay between accelerator design and technical design?

1. FCC timeline and progress with mid-term review recommendations

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.

FCC Scientific Advisory Committee

Riccardo Bartolini (DESY), Alain Chabert (Société Française du Tunnel Routier Fréjus), Heinz Ehrbar (HEP), Brigitte Fargevieille (Électricité de France), Belen Gavela Legazpi (UAM), Gudrun Hiller (Dortmund), Srinivas Krishnagopal (BARC), Peter Krizan (Ljubljana), Philippe Lebrun (CERN, retired), Peter McIntosh (STFC), Michiko Minty (BNL), **Andrew Parker** (**Chair**, Cambridge), Kyo Shibata (KEK), Roberto Tenchini (Pisa)

FCC Cost Review Panel

Carlos Alejaldre (Fusion for Energy), Austin Ball (CERN, retired), Umberto Dosselli (INFN), Heinz Ehrbar (HEP) Vincent Gorgues (CEA), **Norbert Holtkamp** (**Chair**, Stanford), Christa Laurila (National Audit Office, Finland), Ursula Weyrich (German Cancer Research Centre), Jim Yeck (BNL), Thomas Zurbuchen (ETH Zürich)

FUTURE CIRCULAR COLLIDER

FCC Feasibility Study mid-term report

Full Report
8 Chapters/Deliverables
~ 700pp document
~ 16 editors
~ 300 contributors

Executive Summary
8 Chapters/Deliverables
~ 45pp document
~ 16 editors

Both documents are available to the CERN community at:
https://doi.org/10.17181/mhas5-1f263

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

This project has received funding under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

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.

Executive Summary of the
Future Circular Collider
Midterm Report

February 2024

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

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Please note that the midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people without direct access to this page.

You are kindly asked to treat the information with the appropriate level of confidentiality, as defined in the CERN Data Protection Policy.

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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

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

Analysis of mid-term review recommendations from SAC, CRP, SPC, FC and Council (i)

Until/for Feasibility Study March 2025:

- ✓ **Increase resources of FCC FS team (SAC, FC, SPC)**
- **Establish pre-project team to significantly improve confidence in design and cost estimate (CRP)**
- **Ramp-up accelerator R&D and design (CRP)**
- Destination of excavated materials (SAC, FC, SPC)
- CO2 footprint for entire civil engineering project (SAC, SPC, Council)
- ✓ **Decision on FCC-ee injector system (SAC, SPC) and cost (CRP)**
- **Baseline on FCC-hh injector system (SAC, SPC)**
- ✓ **Avoid different RF systems for Z and W/H (SAC)**
- ✓ Decide to have 4 experiments (SAC)
- ✓ Clarify logistic (safety) for a 10 km-long 5.5m-diameter tunnel (CRP)
- Perform safety risk analysis with external consultant (SPC)
- Add missing items (at least energy storage) to cost estimates (CRP)
- Take conservative approach to cost estimate for C&V (CRP)
- **Emphasize system integration and interfaces between work packages (CRP)**
- Reach tripartite agreement with Host States by mid-2024 (CRP, SPC)
- ✓ Reservation of the land for surface sites (SPC)

Analysis of mid-term review recommendations from SAC, CRP, SPC, FC and Council (ii)

For Feasibility Study March 2025:

- Develop various funding models with uncertainties (FC)
- Provide information of potential contributions from outside CERN Budget (FC)
- Provide sensitivity of funding model to CVI > 2% and how to absorb it.
- **Provide FCC-hh cost (although with less precision than for FCC-E) (FC, SPC)**
- State cost of FCC-ee due to preparation for FCC-hh (FC)
- Include a full risk analysis and management in the final FS report (FC, Council)
- ✓ Model for future electricity prices (SAC)
- Sustainable electricity supply concept (FC, Council)
- Detail OPEX costs in the funding model and include cost of land acquisition, equipment installation, second campus, etc. (FC)
- ✓ Identify opportunities for heat recovery to the benefit of local use (SAC)
- Reduce cost uncertainty on CE as much as possible and remove uncertainty on tunnel diameter (FC).
- Innovative procurement mechanism for civil engineering, allowing early interactions (CRP)
- Include cost of experiments and their operation in the funding model (FC, SPC)
- Develop human resources model and impact on Pension Fund (FC)
- Communication campaign with local population, including physics case, socio-economic benefits (SAC, FC, SPC)

Analysis of mid-term review recommendations from SAC, CRP, SPC, FC and Council (iii)

For Feasibility Study March 2025:

- **Clarify LHC role in the FCC-ee era (FC)**
- Financial implications of the various operational sequences and e.g. running at H peak (FC, SPC)
- **For final report provide well-defined baseline layout for all aspects of the FCC ee machine (SPC)**
- **Provide well-understood and prioritized R&D plan for FCC-hh in the final FS report (SPC)**
- Develop roadmaps for LTS & HTS magnets for FCC-hh and include report on HFM about FCC-hh feasibility (SPC)
- **Provide more detailed construction schedule for tunnel and accelerator (SPC)**
- **Provide more info on the reliability of the simulation of transport and logistics for installation phase (SPC)**
- **Workshop to further define accelerator scope, define interfaces, identify missing scope/cost (CRP)**
- **Include FTEs needed for R&D, design and construction phases (SPC)**
- Provide more flexible funding model in terms of cash vs in-kind contributions (SPC)
- More emphasis on discovery potential through precision measurements in particular at the Z-pole (SPC)
- Explain importance of ttbar running (SPC)
- ✓ Demonstrate that size of two “small caverns” is ok for FCC-hh programme (SPC)
- ✓ Studies of comparable cases of tunnels in molasse and increase exchanges other large tunnels projects (CRP)
- For final report, use more full simulation for physics studies (SPC)
- Discuss return to Member States, not just to Host States (Council)

Analysis of mid-term review recommendations from SAC, CRP, SPC, FC and Council (iv)

For 2027-2028, project approval, start of CE design contract:

- Compensation for the land used at surface sites (SAC)
- CO2 footprint over full project lifecycle (SAC, SPC, Council)
- **Environmental impact and sustainability (FC, Council)**
- **Discuss sustainability issues for FCC-hh (SPC)**
- Communication campaign with local population, including physics case, socio-economic benefits (SAC, FC, SPC)
- **SCRF performance improvement (Q and gradient) (SAC)**
- R&D on NEG coating to reduce risks (SPC)
- **Procedures for conservation of He (SAC)**
- Sensitivity to commodity prices (SAC)
- **Continue to develop benchmarks as reference for FCC-ee cost (CRP)**
- Revisit CERN's procurement policies and learn for other big facilities to ensure balanced industrial return without increasing cost (FC)
- **Risks of not achieving FCC-ee luminosity (SPC)**
- Provide discussions of additional science (dark sector, forward physics, etc.) (SPC)

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Analysis of mid-term review recommendations from SAC, CRP, SPC, FC and Council (vi)

For 2031-32, start of CE construction:

Heat recovery to the benefit of local use technical implementation (SAC)

FCC-hh magnet R&D (SAC)

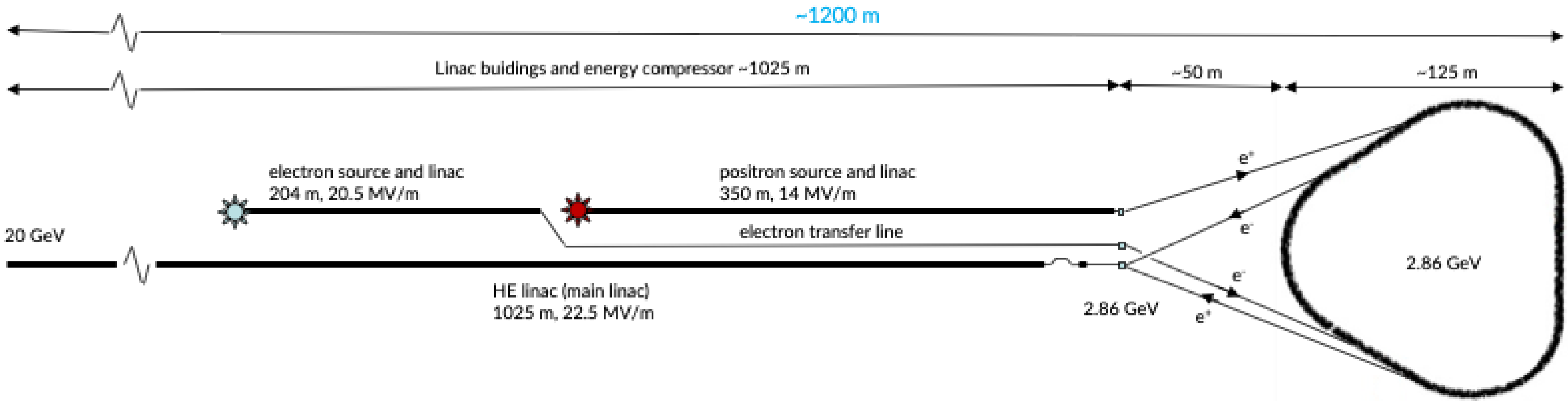
Theory work for FCC-ee precise calculations (SAC)

Work with the community and funding agencies to ensure support for 4 experiments (CRP)

Evaluate pros/cons of commercial vs in-house systems for controls (SPC)

Optimized injector concept and parameters

- **Mid-term review recommendations to reduce gradients and repetition rate → new linac optimization in terms of cost and power density and new injector overall layout**
  - Overall power consumption (for linacs) is reduced by **more than a factor 3** by means of:
    - new accelerating structures with higher shunt impedance;
    - lower gradient (29.5 MV/m → 22.5/20.5 MV/m);
    - lower repetition rate (200/400 Hz → 100 Hz).
  - Repetition rate of **100 Hz with 4 bunches** per rf pulse
  - New layout: **Damping Ring at higher energy 2.86 GeV**, no common linac with 2x repetition rate.

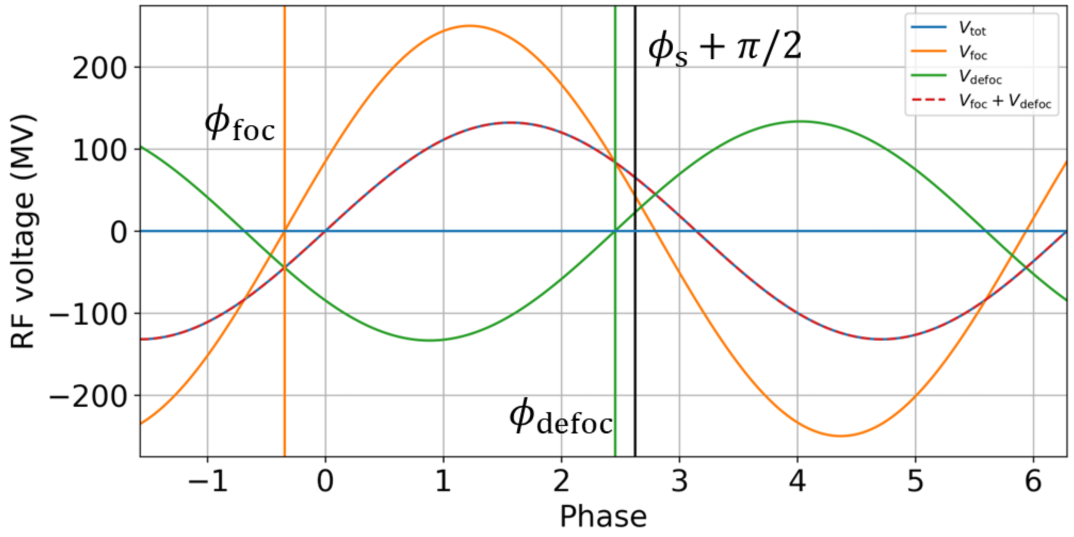


400 MHz SRF progress – one system for 3 energies

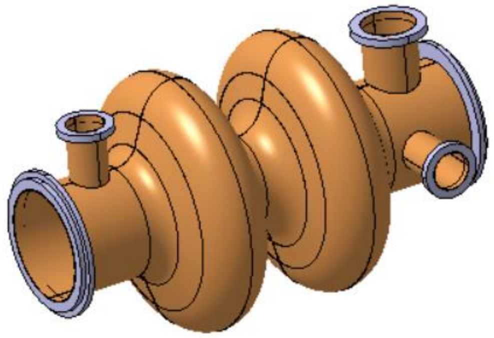
Same two-cell RF cavities for Z, WW and ZH operation with constant cavity coupling thanks to **reverse phase operation**: (1) experimentally verified w high beam loading at KEKB *(Y. Morita et al., 2009)*, (2) Baseline solution US EIC

- No longer any 1-cell 400 MHz cavities
- Reduced installation time
- Reduced commissioning effort
- Fast switching between Z, WW and ZH operation

RF waves



400 MHz cavities



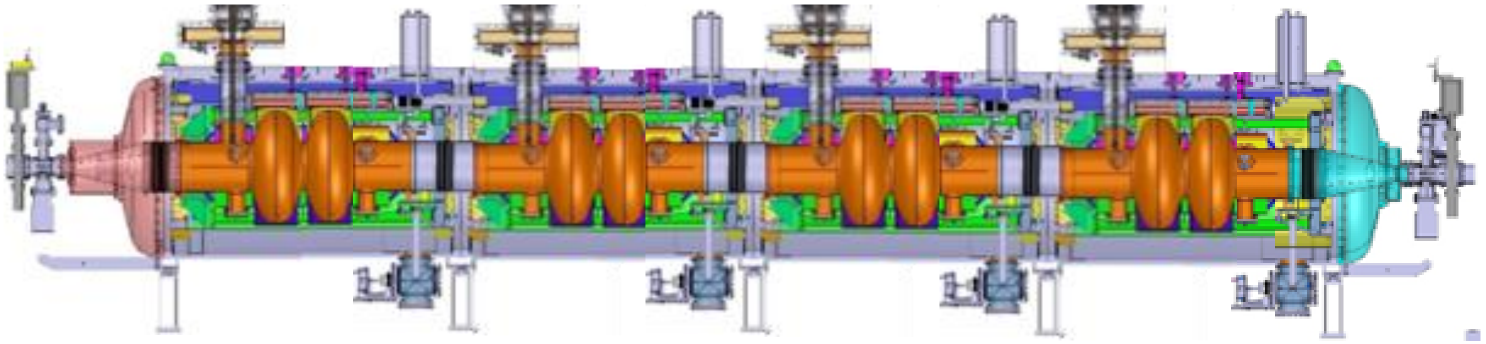
Z, W, ZH

X 264

400 MHz 2-cell cavity
Niobium thin film on Copper,
Operation at 4.5 Kelvin
Max. accel. gradient E_{acc} = 13 MV/m
Quality factor Q_0 = 3.3 x 10^9

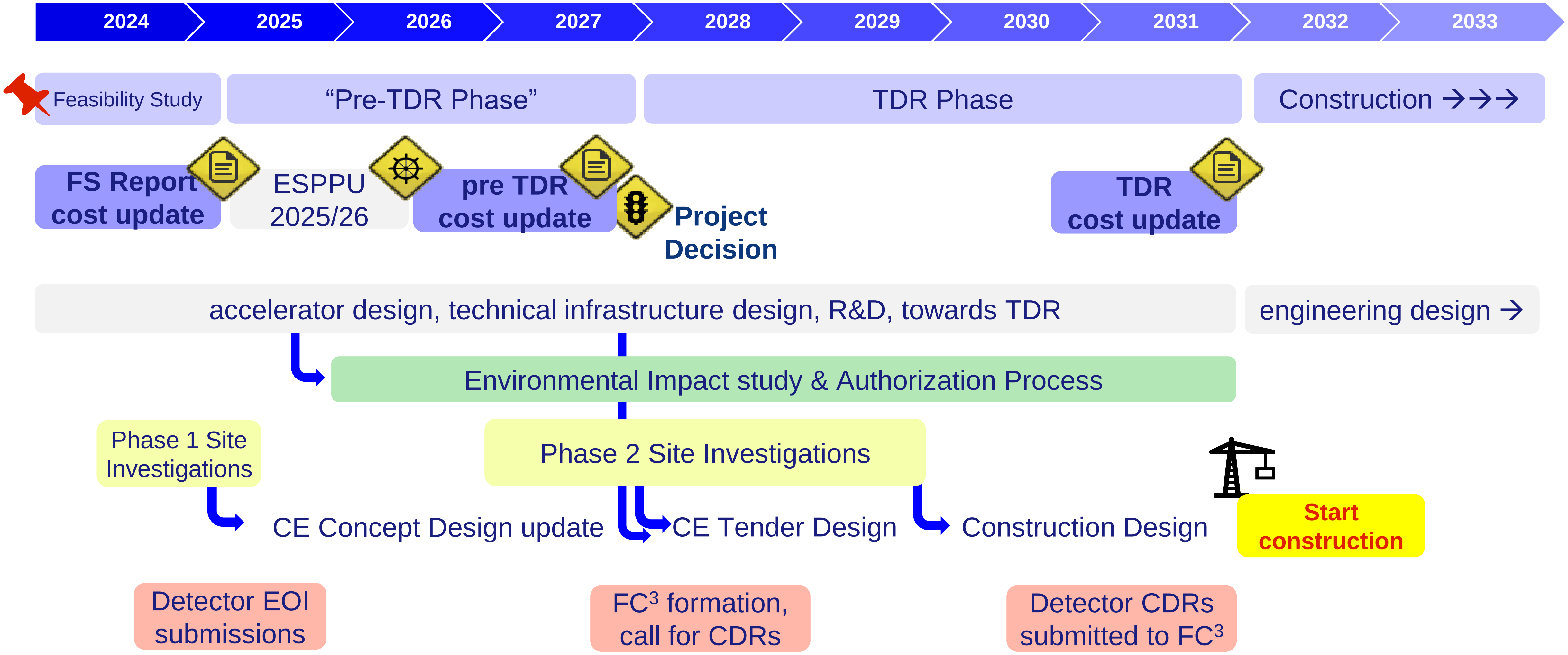
cryomodule

X 66



400 MHz cryomodule, ~12 m long

Timeline till start of construction



FC³ = Future Circular Collider Committee

2. Present baseline, machine parameters and optics; is a major evolution needed/expected in the pre-TDR phase?

Present baseline, machine parameters and optics for FSR

Parameters and optics: the same as for mid-term review

- GHC optics (K. Oide), different cell length for Z, WW & ZH, ttbar
- integration of inj.extr., RF & collimation sections in progress (G. Roy)

Possible future evolution

- same optics for Z, WW & ZH (less magnet & cables, greater flexibility)
- switch to LCC optics (P. Raimondi)
- developments of hybrid LCC/GHC optics
- modified IR optics w/o antisolenoid

FCC-ee: MTR main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

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

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

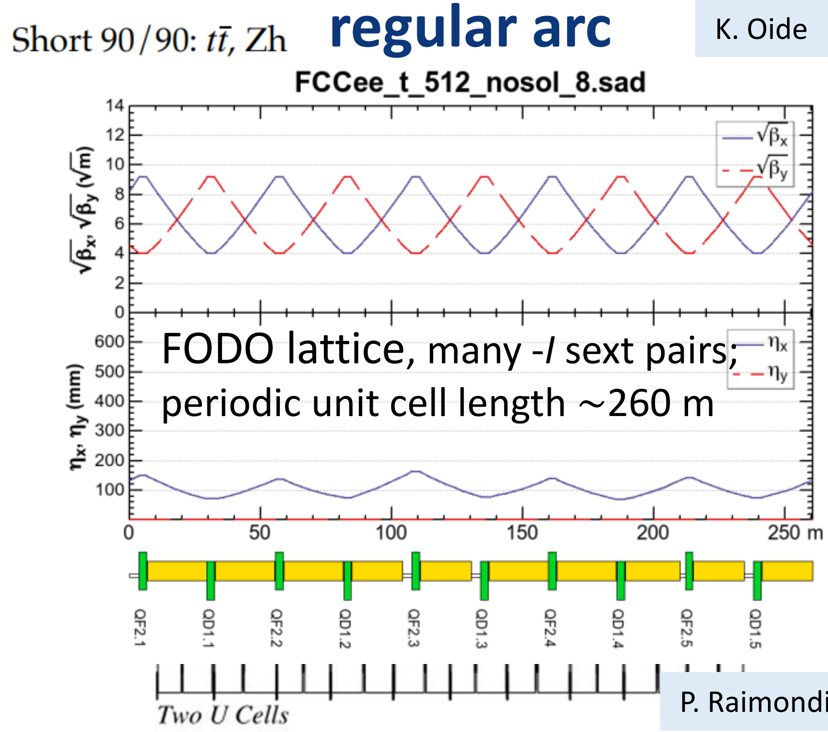
Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

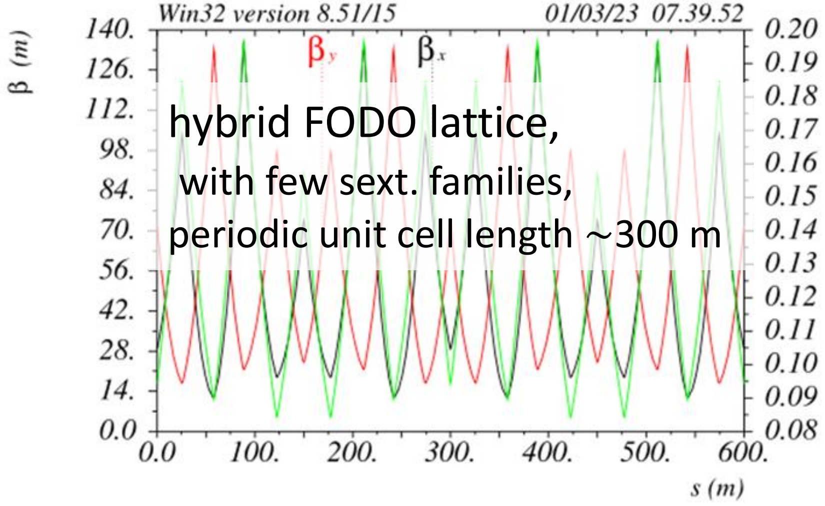
FCC-ee optics baseline & possible further evolution(s)

regular arc

K. Oide

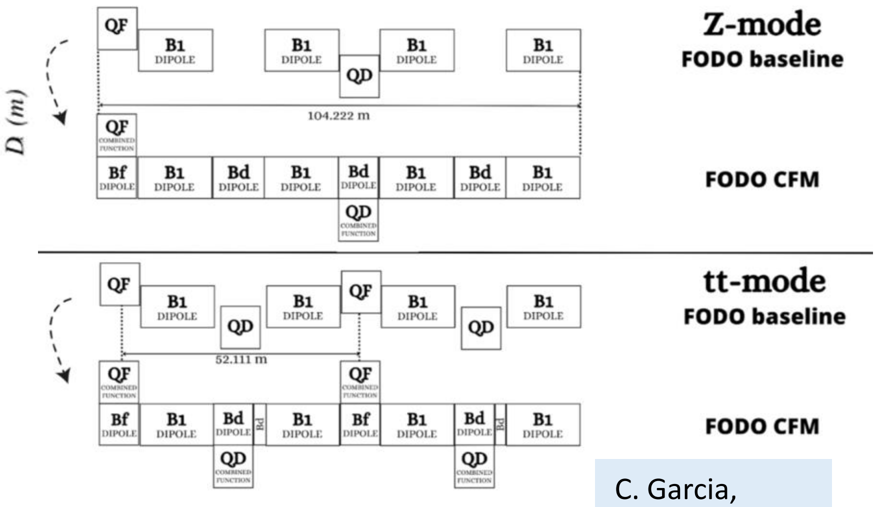


P. Raimondi



optimisation goals:

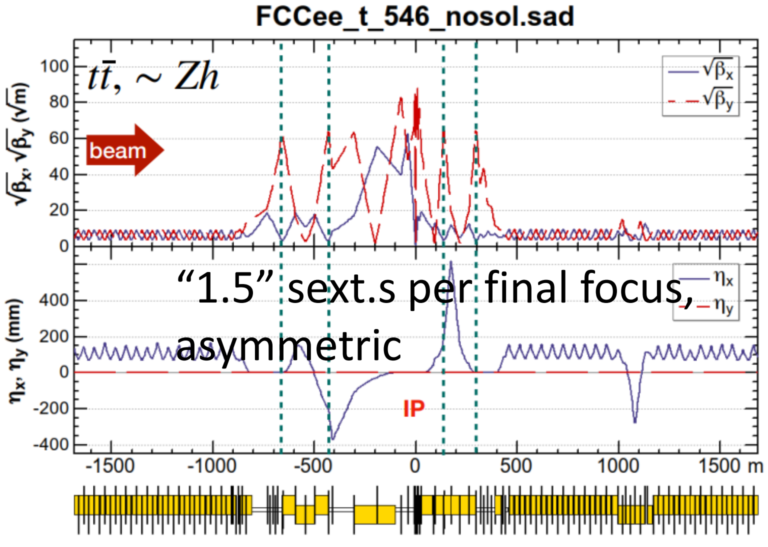
- reduced power consumption
- lower SR energy loss
- increased momentum acceptance
- relaxed tolerances
- larger dynamic aperture
- simplified powering schemes



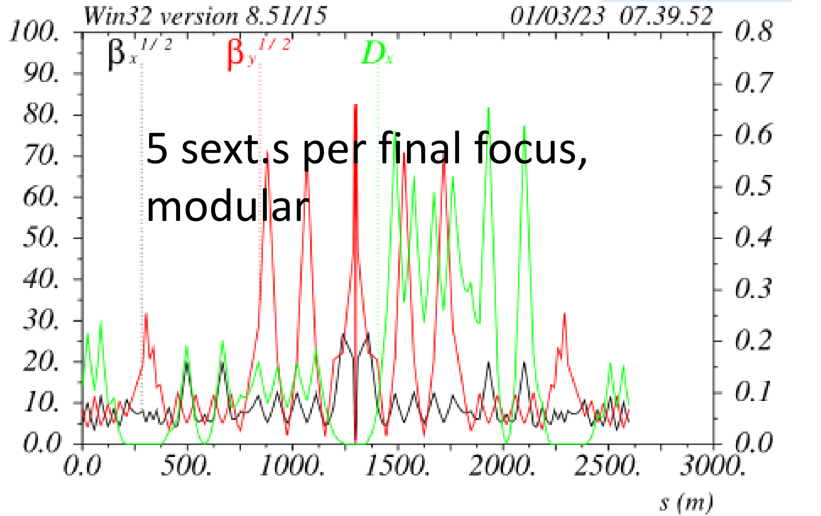
C. Garcia,
R. Tomas, et al.

interaction region

K. Oide



P. Raimondi



3. Expectations and priorities for the pre-TDR phase in terms of machine design, equipment design, and R&D for SY systems; in particular, which level of detail is expected for system/equipment design?

Expectations for 2027 – civil engineering side

- Requirements from accelerator and technical infrastructure for CE design
  - By mid 2027 we will need to start the next phase of the site investigation. This means the alignment and layouts of all underground areas must be frozen otherwise drillings would be in the wrong places… (a metre or two would not make much difference).
  - In mid-2027 we would also be signing the contract(s) with the consultants who would do the next phase of design and prepare all the tender documents for the CFT for contractors.
  - Therefore we would need to have a new baseline with the internal dimensions of all CE structures defined (space requirements).
  - We would also need upper bound values for major loads e.g. detector mass, loads on the tunnel floor, loads on the walls etc. These could be reasonable upper bound numbers.
  - We would also need improved surface building requirements, mainly space requirements (height, length, width), Floor loads (upper bound) and crane loads and numbers of cranes (again best estimate upper bound).

Expectations for 2027 – accelerator side

- Adequate level of technical design for long-lead items and items with significant impact on cost and/or performance. → Input for project decision
- Concepts defined for all technical systems/elements to enable full integration work, R&D steering, technical infrastructure specifications, etc.
  - prototype 2-cell 400 MHz SRF cavity
  - prototype high efficiency klystron or IOT at 400 MHz
  - cryomodule designs for 400 & 800 MHz
  - prototype electrostatic+magnetic separators
  - design and integration of radiation shielding system(s)
  - BLM system concept proven
  - BPM design and prototype

Expectations for 2027 – territorial implementation side

- Adequate description of the entire project to enable launching authorization procedures with host states.

- Adequate level of concept/technical design of all technical infrastructures and technical systems/elements with impact on environment to enable evaluation processes with host state authorities.

4. Strategy for the project work organisation, interfaces, processes and WBS for the pre-TDR phase (2025-2027) and afterwards (from 2028),
in particular:

- how are equipment groups/specific study groups present/represented in the overall structure?
- formalization of work packages?
- is a second-layer management below the pillar management needed/foreseen?

Project work organisation for pre-TDR phase 2025 – 2027 (i)

- Keep overall project structure similar to feasibility study phase

- Organisation structure on accelerator and technical infrastructure side:
  - Accelerator Pillar with sub-structure (2^{nd} layer below pillar)
    - Accelerator Technical Design (technical elements), following more or less CERN structure
    - Accelerator Design (optics and operation),
    - Injector Project (integrating also TI and CE aspects)
    - Transfer lines
    - FCC-hh Design
  - Technical infrastructure Pillar (no 2^{nd} layer below pillar), following more or less CERN structure

- Additional working groups (partially ad-hoc) with specific mandates on topics with transverse character e.g. machine protection, synchrotron radiation shielding

Project work organisation for pre-TDR phase 2025 – 2027 (ii)

- Development of work program, planning and resource needs for pre-TDR phase and beyond with equipment groups and collaboration partners
  - “Reverse schedule” from T0 (start of equipment installation) with main preceding development phases and milestones and requirements for external input from ALL domains.
  - Iterations to derive an integrated overall work plan, schedule and resource estimate.

- Further discussion on organization structure (probably) with next management.

- Structure after completion of pre-TDR, i.e. from 2028 will depend on potential project decision.
  - To be developed with next management in parallel to EPPSU, council discussions, etc.

FCC overall organigram

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FCC Feasibility Study

EU Projects
NN

Collaboration building
Emmanuel Tsesmelis

Communications
Panagiotis Charitos, Arnaud Marsollier

Study Support and Coordination
Study Leader: Michael Benedikt
Deputy Study Leader: Frank Zimmermann

Study Support Unit
IT: Sylvain Girod
Procurement: Adam Horridge
Quality management: Beatriz Arias
Resources: Sylvie Prodon
Secretariat: Julie Hadre

Physics, Experiments and Detectors
Patrick Janot, Christophe Grojean

- **Physics programme** — Matthew McCullough, Frank Simon
- **Detector concepts** — Mogens Dam, Marc-André Pleier, Felix Sefkow.
- **Physics performance** — Patrizia Azzi, Emmanuel Perez, Michele Selvaggi
- **Software and computing** — Gerardo Ganis, Brieuc François

Accelerators
Tor Raubenheimer
Frank Zimmermann

- **FCC-ee accelerator design** — Christian Carli, Frank Zimmermann
- **FCC-ee technical implementation** — Jean-Paul Burnet, Tor Raubenheimer
- **FCC-ee injector** — Paolo Craievich, Alexej Grudiev
- **FCC transfer lines** — Wolfgang Bartmann
- **FCC-hh design** — Massimo Giovannozzi

Technical Infrastructures
Jean-Paul Burnet
Klaus Hanke

- **Integration** — Jean-Pierre Corso
- **Geodesy & survey** — Hélène Mainaud Durand
- **Electricity and energy management** — Jean-Paul Burnet
- **Cooling and ventilation** — Guillermo Peon
- **Cryogenics systems** — Laurent Delprat
- **Computing and controls infrastructure, communication and network** — Pablo Saiz
- **Safety** — Thomas Otto
- **Operation, maintenance, availability, reliability** — Jesper Nielsen
- **Transport, installation concepts** — Roberto Rinaldesi

Host State processes and civil engineering
Timothy Watson

- **Administrative processes** — Friedemann Eder
- **Placement studies** — Johannes Gutleber
- **Environmental evaluation** — Johannes Gutleber
- **Tunnel, subsurface design** — John Osborne
- **Surface sites layout, access and building design** — A. Mayoux

Organisation and financing models
Florian Sonnemann

- **Project organisation model** — NN
- **Financing model** — Florian Sonnemann
- **Procurement strategy and rules** — Anders Unnervik
- **In-kind contributions** — Anders Unnervik
- **Operation model** — Verena Kain

5. Technical baseline and change management process:

- how is all the information collected across equipment groups/study groups?
- which bodies take decisions?
- how are decisions documented and communicated to equipment/study groups?
- interplay between accelerator design and technical design?

Technical baseline development and change management

- Work steering and information management via the main project meetings:
  - ATDC, ADC, TI Coordination, FCC CGM and FCC-Directorate meeting.
- Decision making and validation of baselines at adequate level of committees mentioned above.
- Interface management via dedicated persons in each of the main project meetings and via formalisation of requirement specifications PRIOR to major technical system design work.
- Decisions are discussed and communicated via above committees and documented in the relevant meeting minutes. Further documentation mid term report (9/23), feasibility study report (3/25), placement report (11/24), environmental report (3/25).
- Interplay between accelerator design and technical design to be organised via cross-attendance or committee chairs and key persons. Further mitigation as required at Pillar level or CGM level with integration of key persons
- Development of a project documentation and configuration management system during pre-TDR

Save the dates: 19 – 23 May 2025

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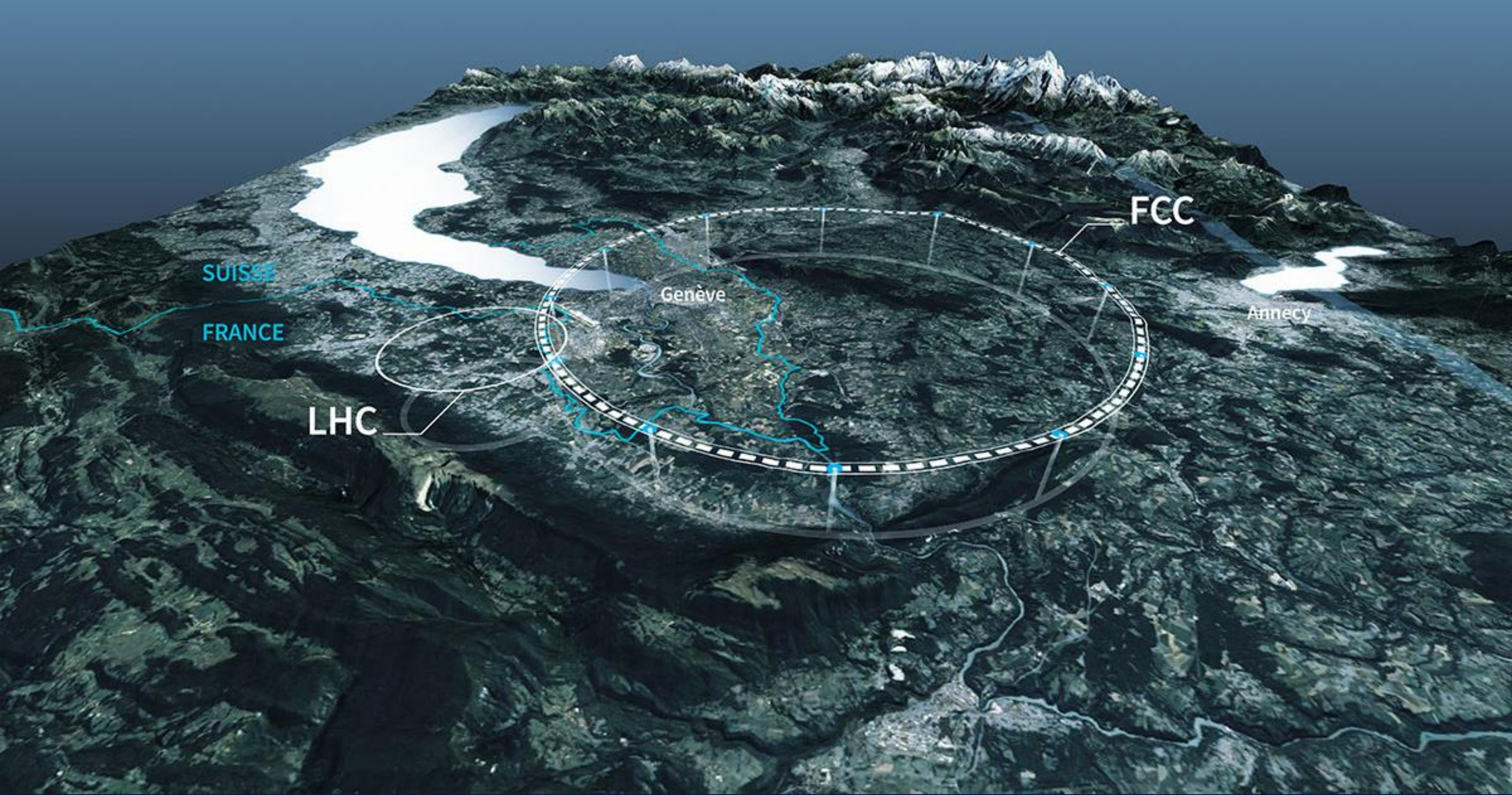
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SUISSE
Genève
Annecy
FRANCE
LHC