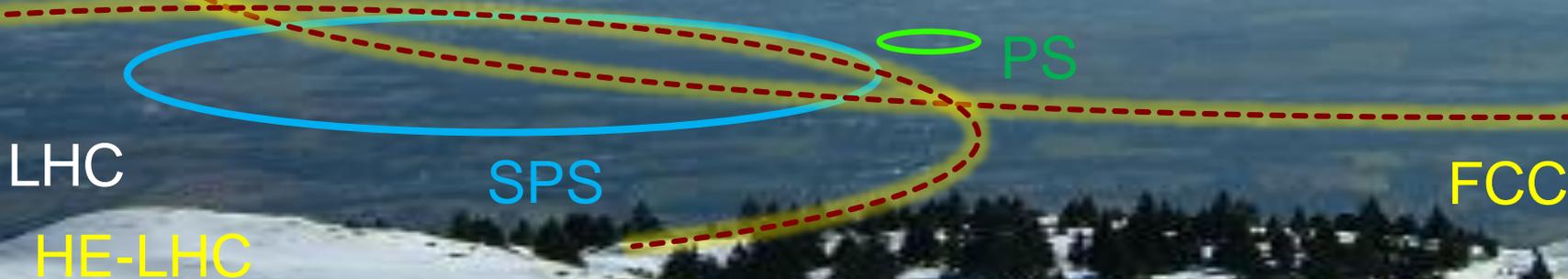


Overview and status of the Future Circular Collider Study

M. Benedikt, F. Zimmermann

gratefully acknowledging input from FCC coordination group,
global FCC design study team and all other contributors



European
Commission

Horizon 2020
European Union funding
for Research & Innovation

Work supported by the **European Commission** under the **HORIZON 2020** projects **EuroCirCol**, grant agreement 654305; **EASITrain**, grant agreement no. 764879; **ARIES**, grant agreement 730871; and **E-JADE**, contract no. 645479

- **Introduction to FCC study goals and organisation**
- **Results of FCC phase 1 conceptual design study and input to European Particle Physics Strategy Update (EPPSU)**
- **Next steps and outlook 2019 – 2026**



Summary: European Strategy Update 2013

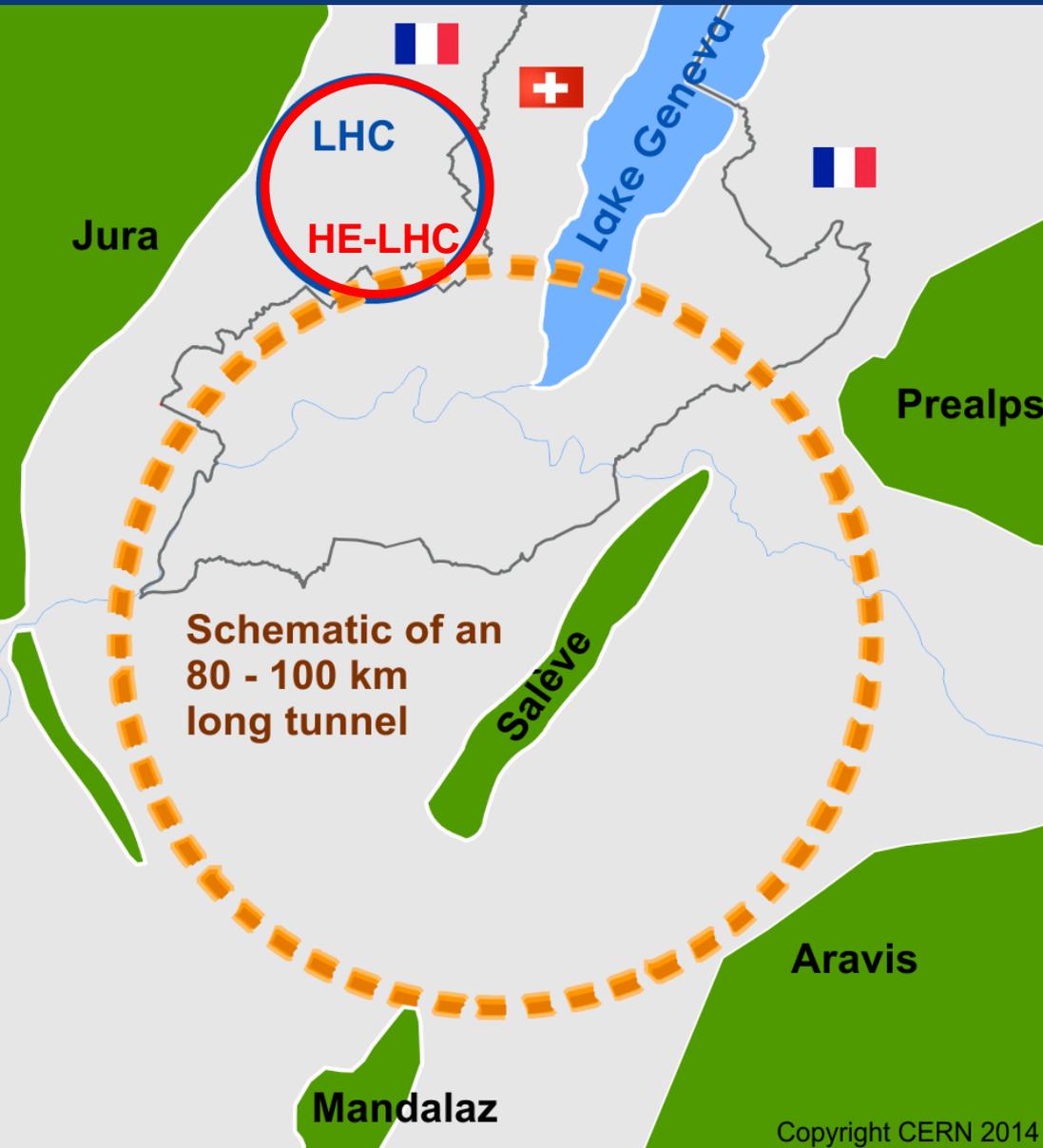
Design studies and R&D at the energy frontier

....“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

d) CERN should undertake design studies for accelerator projects in a global context,

- *with emphasis on proton-proton and electron-positron high-energy frontier machines.*
- *These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***
- **<http://cds.cern.ch/record/1567258/files/esc-e-106.pdf>**





International FCC collaboration with CERN as host lab to study:

- ~100 km tunnel infrastructure in Geneva area, linked to CERN
- e^+e^- collider (*FCC-ee*),
→ potential first step
- pp -collider (*FCC-hh*)
→ long-term goal, defining infrastructure requirements

~16 T \Rightarrow 100 TeV pp in 100 km

- HE-LHC with *FCC-hh* technology
- Ions and lepton-hadron options with hadron colliders



FCC : physics and performance targets

FCC-ee:

- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) (m_Z , m_W , m_{top} , $\sin^2 \theta_w^{\text{eff}}$, R_b , $\alpha_{\text{QED}}(m_Z)$, $\alpha_s(m_Z)$, $m_Z m_W m_\tau$), Higgs and top quark couplings)
- Exploring 10 - 100 TeV energy scale via couplings with precision measurements
- Machine design for highest luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

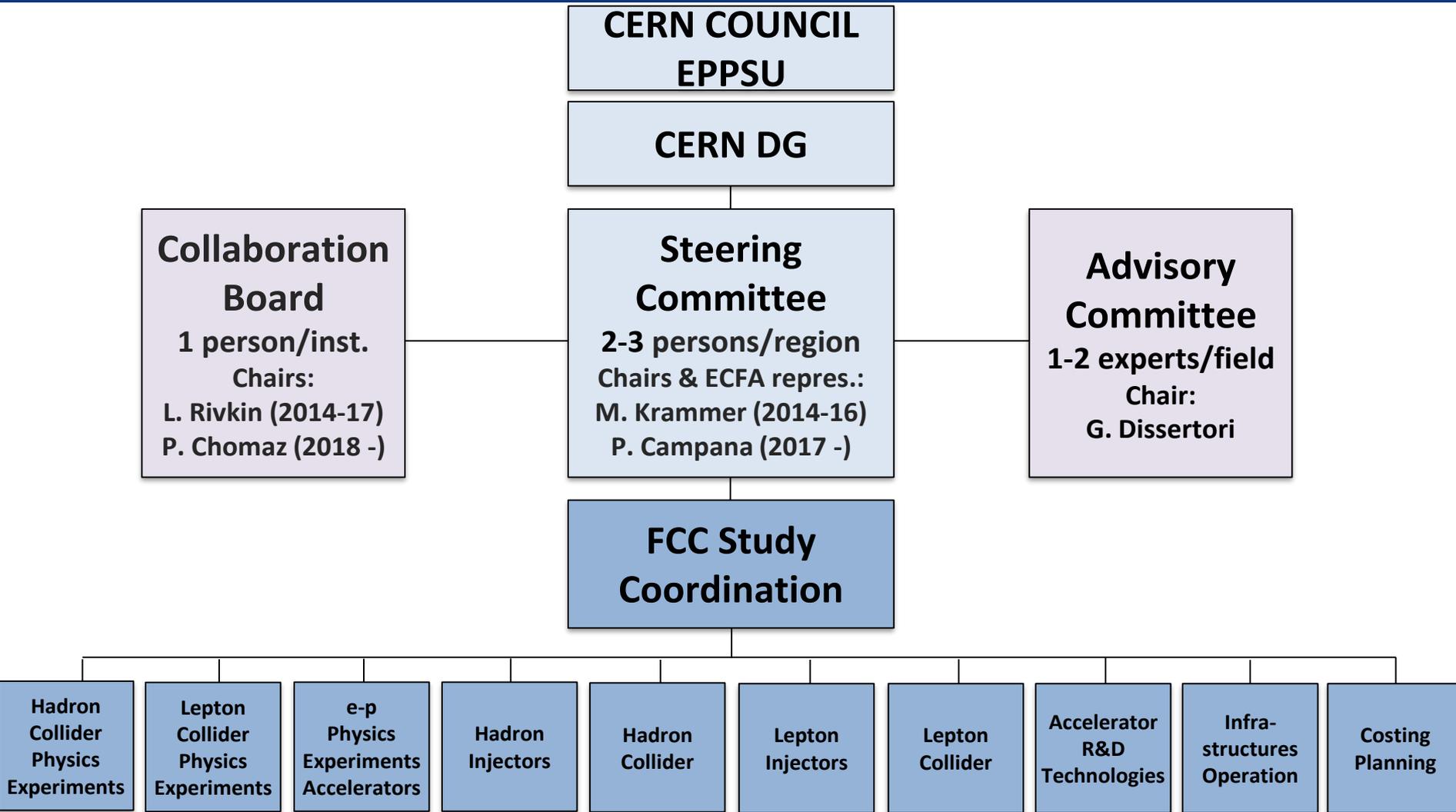
- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge rates for single and multiple production of SM bosons (H,W,Z) and quarks
- Machine design for ~100 TeV c.m. energy & int. luminosity ~ 20ab⁻¹ in 25 years

HE-LHC:

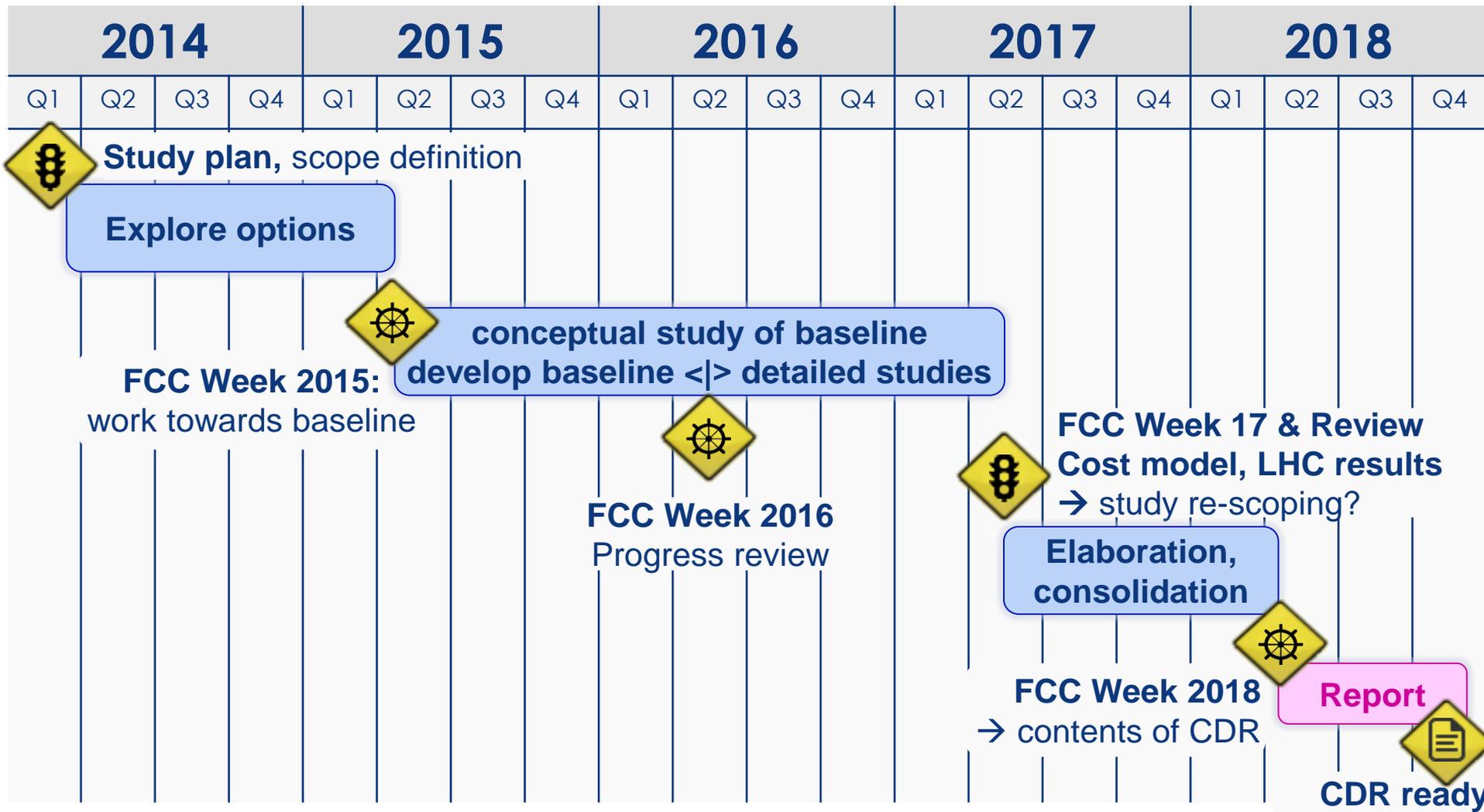
- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC
- Machine design within constraints from LHC CE and using HL-LHC and FCC techn.



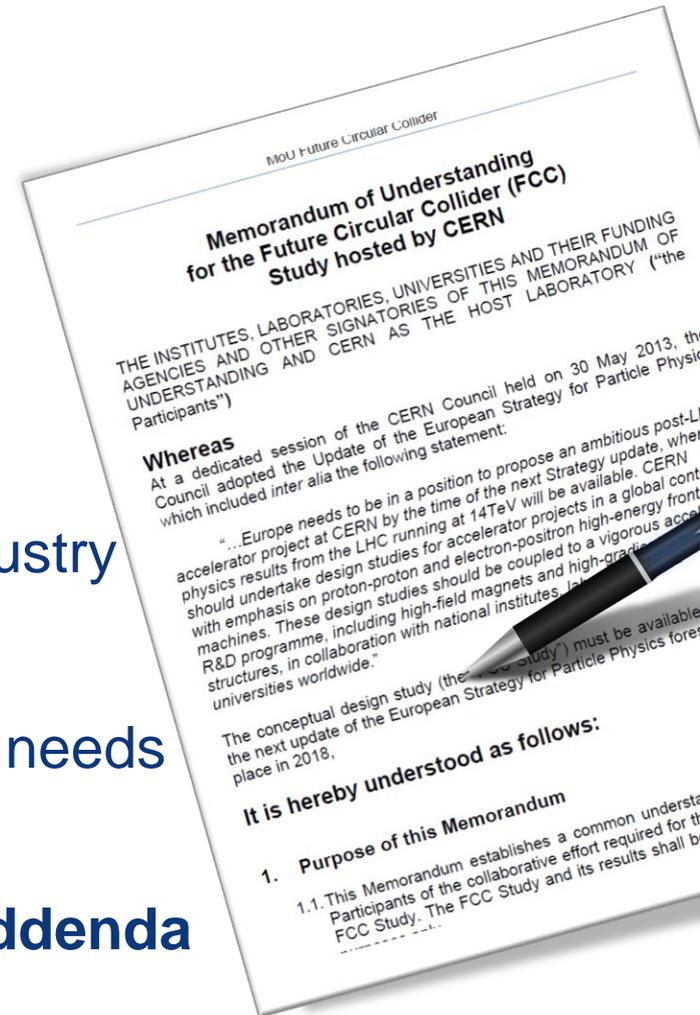
FCC study organization and governance



CDR Study Time Line (from 2014)



- A **consortium** of partners based on a Memorandum Of Understanding (MoU)
- Working together on a **best effort basis**
- Pursuing the same **common goal**
- **Self governed**
- **Incremental & open** to academia and industry
- **Light general framework**, adapted to the needs during a conceptual design study
- Detailed project descriptions in **specific addenda**





Status of global FCC Collaboration



136
Institutes

32
Companies

34
Countries

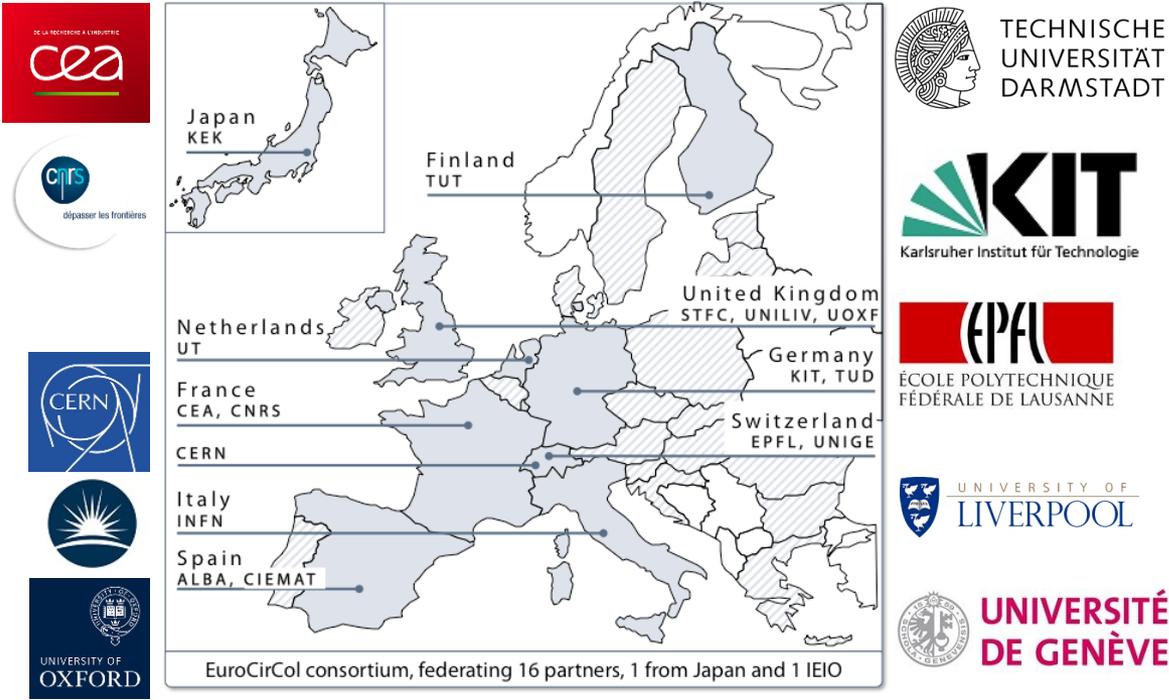


Futu
Mich
FCC

ussels

European Union Horizon 2020 program:

- 3 MEURO co-funding
- Started June 2015, ends in Dec 2019
- 15 European beneficiaries & KEK & associated FNAL, BNL, LBL, NHFML



Covers FCC-hh key work packages:

- Optics design (arc & IR)
- Cryogenic beam vacuum system design including beam tests at ANKA
- 16 T dipole design, construction folder for demonstrator magnets



EU H2020 Marie Curie ITN EASITrain



**European Advanced Superconductivity Innovation and Training Network
Funding 15 Early Stage Researchers over 3 years & training in key areas**

- SC wires at low temperatures for magnets (Nb_3Sn , MgB_2 , HTS)
- Superconducting thin films for RF and beam screen (Nb_3Sn , TI)
- Electrohydraulic forming for RF structures
- Turbocompressor for Helium refrigeration
- Magnet cooling architectures

➤ **started 1 October 2017**

13 Beneficiaries

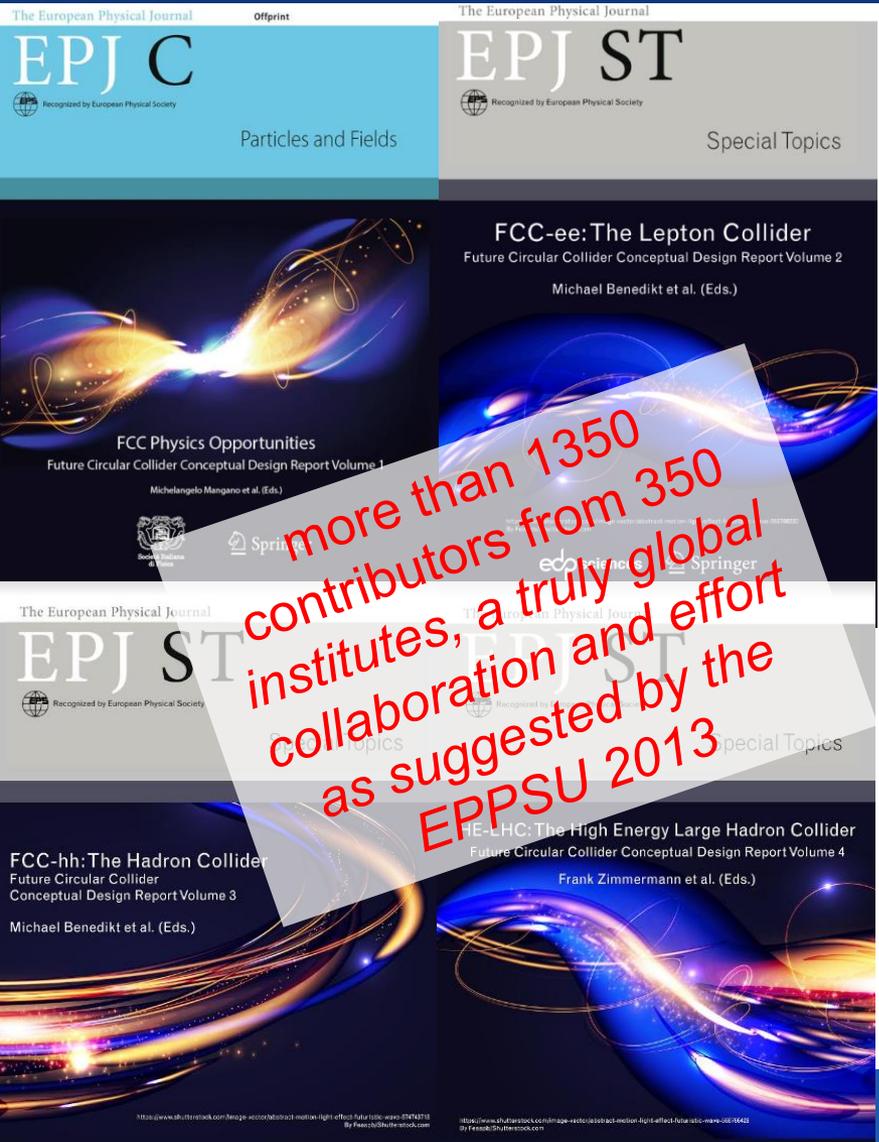


12 Partners





Results of FCC Conceptual Design Study



Study Documentation:

4 CDR volumes submitted to EPJ in December 2018.

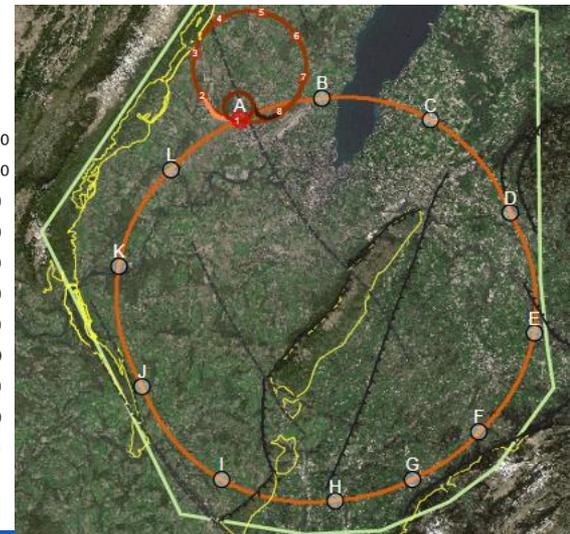
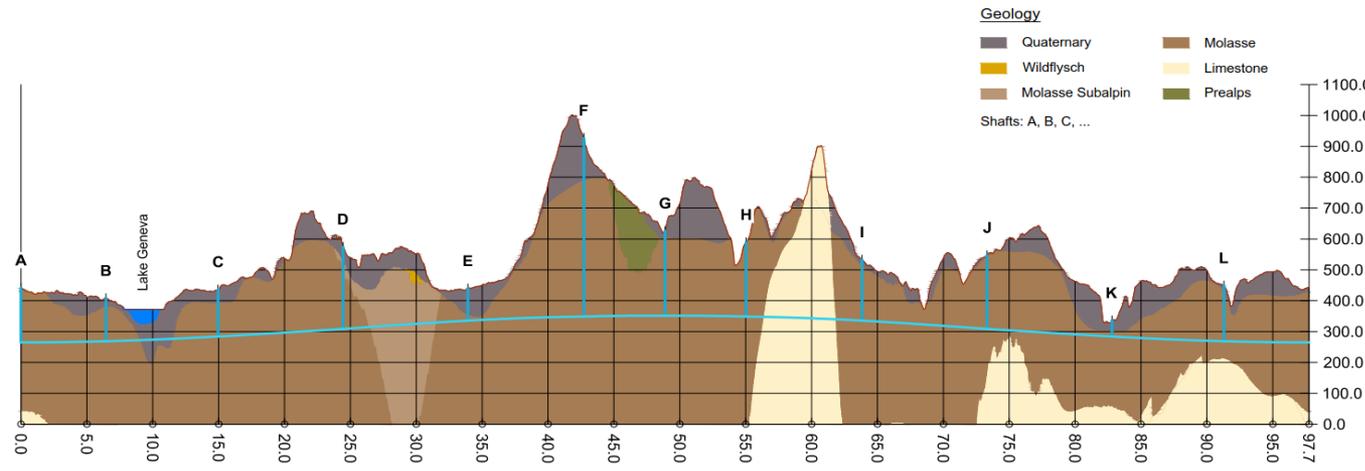
- FCC Physics Opportunities
- FCC-ee
- FCC-hh
- HE-LHC
- Preprints available since 15 January 2019
<http://fcc-cdr.web.cern.ch/>

CDR presentation during welcome event this evening.

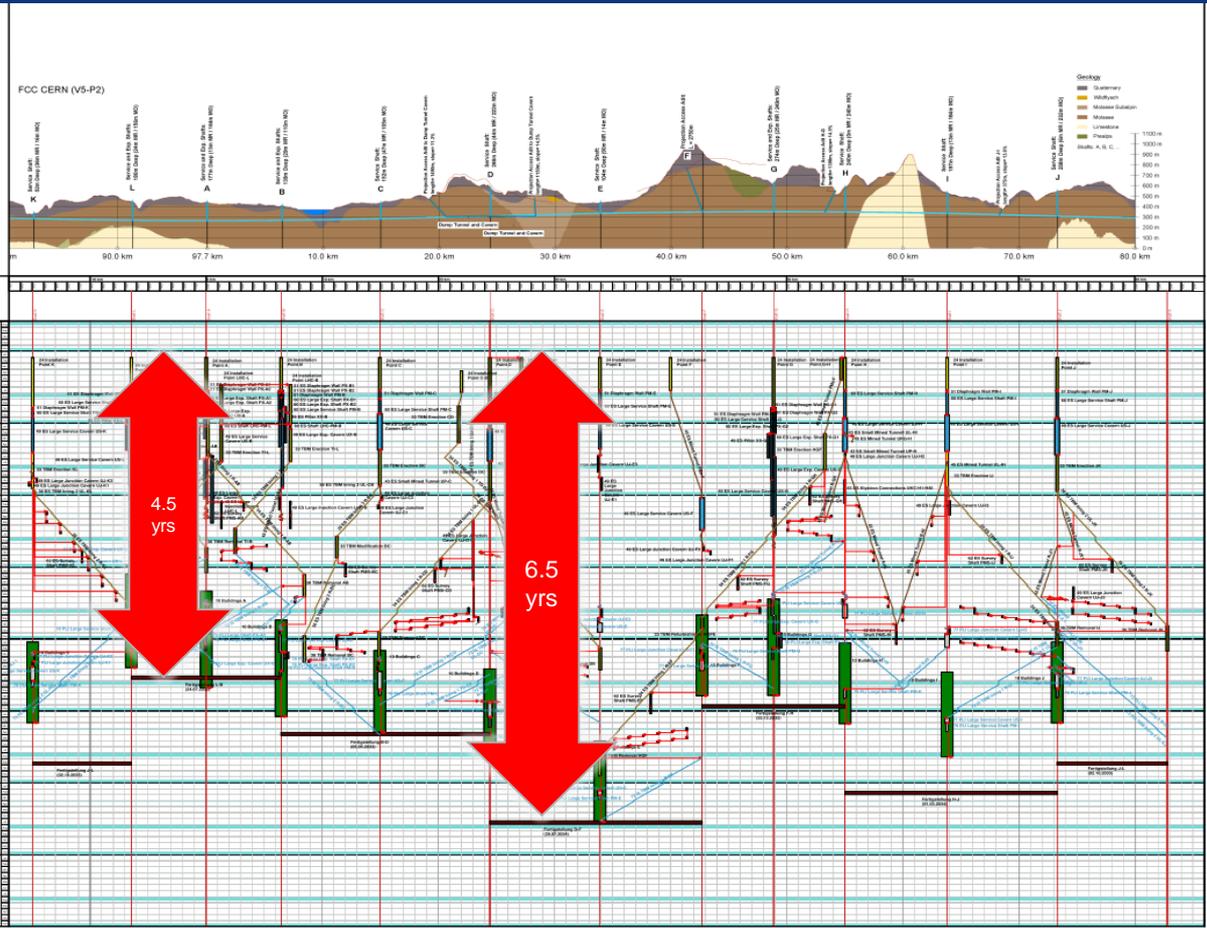
Paper copies can be requested at
• <http://get-fcc-cdr.web.cern.ch>

Comprehensive cost-effective program maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs factory, EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- Complementary physics
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP in Europe.

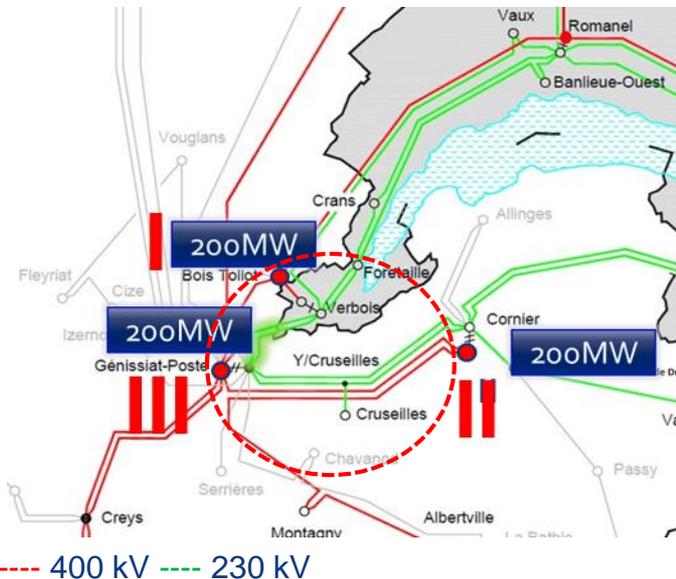


Implementation studies

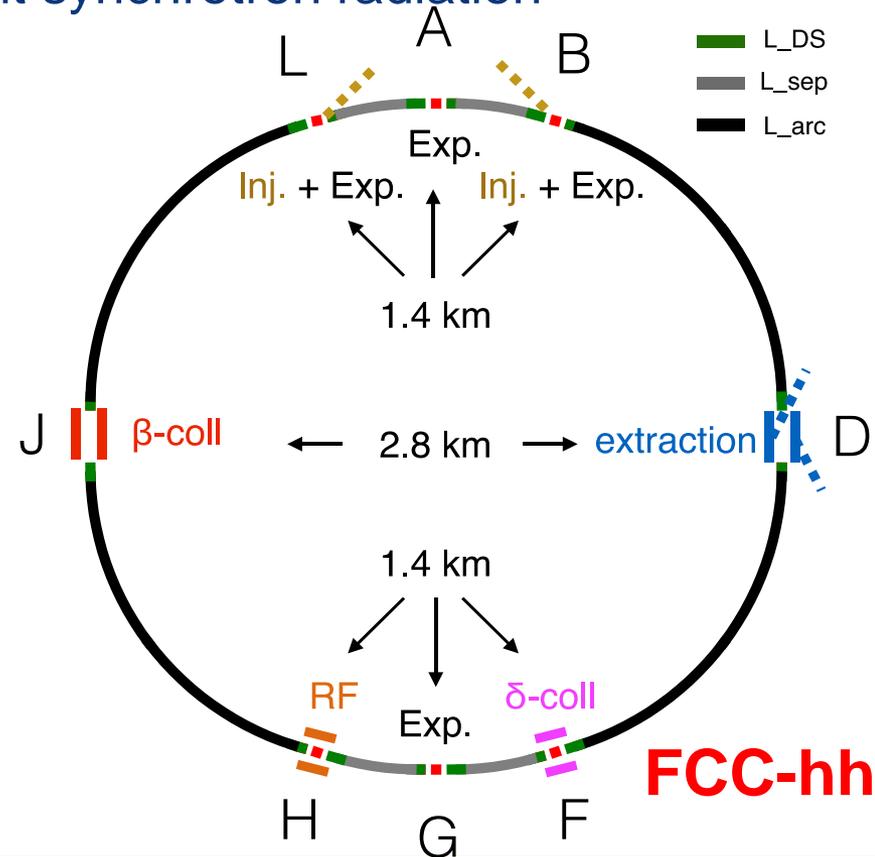
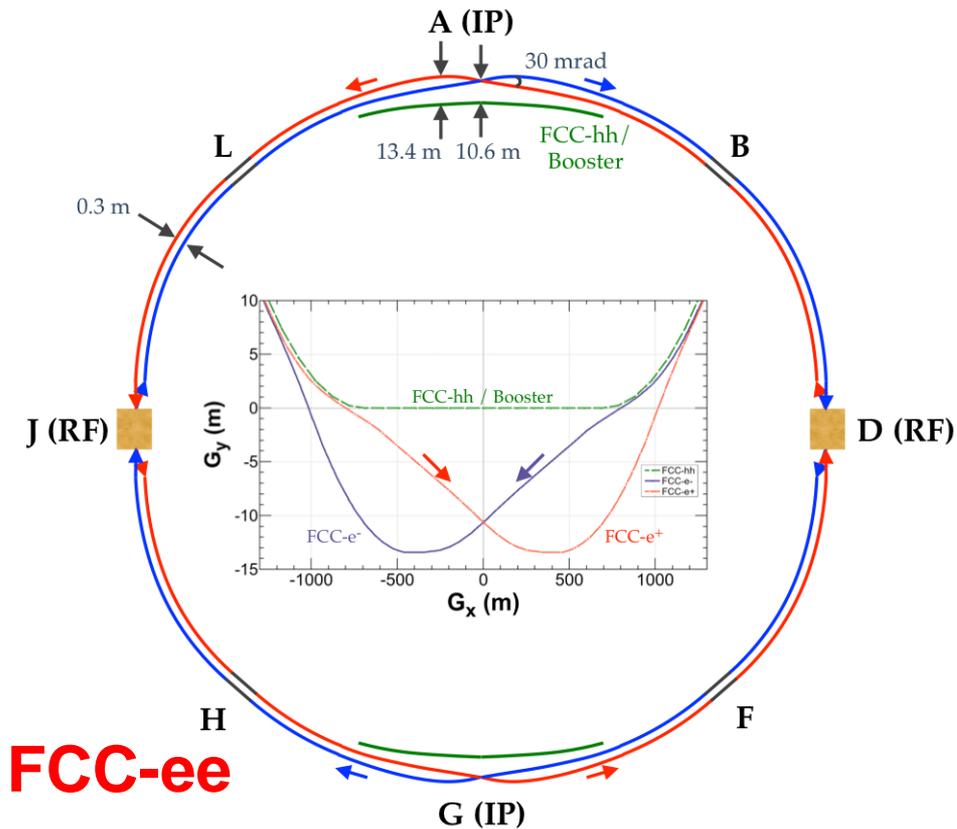


- Total construction duration 7 years
- First sectors ready after 4.5 years

Additional 200 MW available for FCC at each of the three 400 kV sources from European grid



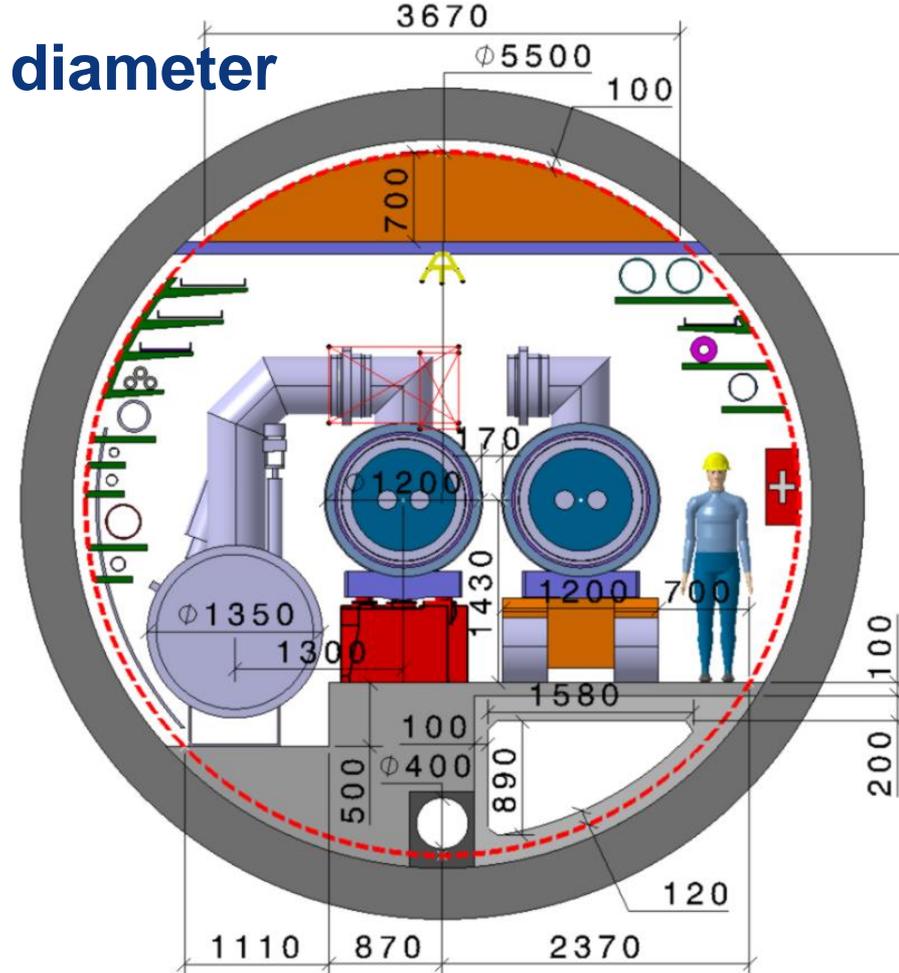
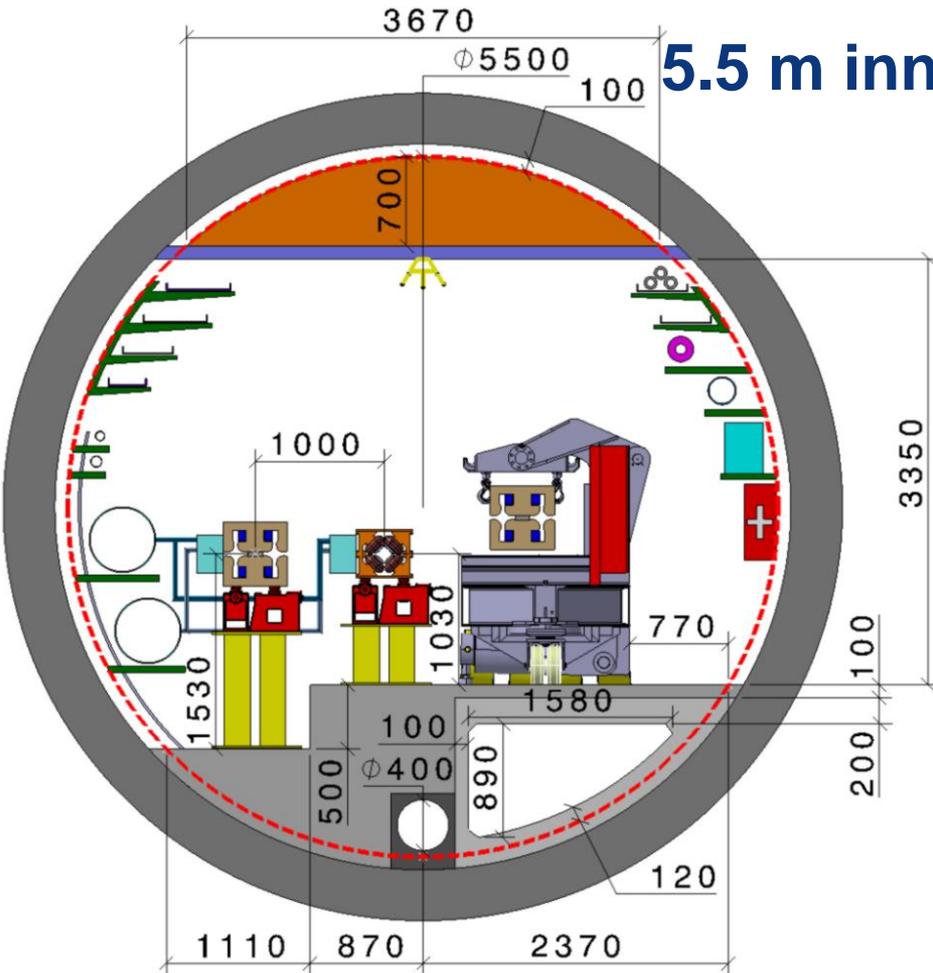
- Two main IPs in A, G for both machines.
- Common footprint except around IPs.
- FCC-ee asymmetric IR layout to limit synchrotron radiation



FCC-ee

FCC-hh

5.5 m inner diameter

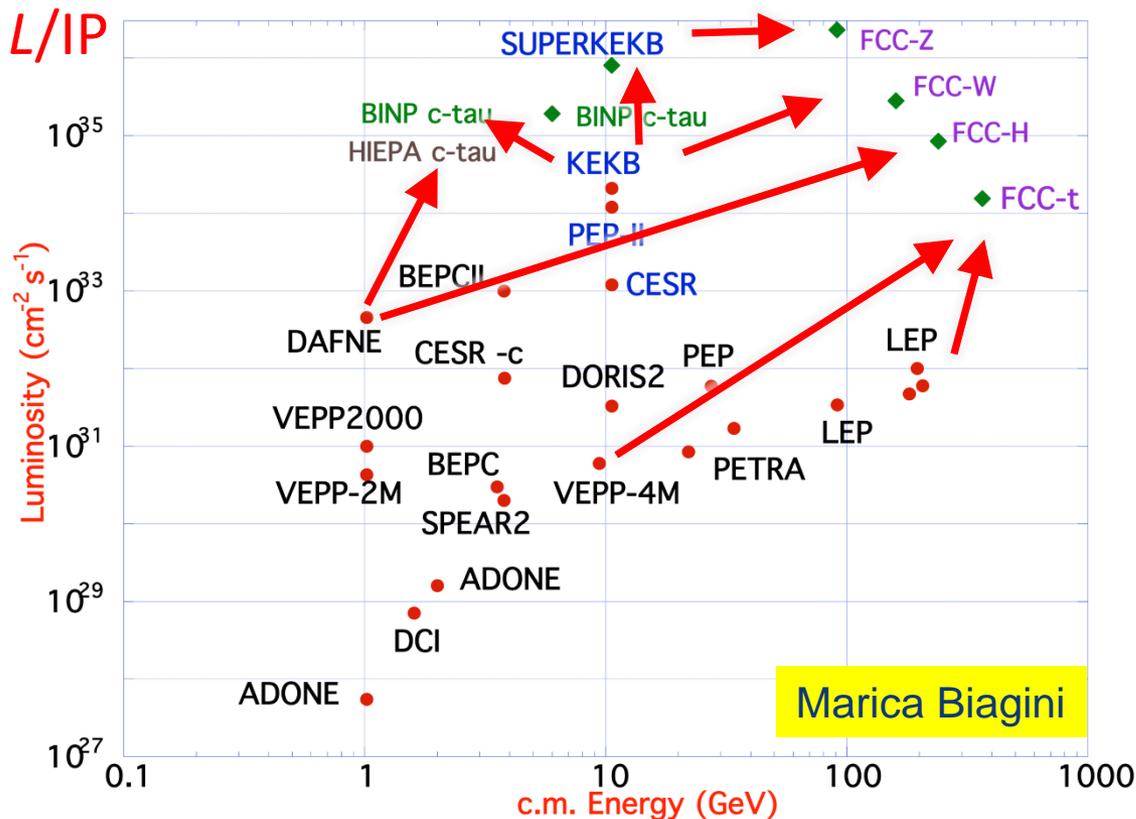




FCC-ee – EW factory: performance

FCC-ee reaches highest luminosities & energies

by combining ingredients and well-proven concepts of several recent colliders:



B-factories: KEKB & PEP-II:
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

Super B-fact., S-KEKB: low β_y^*

LEP high energy, SR effects

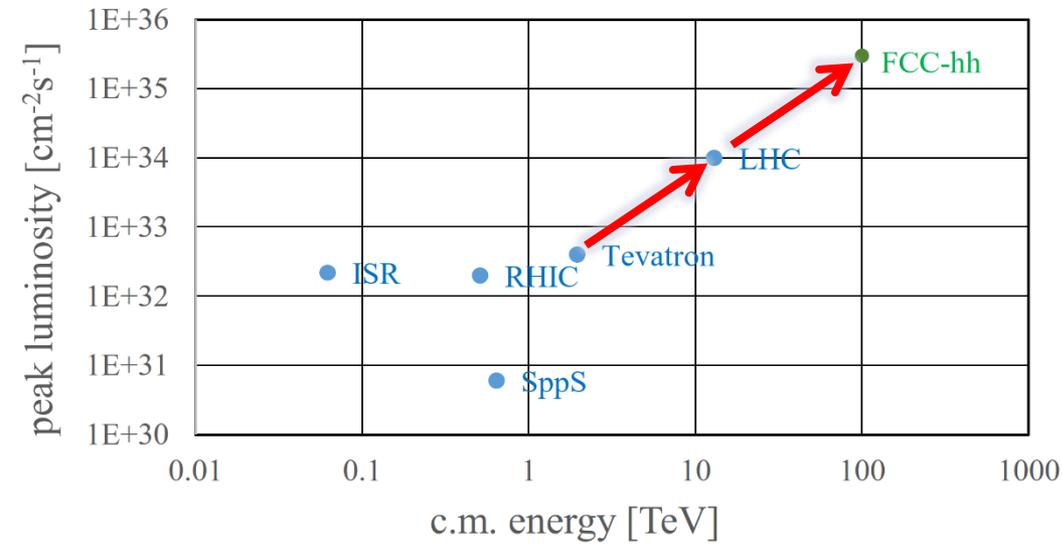
VEPP-4M, LEP:
precision E calibration

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

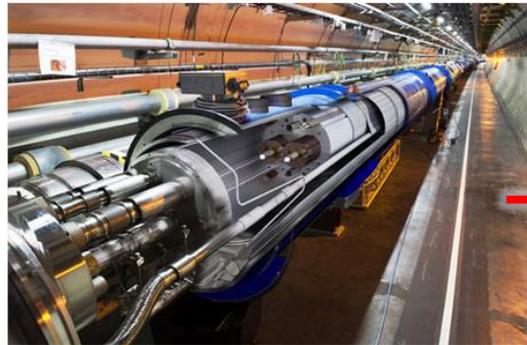


FCC-hh: performance



- Aim at **~one order of magnitude performance increase** in both **energy and luminosity w.r.t LHC**
- **100+ TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation time (vs 3 ab^{-1} for LHC).
- Similar performance increase as from Tevatron to LHC.
- **Key technology: High-field magnets**

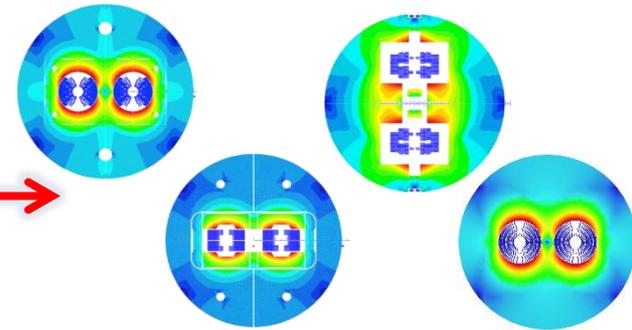
From LHC technology
8.3 T NbTi



via HL-LHC technology
11 T Nb₃Sn

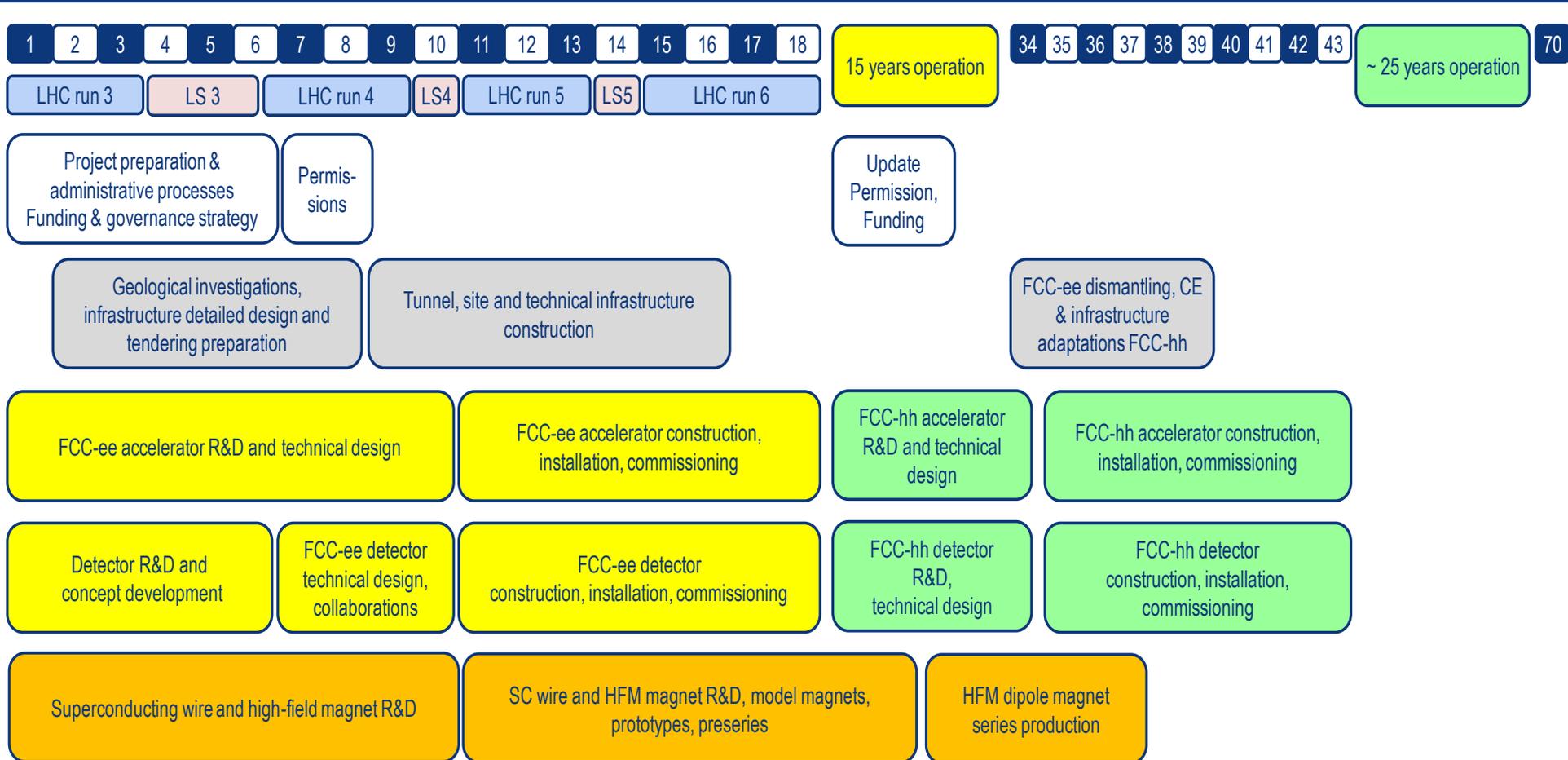


to 16 T Nb₃Sn
EuroCirCol, Chart, US MDP





FCC integrated project technical schedule

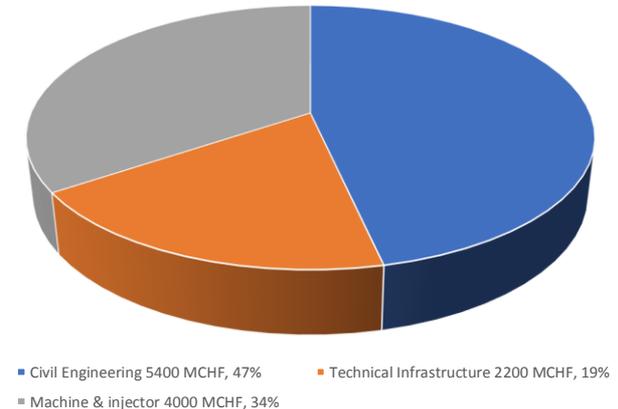


- **FCC integrated project plan is fully integrated with HL-LHC exploitation**
- **provides for seamless further continuation of HEP in Europe.**

Construction cost **phase1 (FCC-ee)** is 11,6 BCHF

- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)

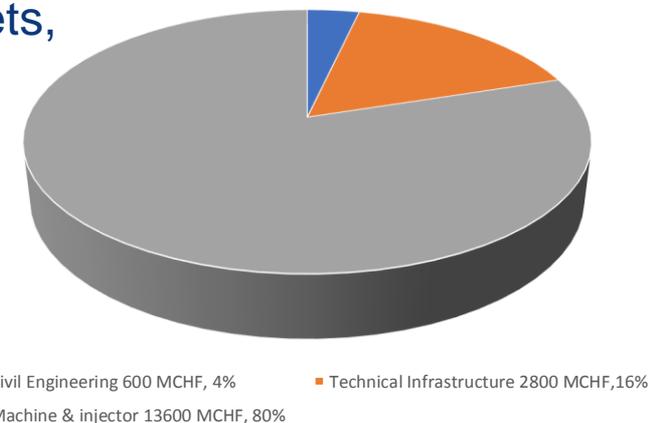
FCC-ee (Z, W, H, t): capital cost per domain



Construction cost **phase 2 (FCC-hh)** is 17,0 BCHF.

- 13,6 BCHF accelerator and injector (57%)
 - Major part for 4,700 Nb₃Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics

FCC-hh - combined mode: capital cost per domain



(Cost **FCC-hh stand alone** would be 24,0 BCHF.)



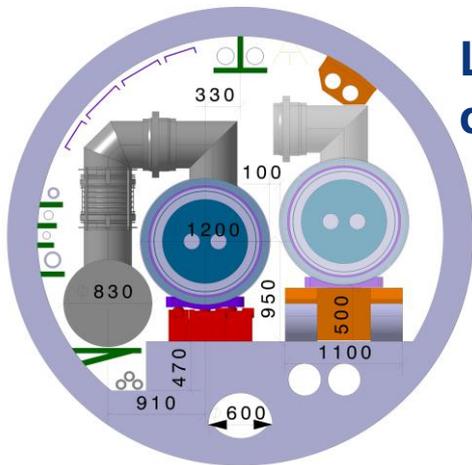
FCC work with host states



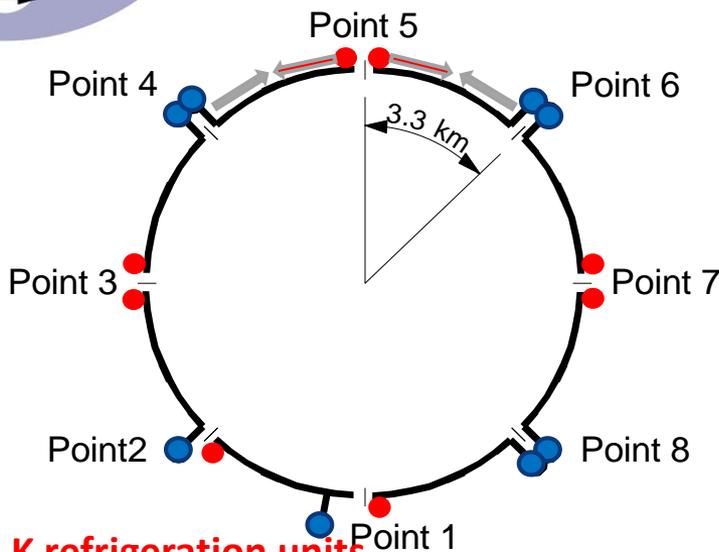
 **General secretariat of the region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”**

 **Working group with representatives of federation, canton and state of Geneva and representation of Switzerland at the international organisations and consultancy companies**

- Administrative processes for project preparatory phase developed.
- Requirements for urbanistic, environmental, economic impact, land acquisition and construction permit related processes defined.
- **Common review of tunnel and surface site placement ongoing.**



LHC tunnel diameter 3.8 m



8 additional 1.8 K refrigeration units
8 new higher-power 4.5 K cryoplants

Performance

- 26 - 27 TeV cm collision energy
- $\sim 10 \text{ ab}^{-1}$ per experiment collected over 20 years
- Key technology: high-field magnets FCC-hh

Very challenging option due to existing boundary conditions:

- Machine integration due to space limitations (tunnel cross section, straight section length, caverns) of existing underground infrastructures
- Compatibility with safety requirements
- Increased cryogenics requirements
- Injector requirements



ESG request for parameters of a lower-energy hadron collider

parameter	FCC-hh		FCC-hh-6T	HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		37.5	27	14	14
dipole field [T]	16		6	16	8.33	8.33
beam current [A]	0.5		0.6	1.1	1.1	0.58
synchr. rad. power/ring [kW]	2400		57	101	7.3	3.6
peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	30	10 (lev.)	16	5 (lev.)	1
events/bunch crossing	170	1000	~300	460	132	27
stored energy/beam [GJ]	8.4		3.75	1.4	0.7	0.36

- **NbTi technology from LHC, magnet with single-layer coil providing 6 T at 1.9 K:**
 - Corresponding beam energy 18.75 TeV or 37.5 TeV c.m.
 - Significant reduction of synchrotron radiation wrt FCC-hh (factor 50) and corresponding cryogenic system requirements.
- **Luminosity goal 10 ab^{-1} over 20 years or 0.5 ab^{-1} annual luminosity:**
 - Beam current 0.6 A or 20% higher than for FCC-hh, $1.2\text{E}11$ ppb (FCC-hh: 1.0 ppb).
 - Stored beam energy 3.75 GJ vs 8.4 GJ for FCC-hh.
- **Analysis of physics potential, technology requirements and cost ongoing.**



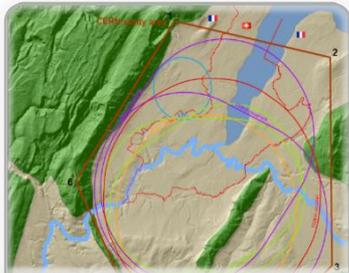
Next steps 2019 - 2020

- Iteration of tunnel and surface structures layout and implementation with host states.
- Adaptation of CE, machine designs, etc. according to implementation optimisation.
- Following Integral Project proposal, presently focus on FCC-ee as potential first step (awaiting strategy recommendation).
 - Review and more detailed design for FCC-ee injector concept
 - Detailed design of technical infrastructure for FCC-ee
- Preparation of EU H2020 DS project (INFRADEV call November 2019), focused on preparations for infrastructure implementation.

Preparation of EU H2020 DS project

Goal: Carry out technical design study for a 100 km long frontier circular collider infrastructure at CERN that will extend Europe's leadership in the domain of fundamental physics research until the end of the 21st century.

Focus on priority topics, to prepare construction project by 2026, in line with call scope:



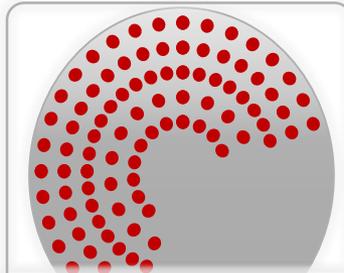
Site Selection

Optimization of collider designs, site selection, placement and implementation, work with host states



Resources & Environment

Plans for construction and operation including resource efficiency & environmental impacts.



Governance Organisation
Construction Operation

Development of governance structure, construction & operation budget and funding strategy



Scientific User
Collaboration

Ensure that a scientific user community is built up to exploit the facility from the start on



Coherently Integrate
Europe

Coherently integrate the infra-structure in the European research landscape



Next steps 2020 - 2026

2020/21 – 2025/26 project preparation phase (if supported by EPPSU and CERN Council)

- Project preparatory activities with host states (landplot identification and acquisition plan, sector plan, EIA, “debat publique”, and study management)
- Civil engineering site investigations and construction tender planning
- Technical design towards CDR++/TDR (ATS) (Accelerators, technology, technical infrastructure)
- Development of financing and governance models for project and operation phases including international in-kind contributions (CERN Council and Directorate).

All 4 activities aim at reaching a level by 2025/26 allowing a definitive project decision.



Conclusions and outlook

- As recommended by the ESU 2013, the FCC study was organised as an international collaboration focused on the conceptual design of high-performance energy frontier circular colliders for the post-LHC era.
- The first phase of FCC conceptual design studies is completed. Baseline machine designs and associated infrastructures, with performance matching the physics requirements, were established and are documented in 4 CDRs.
- A possible integrated FCC programme has been developed and submitted to the ESU, together with descriptions of the individual machines.
- The next steps, in parallel to ESU process and in harmony with its recommendations, will develop a concrete local/regional implementation scenario in collaboration with host state authorities, accompanied by machine optimization, physics studies and technology R&D.



The FCC Week 2019 should:

- Stimulate exchange between participants of all study areas
- Strengthen the collaboration network
- Develop plans for upcoming study phase while awaiting EPPSU.
- Have a great and productive week!