# The Path Towards the Future Circular Collider at CERN


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Workshop on the Standard Model and Beyond
Corfu, Greece
5 September 2023

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


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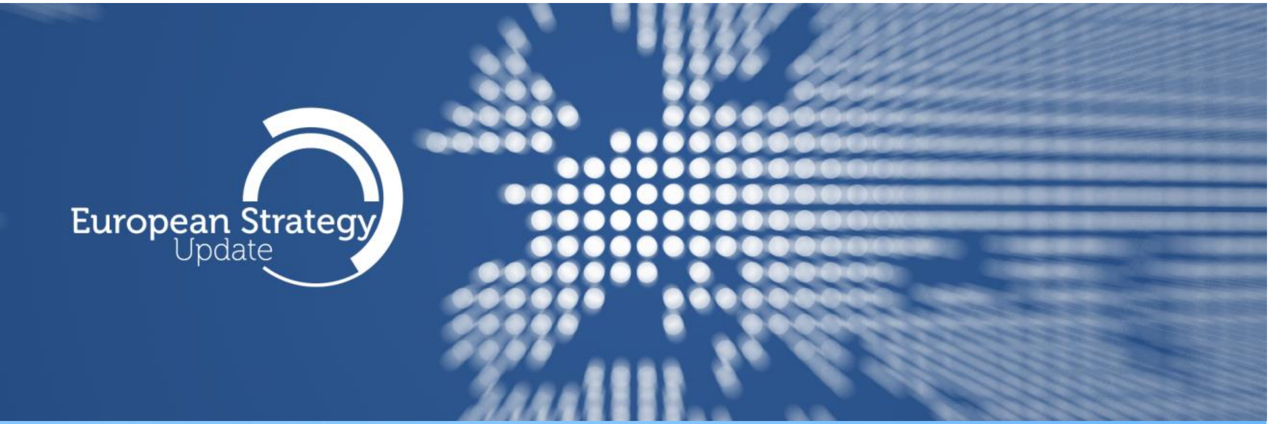
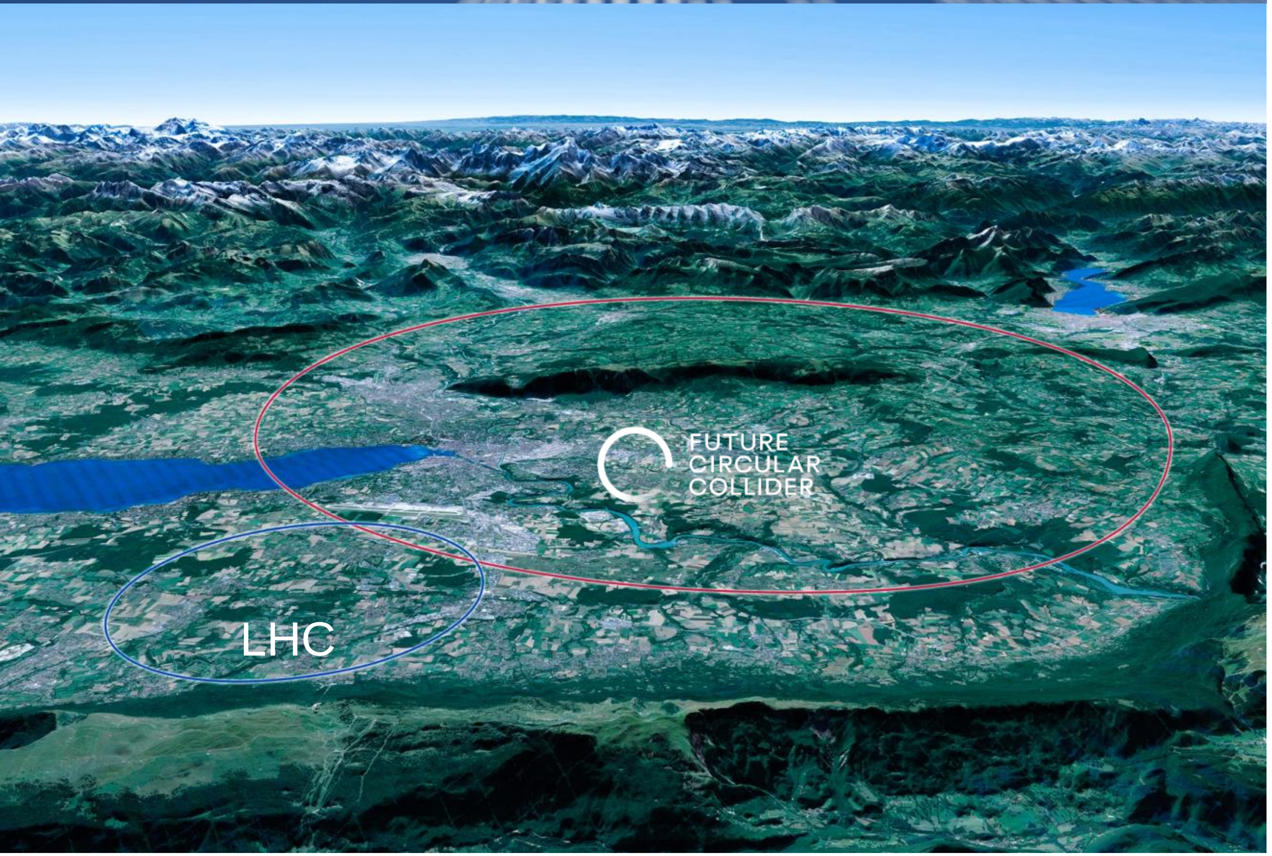
European Commission | Horizon 2020 European Union funding for Research & Innovation


photo: J. Wenninger




# CERN Scientific Priorities for the Future

Implementation of the recommendations of the **2020 Update of the European Strategy for Particle Physics**:

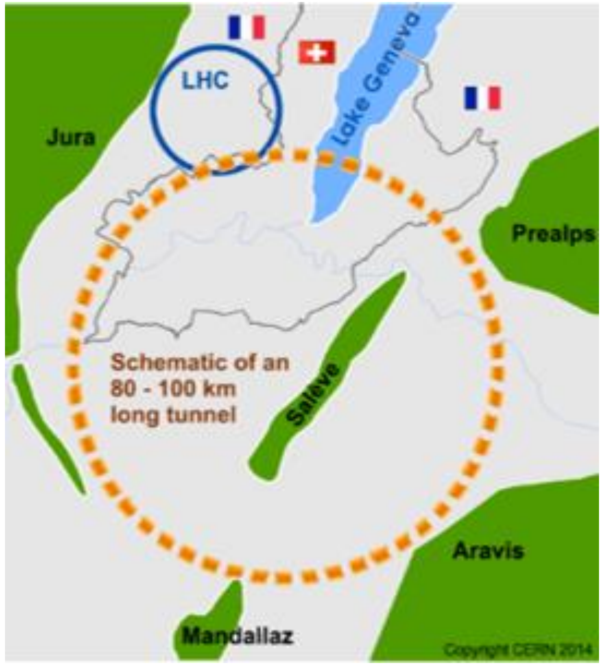
- Fully exploit the LHC & HL-LHC.
- Build a Higgs factory to further understand this unique particle.
- Investigate the technical and financial feasibility of a future energy-frontier 100 km collider at CERN.
- Ramp up relevant R&D.
- Continue supporting other projects around the world.

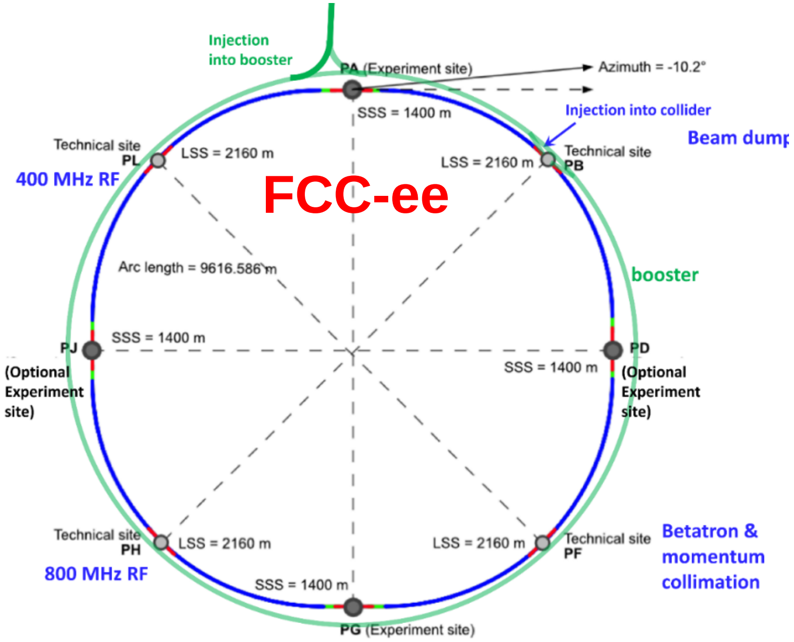
# The FCC Integrated Programme

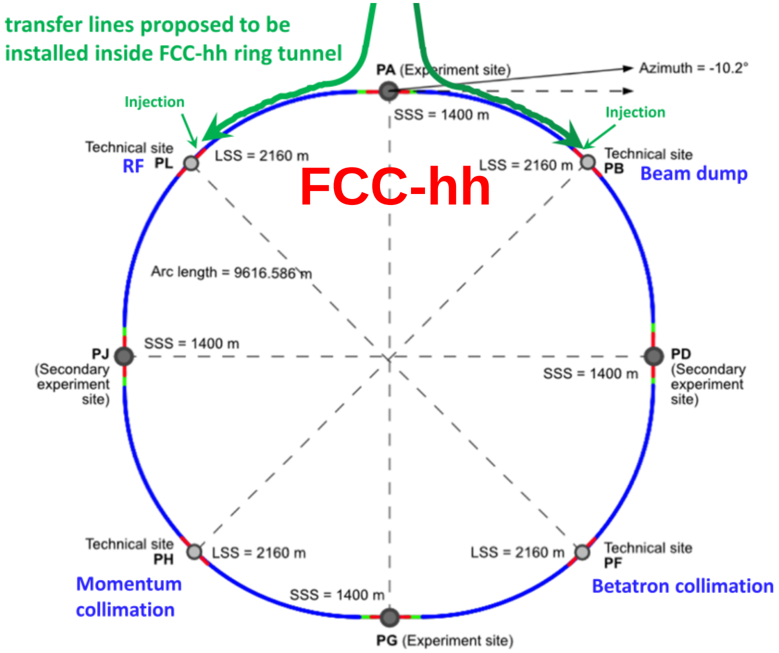
## Inspired by Successful LEP – LHC Programmes at CERN

**Comprehensive long-term programme maximising 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, with ion and eh options**
- Highly synergistic and complementary physics.
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure.
- FCC integrated project allows seamless continuation of HEP soon after completion of the HL-LHC programme.



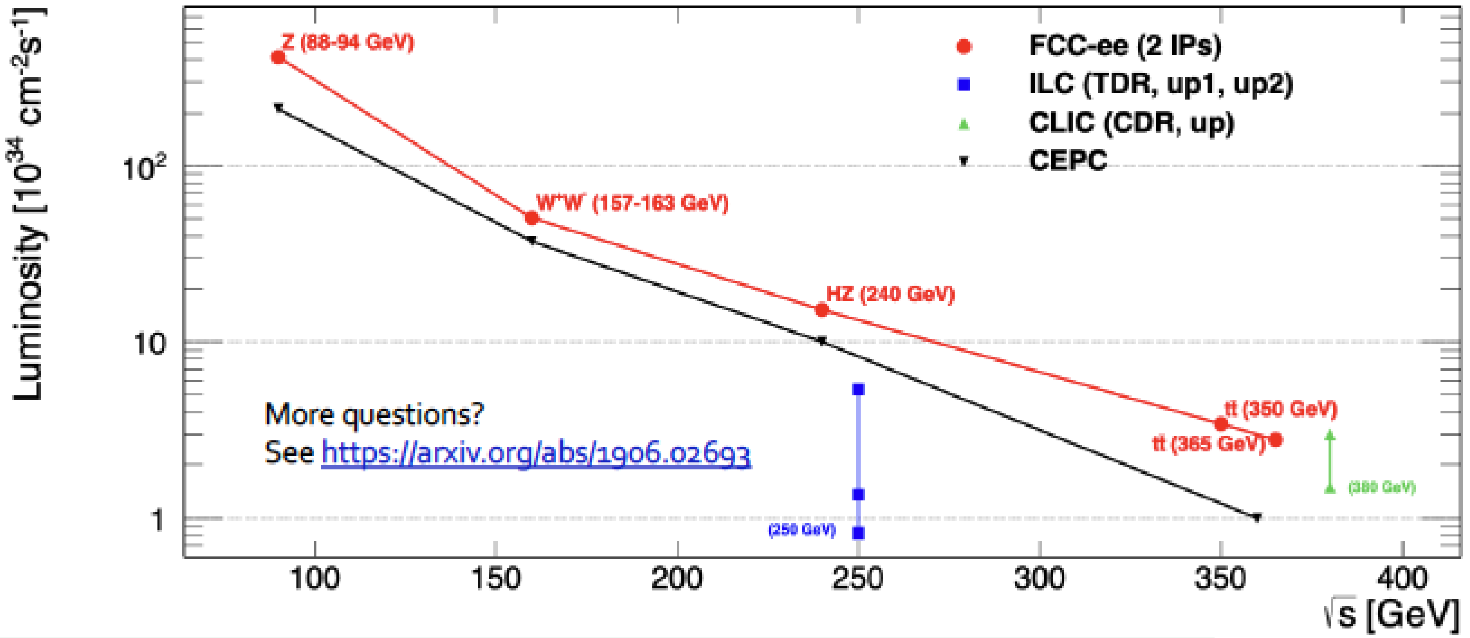




**2020 - 2040** | **2045 - 2063** | **2070 - 2095**

# FCC-ee Higgs and Electroweak Factory

- Great energy range for the SM heavy particles + highest luminosities + √s precision




| | | | | $E_{CM}$ errors: |
|---|---|---|---|---|
| Z peak | $E_{cm}$ ~ 91 GeV | $5 \times 10^{12}$ e+e- → Z | LEP x $10^5$ | <100 keV |
| WW threshold+ | $E_{cm} \geq 161$ GeV | $> 10^8$ e+e- → WW | LEP x $10^3$ | <300 keV |
| ZH threshold | $E_{cm}$ : 240 GeV | $10^6$ e+e- → ZH | Never done | 2 MeV |
| $t\bar{t}$ threshold | $E_{cm}$ ~ 350 GeV | $10^6$ e+e- → $t\bar{t}$ | Never done | 5 MeV |

P. Janot

# Physics Opportunities with FCC-hh

- With 30 $ab^{-1}$ @ 100 TeV in 25 years
  - $2\times10^{10}$ Higgs bosons (180 × HL-LHC)
    - $2\times10^{7}$ Higgs pairs, $10^{8}$ ttH events
  - $10^{12}$ top pairs (300 × HL-LHC)
  - $5\times10^{13}$ W, $10^{13}$ Z (70 × HL-LHC)
  - $10^{5}$ gluino pairs im $m_{gluino}$ ~ 8 TeV
  - …

- High precision study of H and top
  - Exploration of EWSB in all details
    - Higgs self-coupling to 2-3%
  - Rare or BSM decays
    - BR(H → invisible) to $2.5\times10^{-4}$ (DM!)
    - $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$ to 0.5%
      - → FCC-ee standard candle essential

- Sensitivity to heavy new physics
  - With indirect precision probes
    - e.g., with cross-section ratios
    - e.g., with high-$p_T$ final states
  - Trade statistics for systematics
    - Further improved by FCC-ee synergies
  - High-energy phenomena (VBS, DY)

- Direct particle observation
  - Mass reach enhanced by ~5 wrt LHC
    - New gauge bosons up to 40 TeV
    - Strongly interacting particles up to 15 TeV
    - Natural SUSY up to 5-20 TeV
    - Dark matter up to 1.5-5 TeV
      - → Possibility to find or rule out thermal WIMPs as Dark Matter candidates

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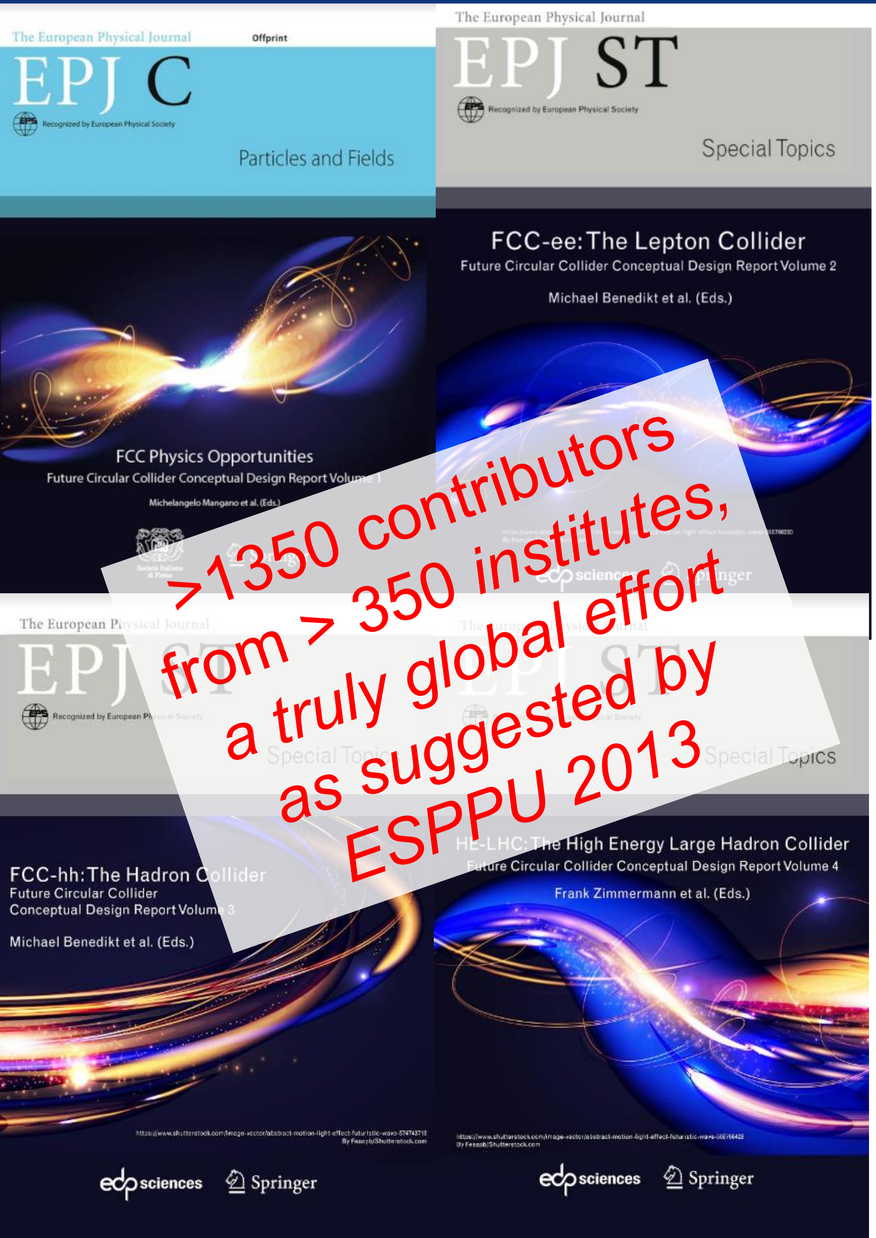
# FCC Conceptual Design Report and Study Documentation




- **FCC-Conceptual Design Reports:**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

    EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,

    EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

FUTURE CIRCULAR COLLIDER

# FCC Feasibility Study

## FCC Feasibility Study

**FCC Feasibility Study (FS) will address a recommendation of the 2020 update of the European Strategy for Particle Physics (ESPP):**

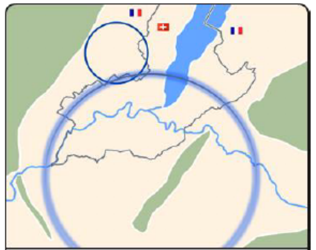
- “Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.
- Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

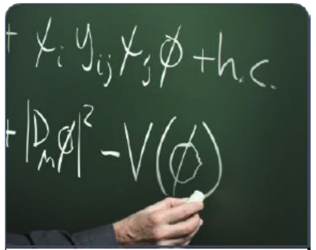

**FCC FS is organised as an international collaboration.**
The FCC FS and a possible future project will profit from CERN’s decades-long experience with successful large international accelerator projects, e.g., the LHC and HL-LHC, and the associated global experiments, such as ATLAS and CMS.

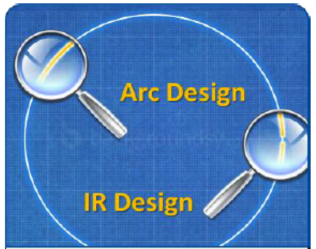
# High-level Goals of Feasibility Study

## High-level goals of Feasibility Study

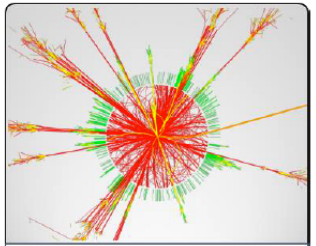
- optimisation of placement and layout of the ring and related infrastructure, and demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval, with a focus on identifying and surmounting possible showstoppers;
- optimisation of the design of the colliders and their injector chains, supported by targeted R&D to develop the needed key technologies;
- development and documentation of the main components of the technical infrastructure;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency;
- identification of substantial resources from outside CERN’s budget for the implementation of the first stage of a possible future project;
- consolidation of the physics case and detector concepts for both colliders.

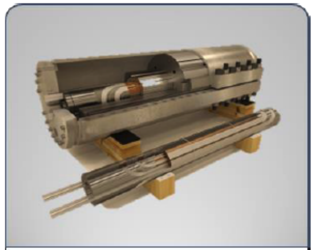

Infrastructures


Physics Cases



Collider Designs

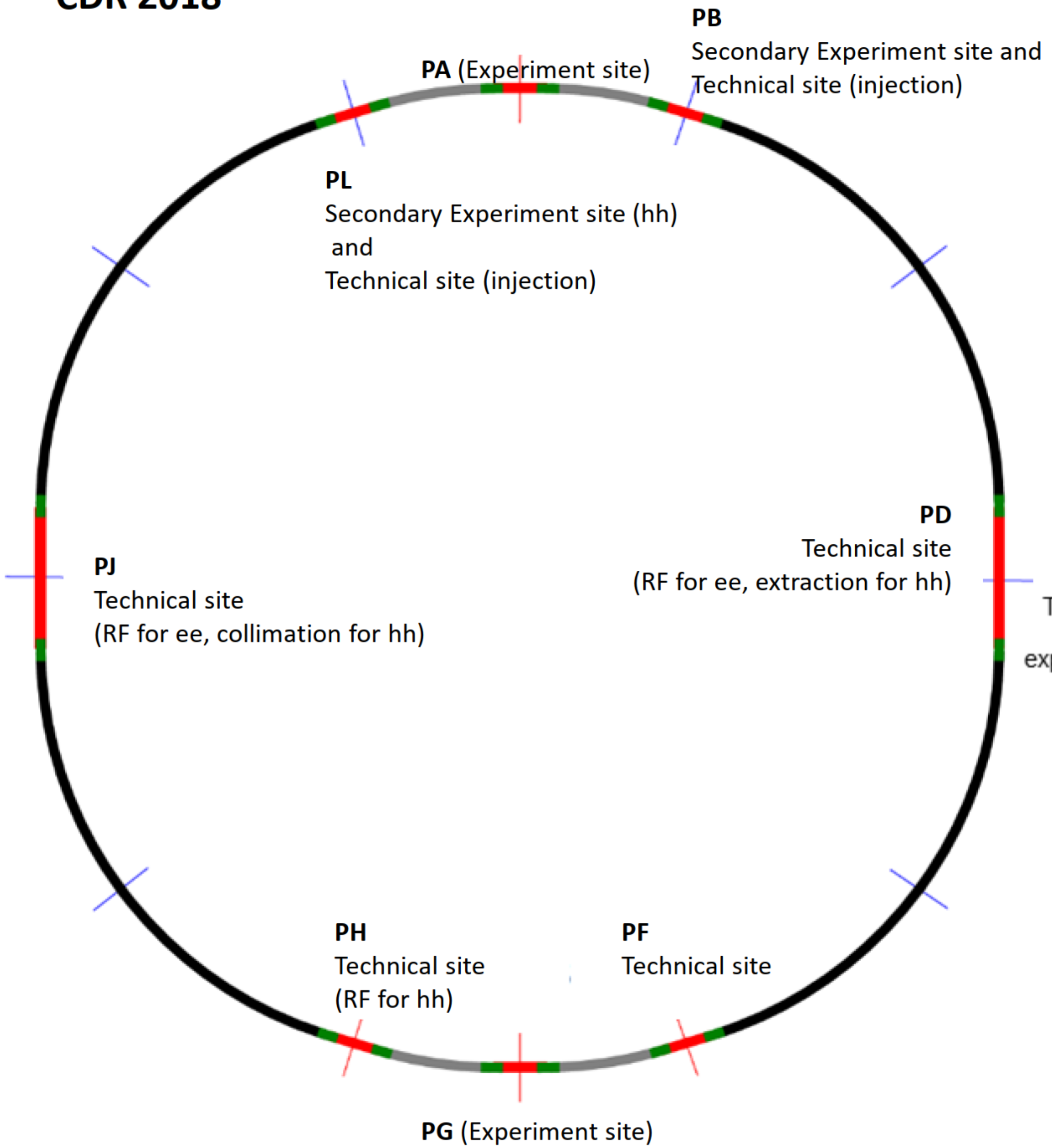

Experiments


R&D Programs

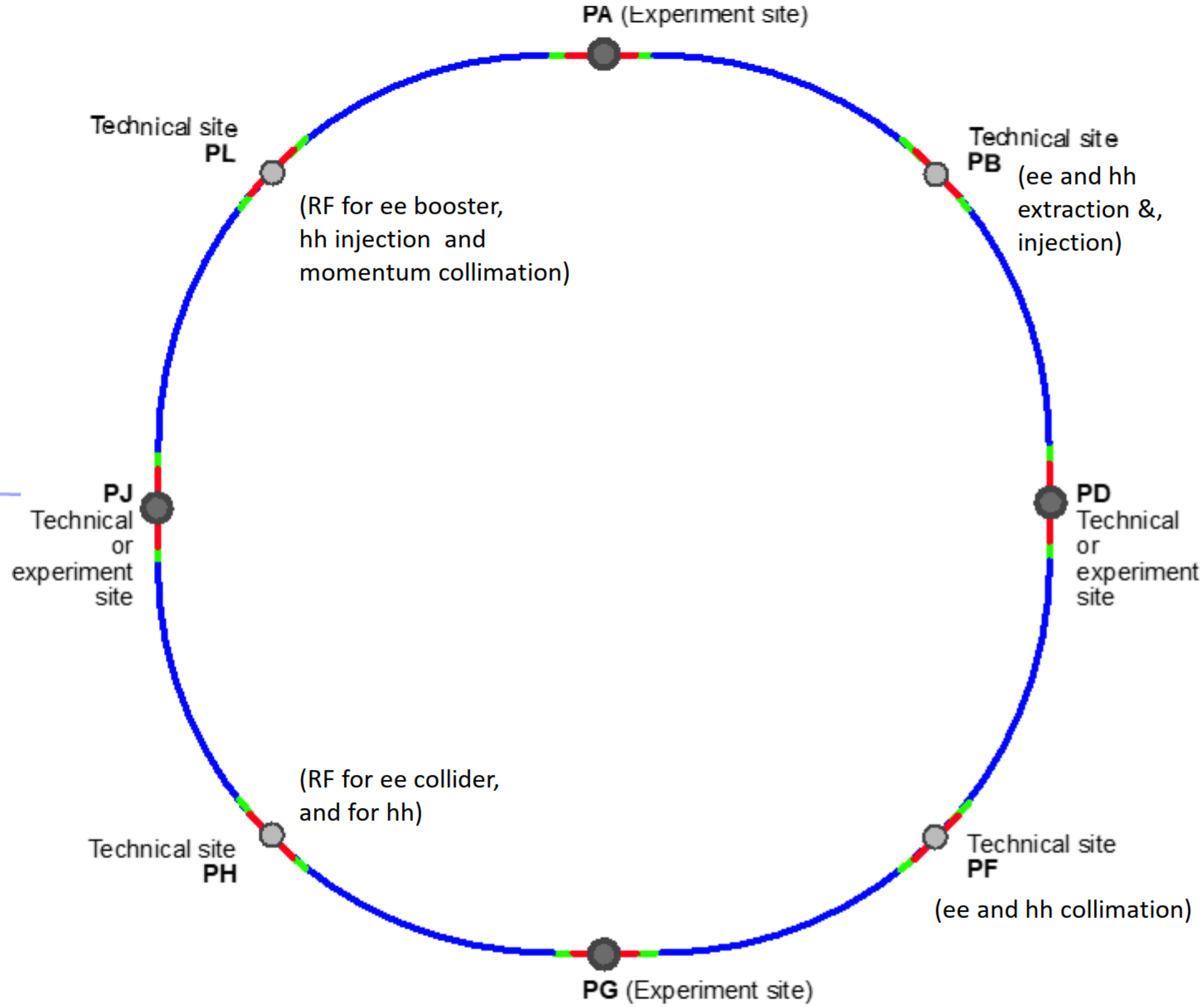
Cost Estimates

# Revised Layout and Geometry

## CDR 2018




## "Optimised" Midterm 2023



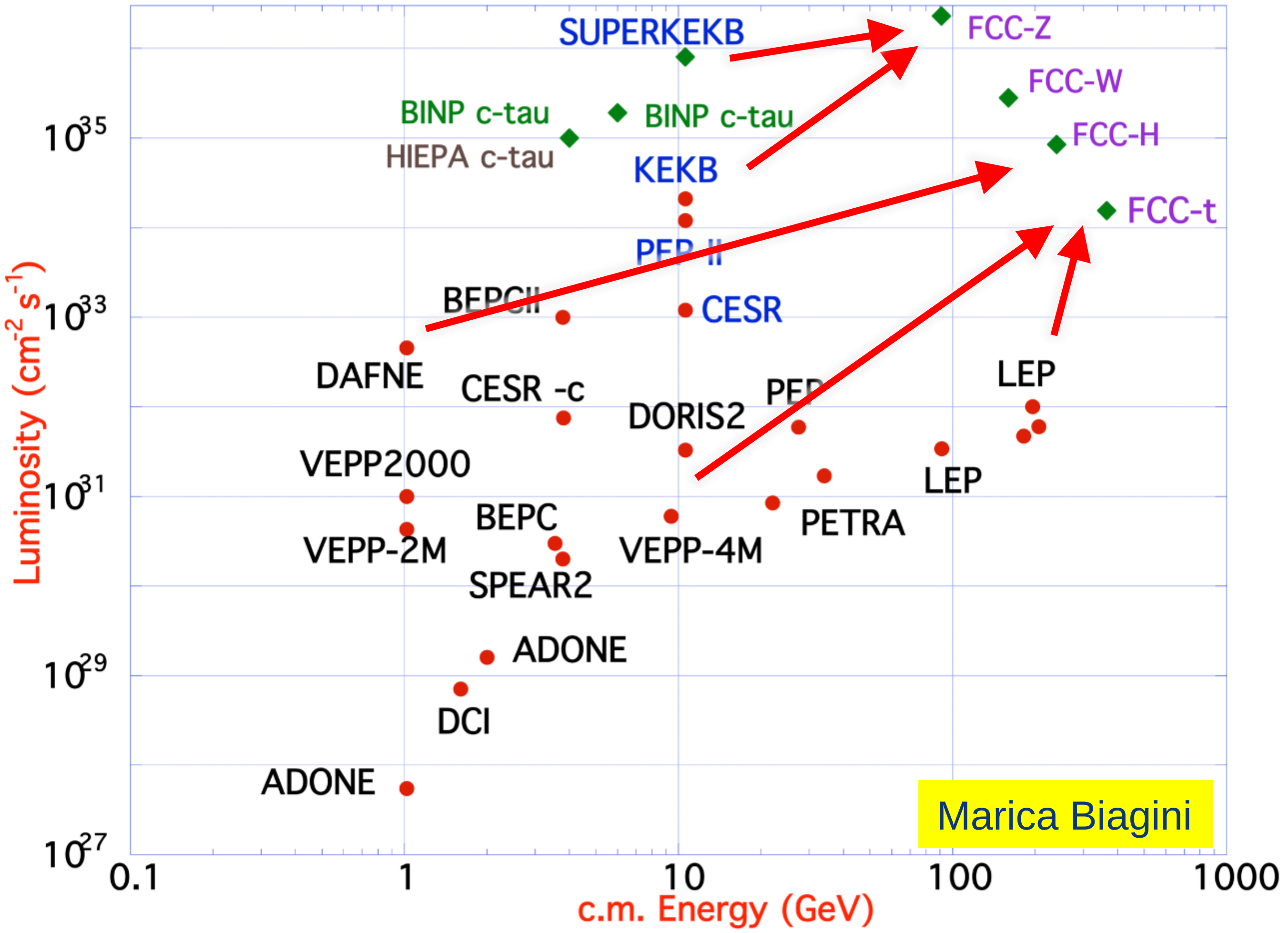

K. Oide, M. Hofer, et al.

# FCC-ee in a Nutshell

- **High luminosity precision study of Z, W, H, and $t\bar{t}$** $2\times10^{36}$ $cm^{-2}s^{-1}$/IP at Z (or total $\sim10^{37}$ $cm^{-2}s^{-1}$ with 4 IPs), $7\times10^{34}$ $cm^{-2}s^{-1}$ at ZH, $1.3\times10^{34}$ $cm^{-2}s^{-1}$ at $t\bar{t}$ , unprecedented energy resolution at Z (<100 keV) and W (<300 keV)
- **Low-risk technical solution** based on 60 years of $e^+e^-$ circular colliders and particle detectors ; R&D on components for improved performance, but no need for “demonstration” facilities; LEP2, VEPP-4M, PEP-II, KEKB, DAΦNE, or SuperKEKB already used many of the key ingredients in routine operation
- Infrastructure will support a **century of physics**
    - FCC-ee → FCC-hh → FCC-eh and/or several other options (FCC-μμ, Gamma Factory ..)
- **Utility requirements** similar to CERN existing use
- **Strong support** from CERN, partners, and 2020 ESPPU
- **Detailed multi-domain feasibility study underway** for 2026 ESPPU

# FCC-ee Design Concept

## Based on lessons and techniques from past colliders (last 40 years)




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

**DAFNE:** crab waist, double ring

**S-KEKB:** low $\beta_y^*$, crab waist

**LEP:** high energy, SR effects

**VEPP-4M, LEP:** precision E calibration

**KEKB:** $e^+$ source

**HERA, LEP, RHIC:** spin gymnastics

**combining successful ingredients of several recent colliders → highest luminosities & energies**

# Stage 1: FCC-ee Collider Parameters

FUTURE CIRCULAR COLLIDER

| 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 $\xi_x$ / $\xi_y$ | 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<br>5 x $10^{12}$ Z<br>LEP x $10^5$ | 2 years<br>> $10^8$ WW<br>LEP x $10^4$ | 3 years<br>2 x $10^6$ H | 5 years<br>2 x $10^6$ tt pairs |

currently assessing technical feasibility of changing operation sequences (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 RF Staging Scenario

## Baseline Operational Sequence Starting from Z

"Ampere-class" machine

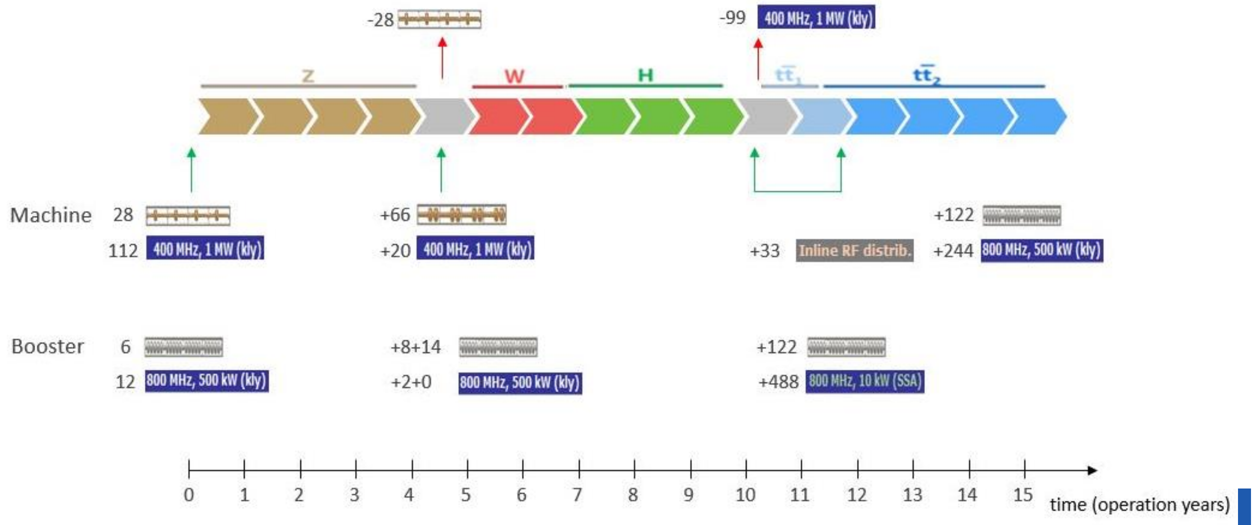
| WP | $V_{rf}$ [GV] | #bunches | $I_{beam}$ [mA] |
|---|---|---|---|
| Z | 0.1 | 16640 | 1390 |
| W | 0.44 | 2000 | 147 |
| H | 2.0 | 393 | 29 |
| ttbar | 10.9 | 48 | 5.4 |

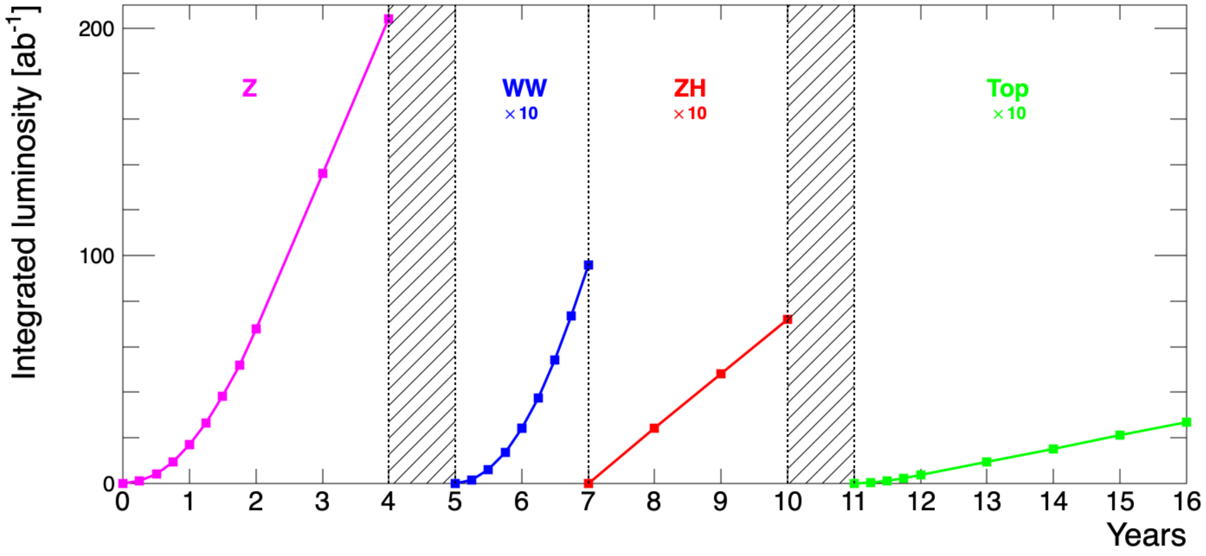
"high-gradient" machine

**Three sets of RF cavities to cover all options for FCC-ee & booster:**

- **High intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **Higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **Installation sequence comparable to LEP ( ≈ 30 CM/shutdown)**

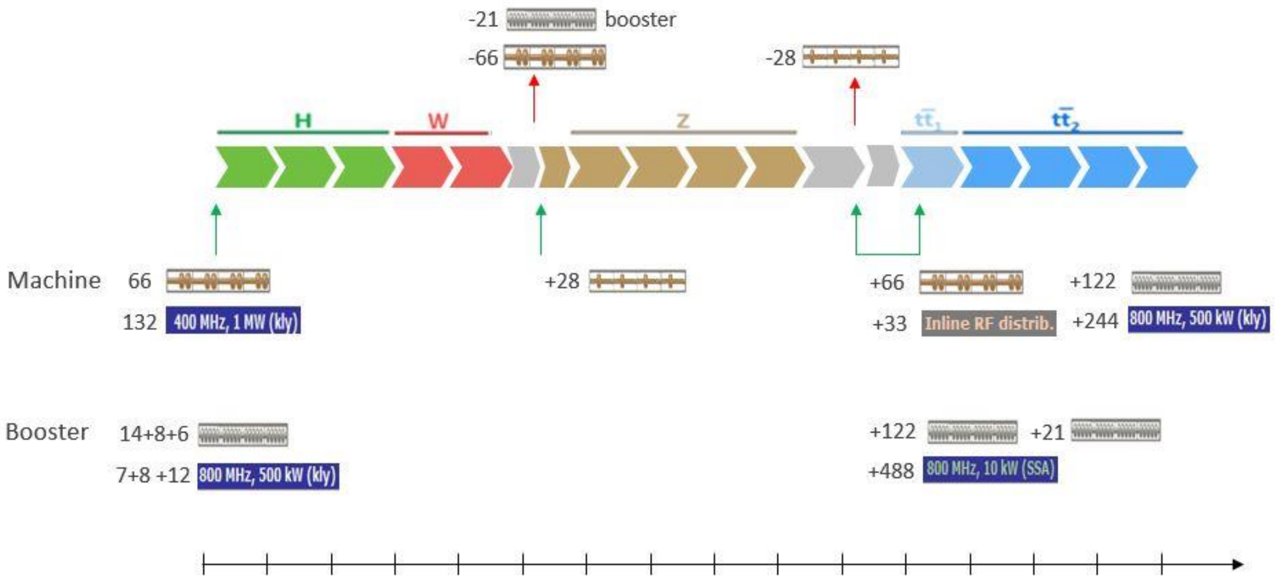
O. Brunner, F. Peauger

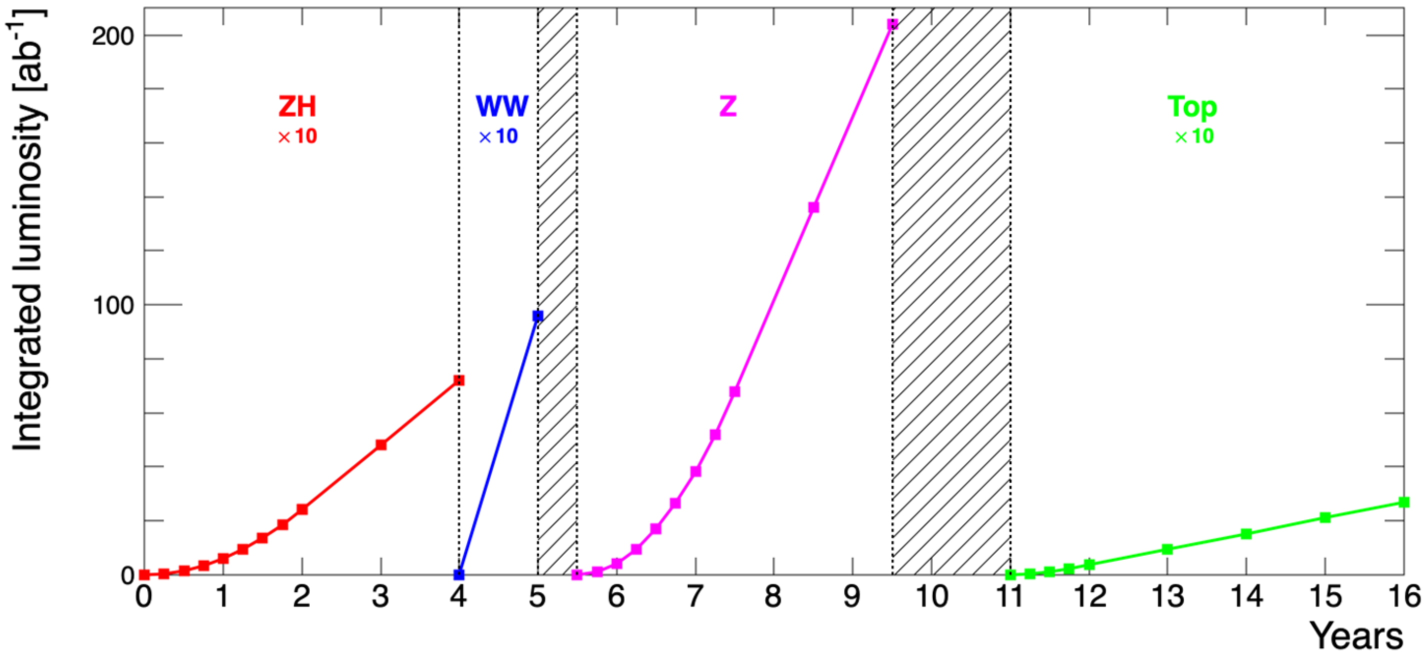


# Alternative Operational Sequence Starting from ZH

O. Brunner, F. Peauger

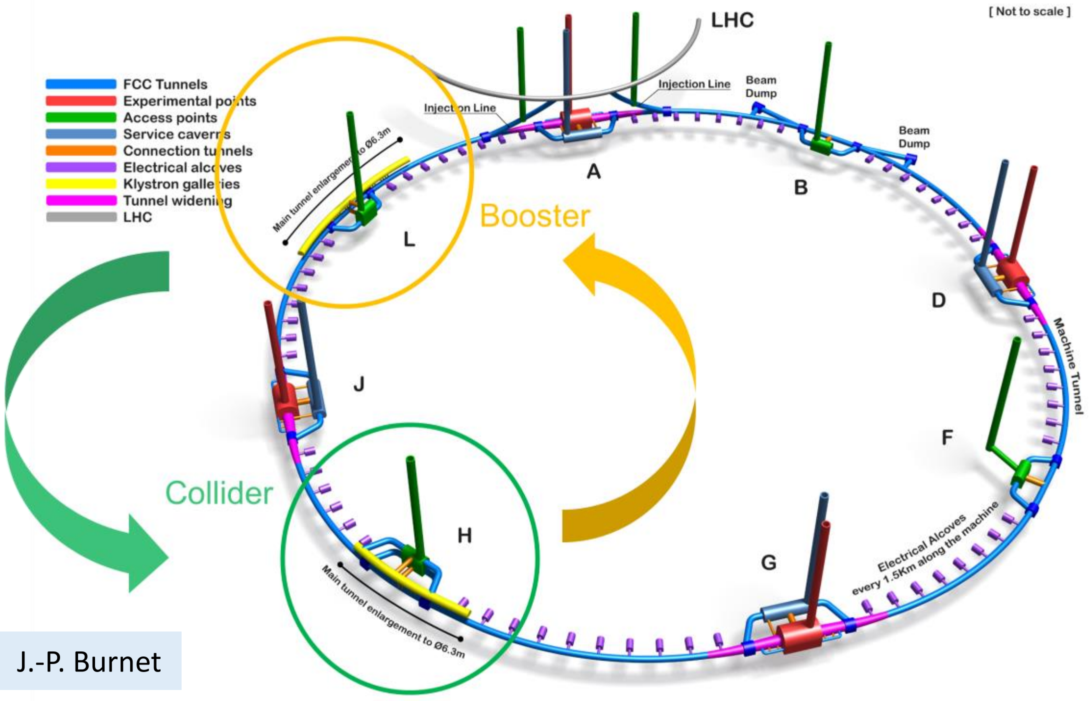



P. Janot

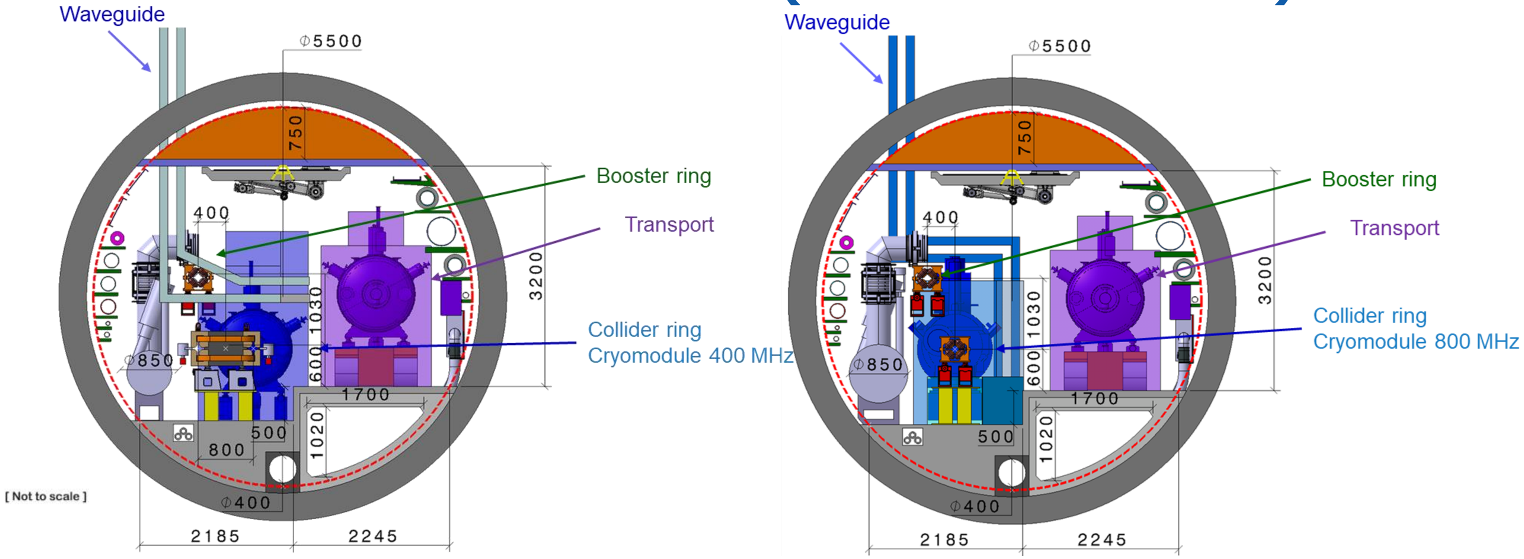
# Modified FCC-ee RF Lay-out

- RF for collider and booster in separate straight sections H and L.
- Fully separated technical infrastructure systems (cryogenics).
- Collider RF (highest power demand) in point H with optimum connection to existing 400 kV grid line and better suited surface site

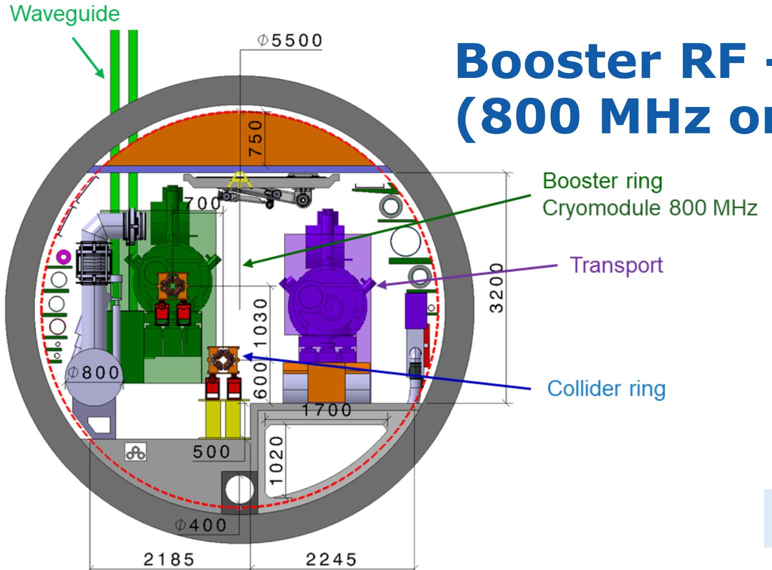



J.-P. Burnet

## Collider RF - Point H (400 and 800 MHz)




## Booster RF - Point L (800 MHz only)



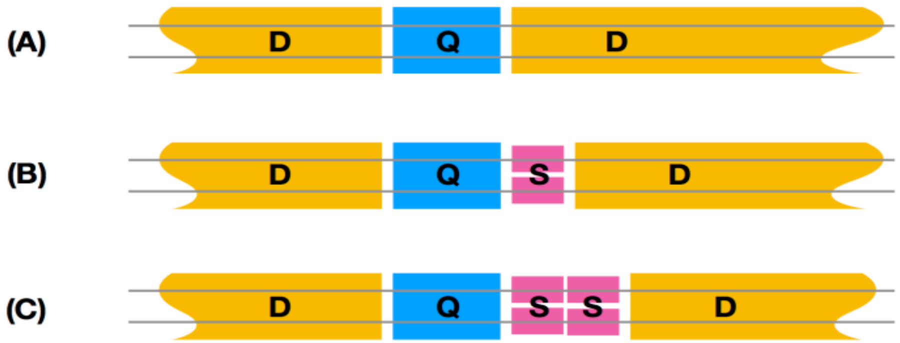

F. Valchkova, F. Peauger

# R&D on HTS Option for FCC-ee Arc Quads and Sextupoles

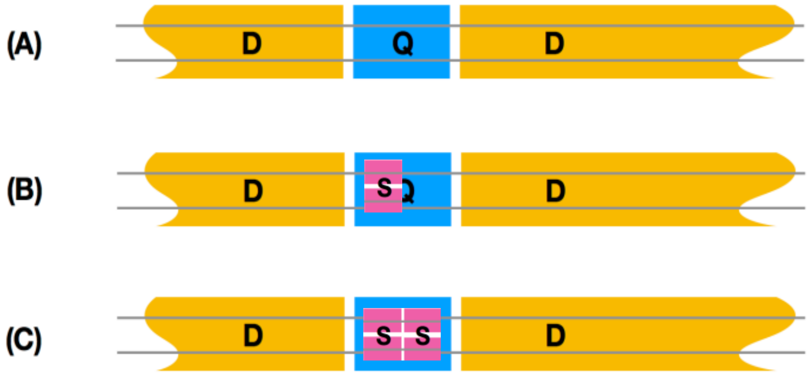
## CDR: 2900 quads & 4700 sextupoles

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

**CDR arc lattice**



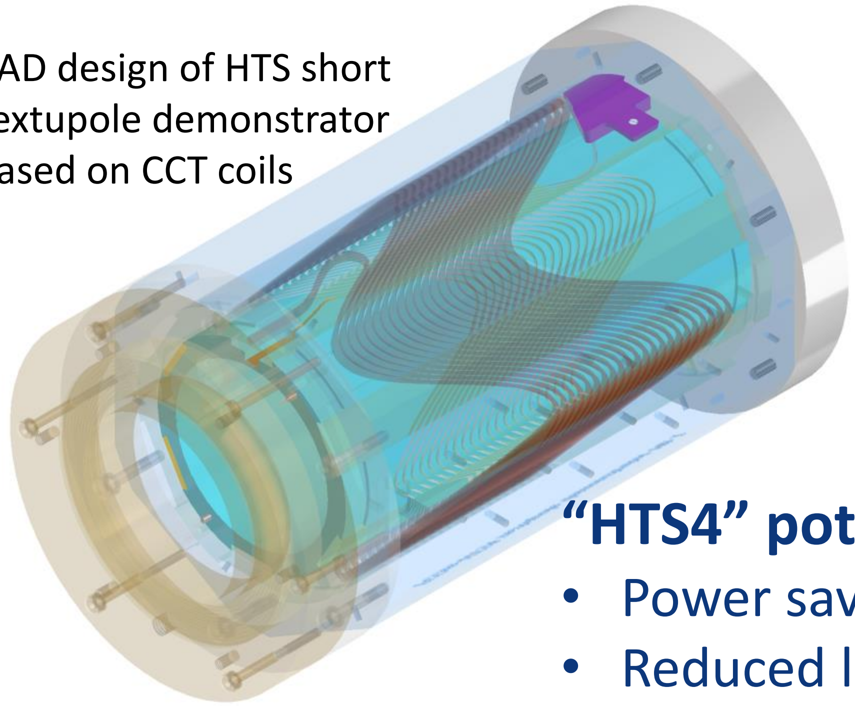

**HTS option**

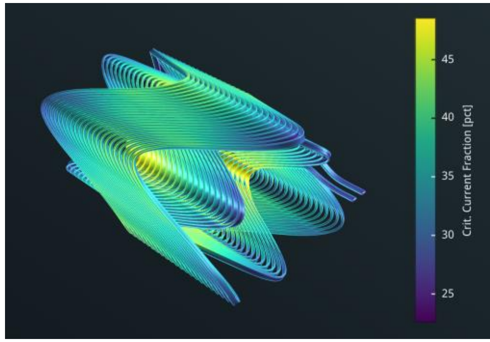



## "HTS4" project within CHART collaboration

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

CAD design of HTS short sextupole demonstrator based on CCT coils






M. Koratzinos, B. Auchmann

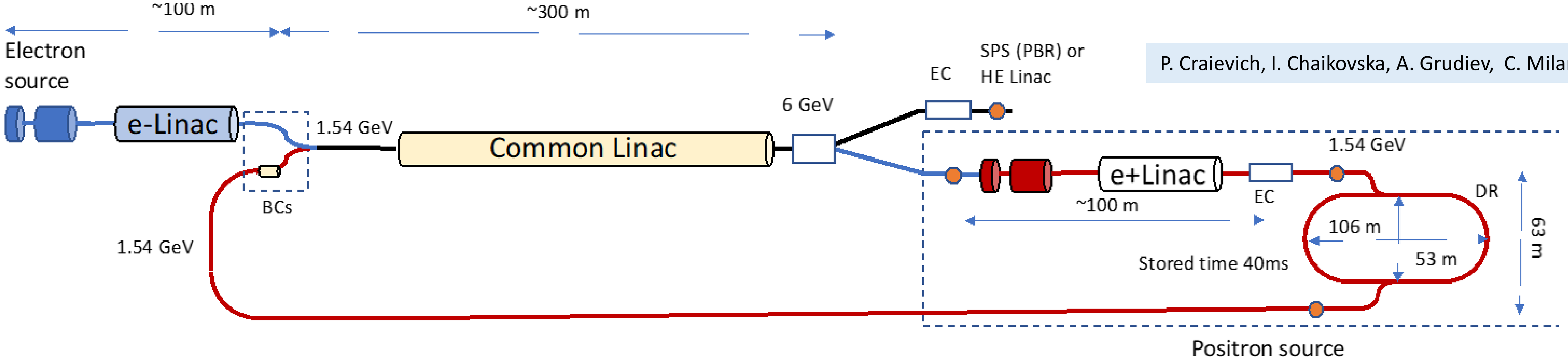
## "HTS4" potential

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

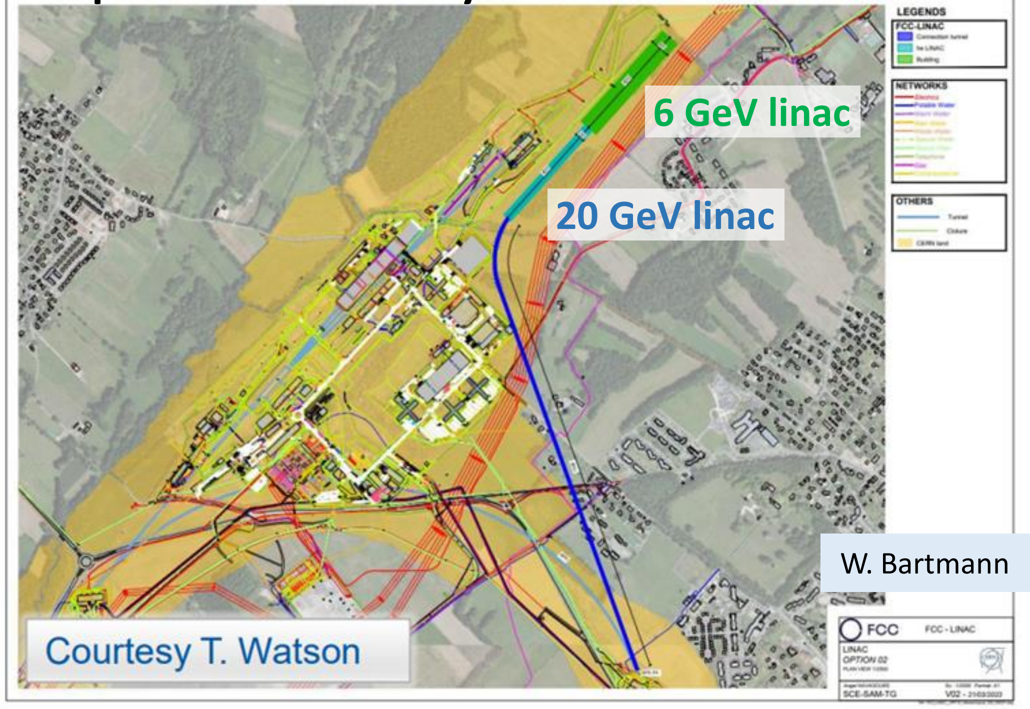
FUTURE CIRCULAR COLLIDER

# New FCC-ee Injector Layout & Implementation

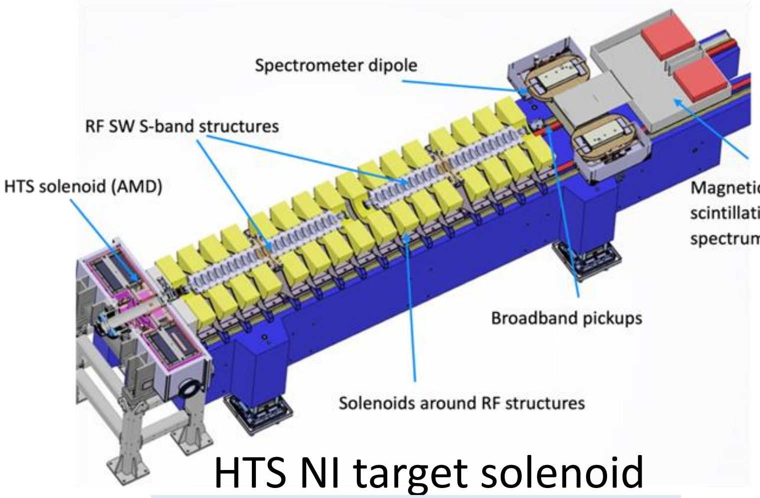
P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

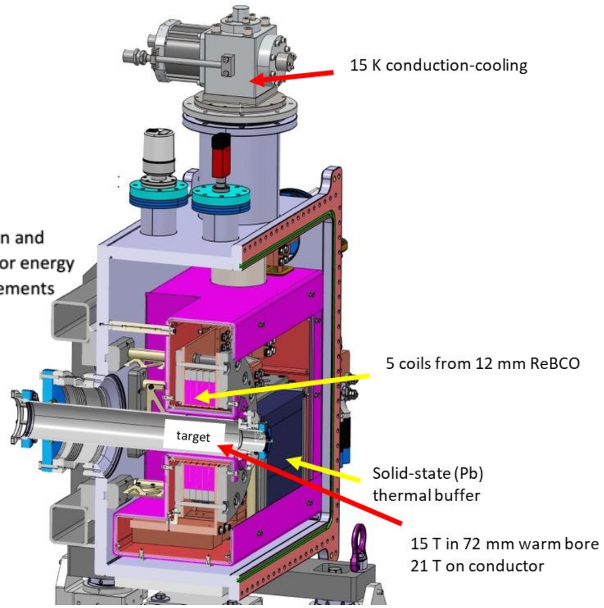



## Implementation study on Prevessin site




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



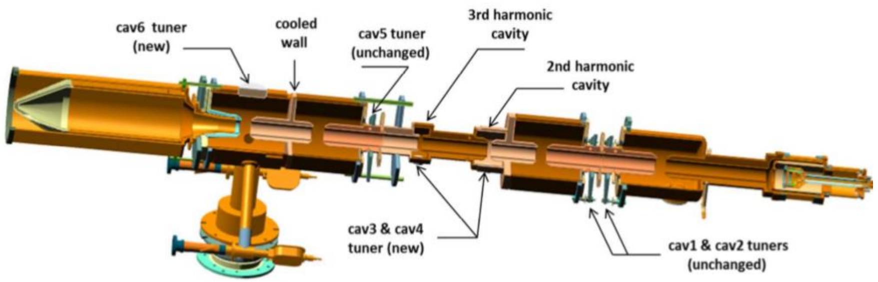

HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues

# FCC-ee Accelerator R&D Examples

## Efficient RF power sources
(400 & 800 MHz)

I. Syratchev




FPC & HOM coupler, cryomodule, thin-film coatings…

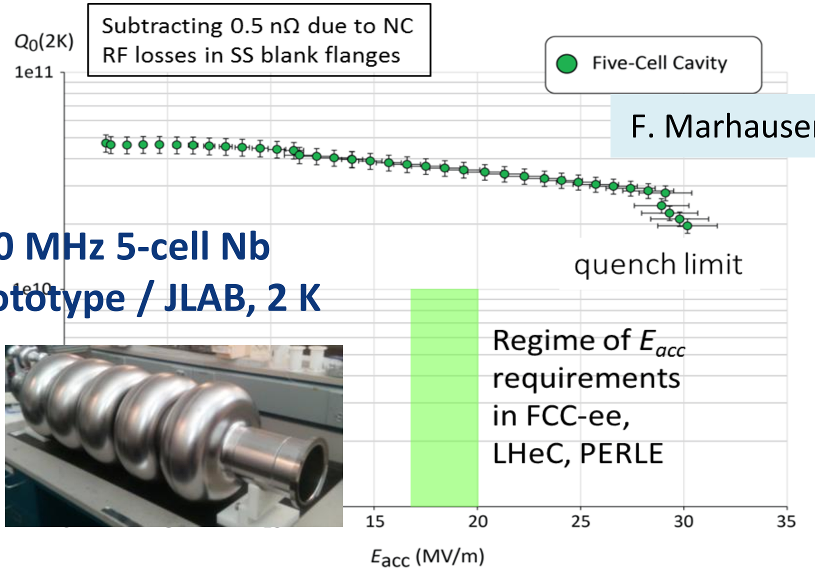
## Efficient SC cavities

Jefferson Lab

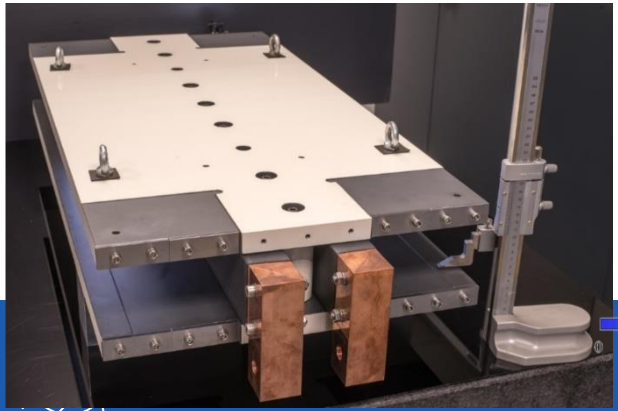
400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

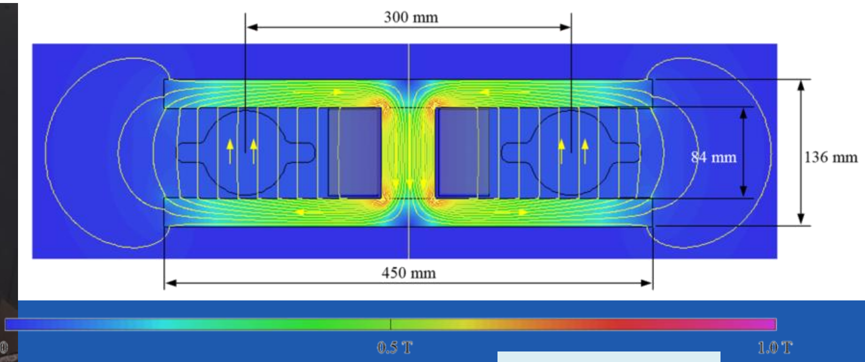
800 MHz 5-cell Nb prototype / JLAB, 2 K

F. Marhauser




## Energy **efficient** twin aperture **arc dipoles**

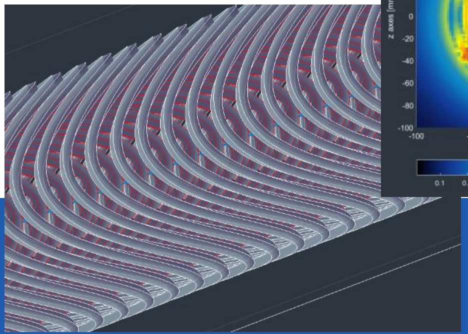


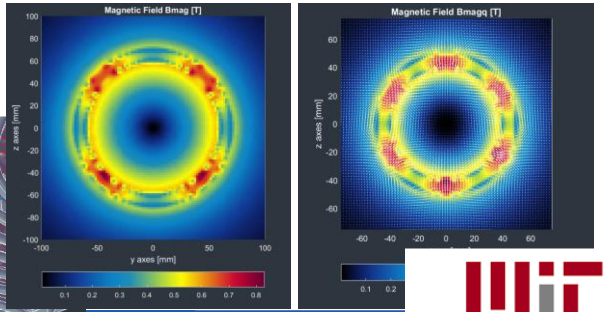



A. Milanese

## Under study: **CCT HTS quad's & sext's for arcs**

PAUL SCHERRER INSTITUT PSI






Massachusetts Institute of Technology

M. Koratzinos

# Stage 2 - FCC-hh (pp) Collider Parameters

FUTURE CIRCULAR COLLIDER

| 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 |

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

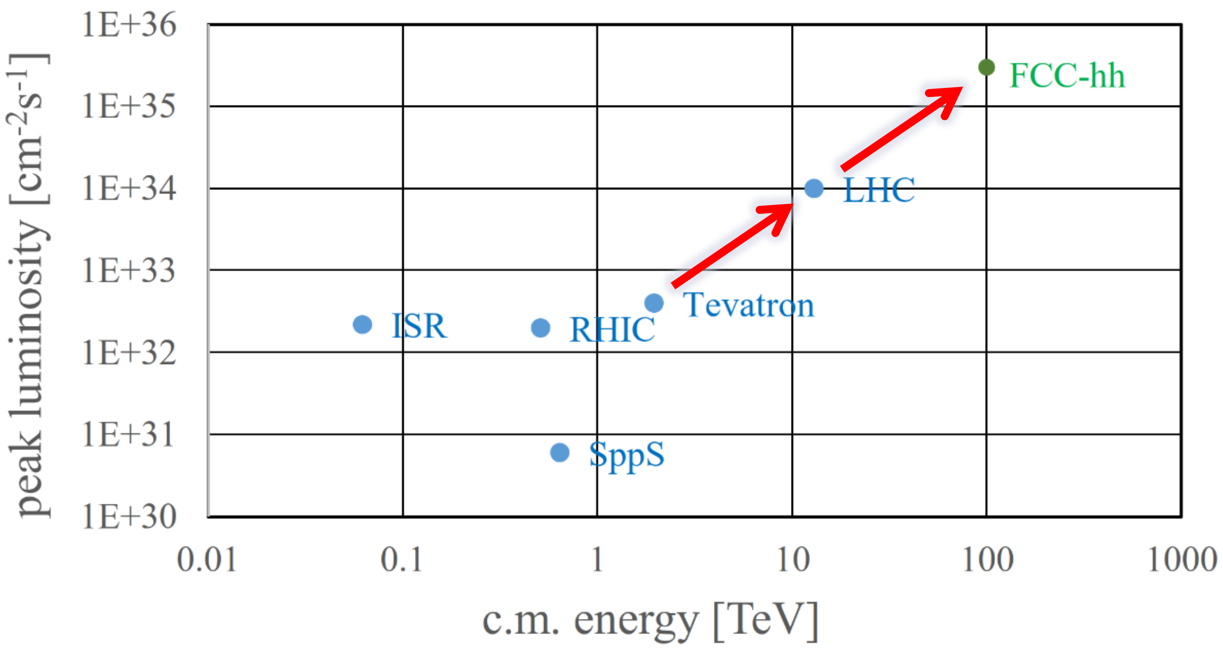
- high-field superconducting magnets: 14 - 20 T
- power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- stored beam energy: ~ 9 GJ → machine protection
- pile-up in the detectors: ~1000 events/xing
- energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

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$\gamma$, μμ)
- Final word about WIMP dark matter

F. Gianotti

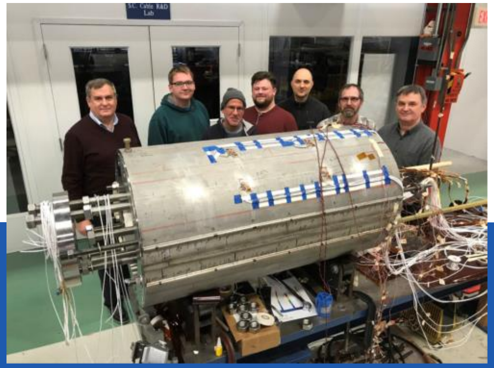
# FCC-hh: Highest Collision Energies




- **Order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab$^{-1}$ per experiment collected over 25 years** of operation (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 dipole**

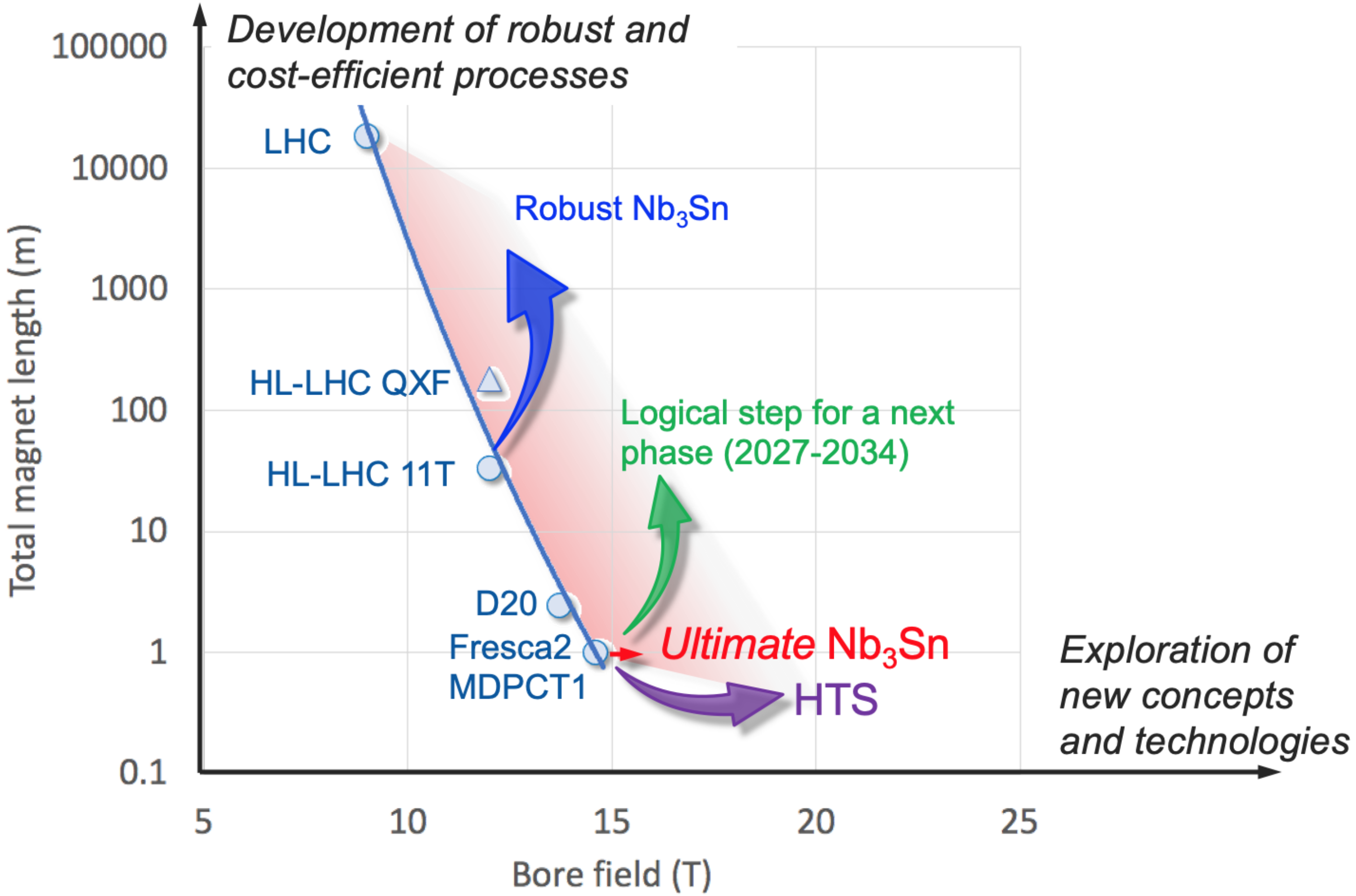
**via**
**HL-LHC technology**
**12 T $Nb_3Sn$ quadrupole**



**FNAL dipole demonstrator**
**14.5 T $Nb_3Sn$**

# High-field Magnet R&D: First steps towards FCC-hh

**In parallel to FCC Study, HFM development programme as long-term separate R&D project**




Main R&D activities:

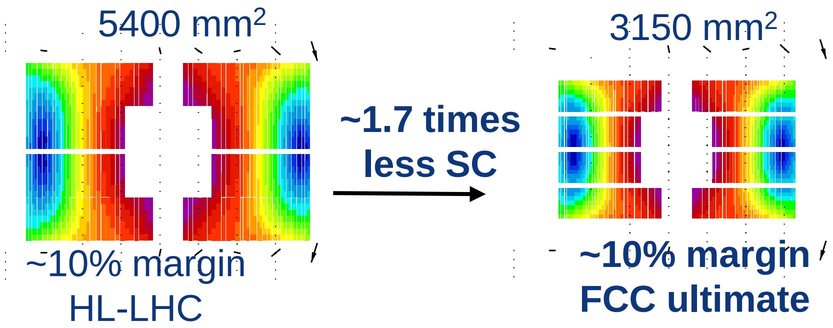
- materials: goal is ~16 T for $Nb_3Sn$, at least ~20 T for HTS inserts
- magnet technology: engineering, mechanical robustness, insulating materials, field quality
- production of models and prototypes: to demonstrate material, design and engineering choices, industrialisation and costs
- infrastructure and test stations: for tests up to ~ 20 T and 20-50 kA

Global collaborations already established during FCC CDR phase.

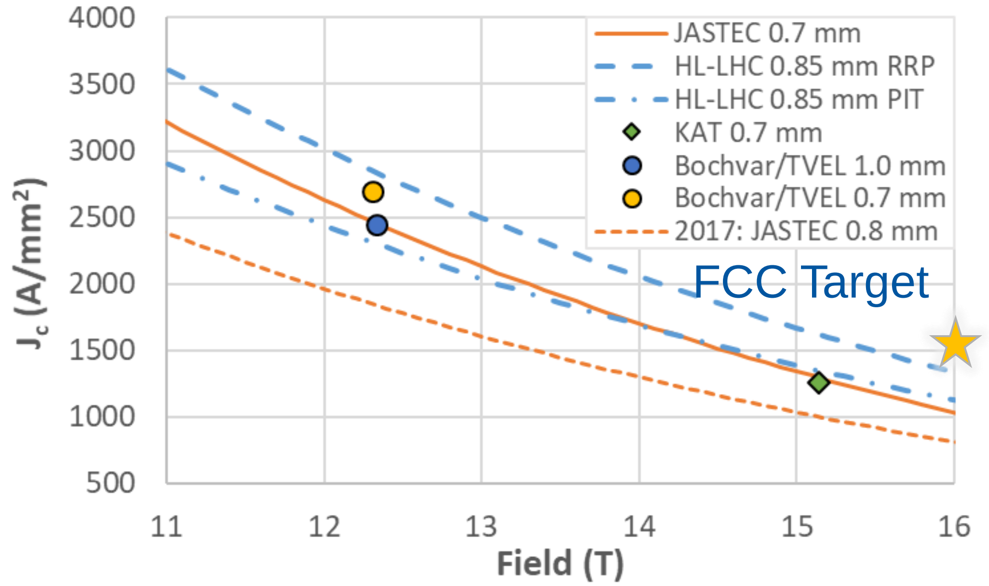
# World-wide FCC $Nb_3Sn$ Programme

**Main development goal is wire performance increase:**

- **$J_c$ (16T, 4.2K) > 1500 A/mm² → 50% increase wrt HL-LHC wire**
- **Reduction of coil & magnet cross-section**




After 1-2 years development, **prototype $Nb_3Sn$ wires from several new industrial FCC partners already achieve HL-LHC $J_c$ performance**




## FCC conductor development collaboration:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **Bruker, Germany, Luvata Pori, Finland**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea, Columbus**, **Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy, University of Freiberg**, **Germany**

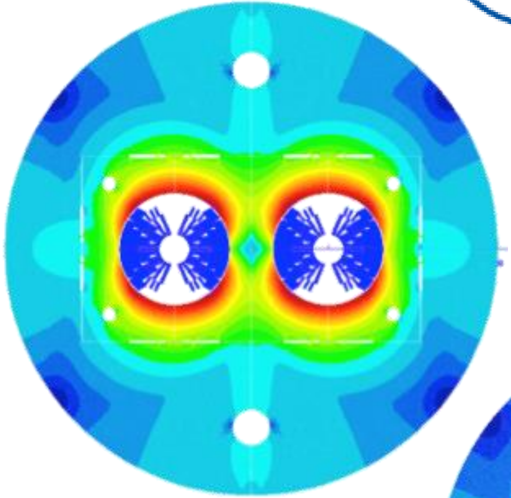
## 2019/20 results from US, meeting FCC $J_c$ specs:

- **Florida State University:** high-$J_c$ $Nb_3Sn$ via Hf addition
- **Hyper Tech /Ohio SU/FNAL**: high-$J_c$ $Nb_3Sn$ via artificial pinning centres based on Zr oxide.

# 16 T Dipole Design Activities and Options

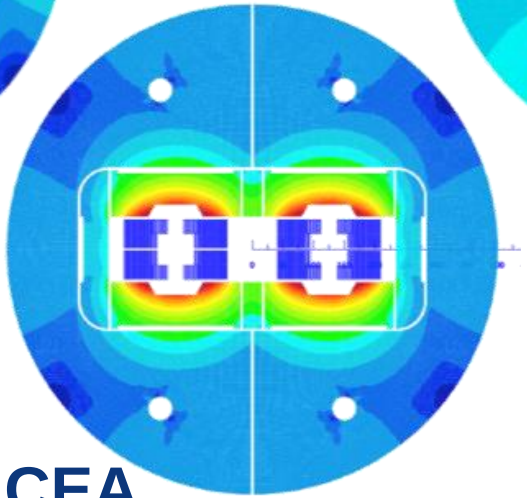
H2020 EuroCirCol A key to New Physics

Cos-theta



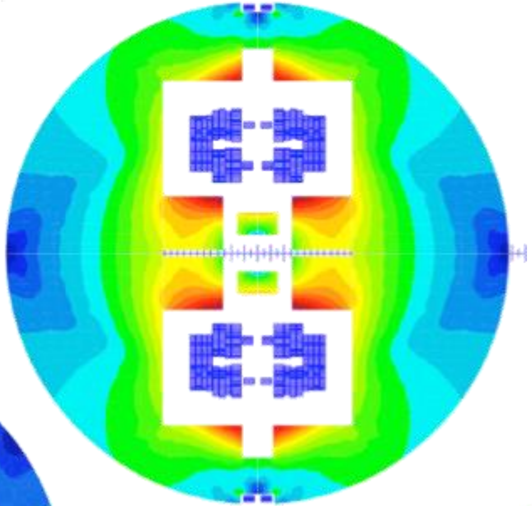
INFN

Blocks



CEA

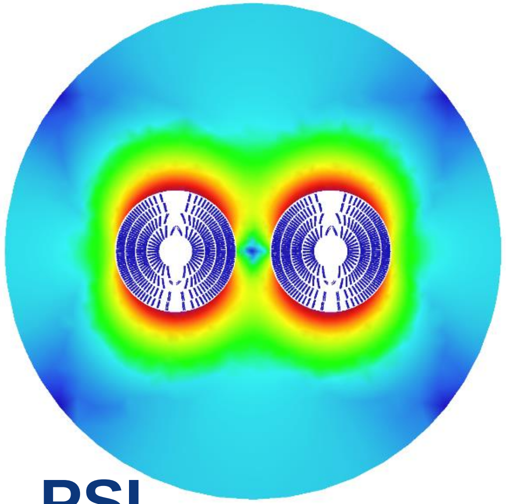
Common coils



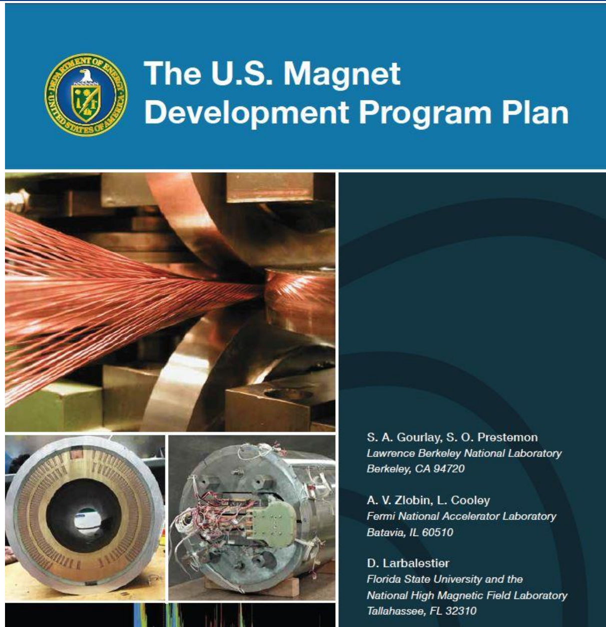
CIEMAT

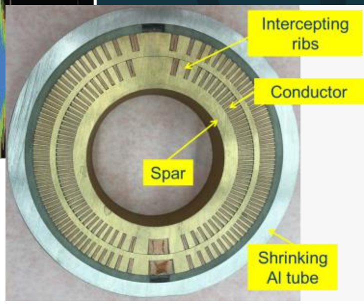
Swiss contribution

Canted Cos-theta

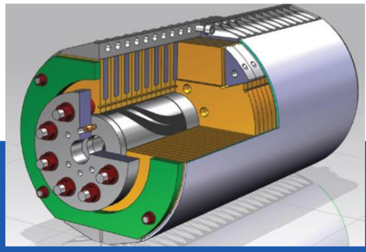


PSI



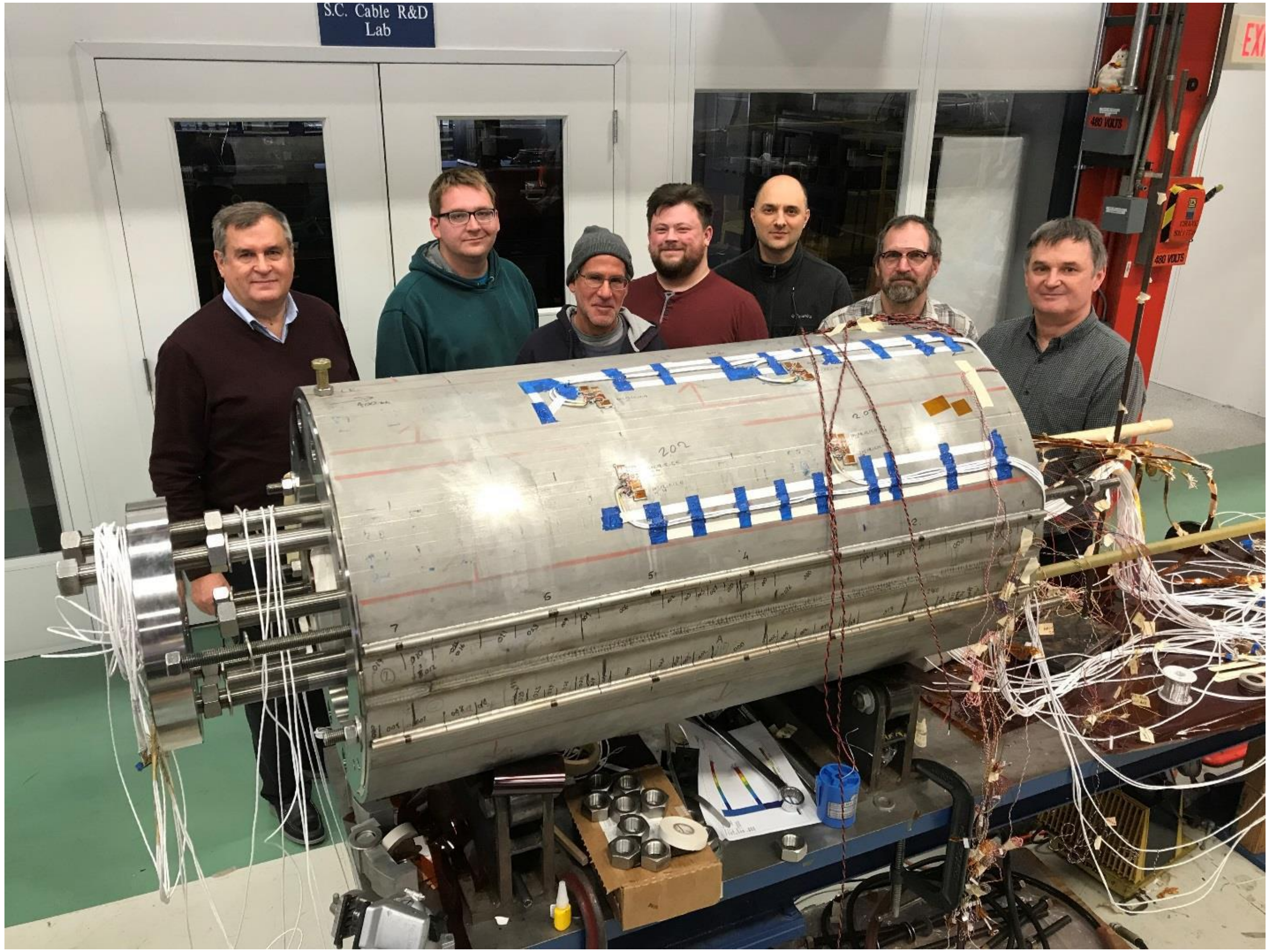

LBNL

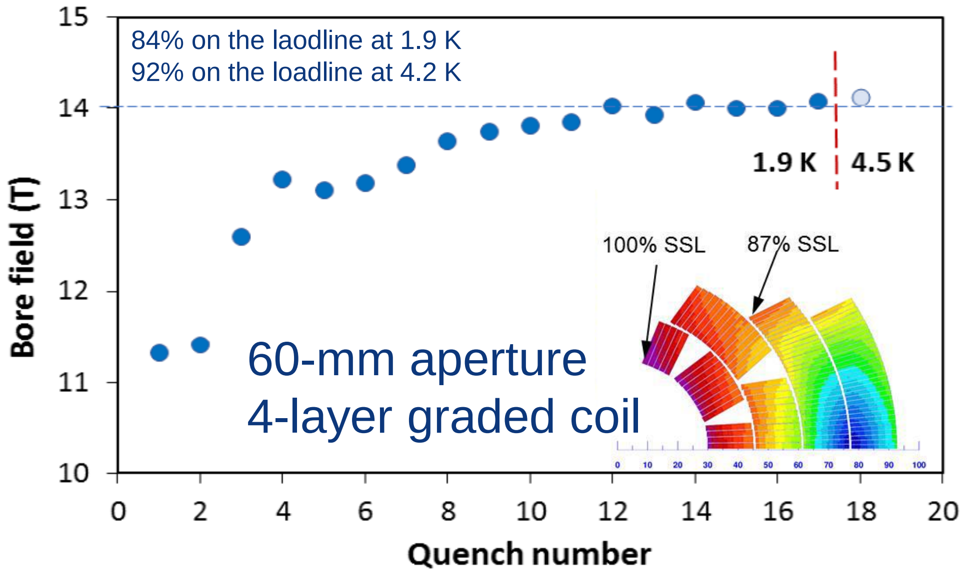


FNAL

**Short model magnets (1.5 m lengths) will be built until 2025**

# US – MDP: 14.5 T Magnet Tested at FNAL




- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

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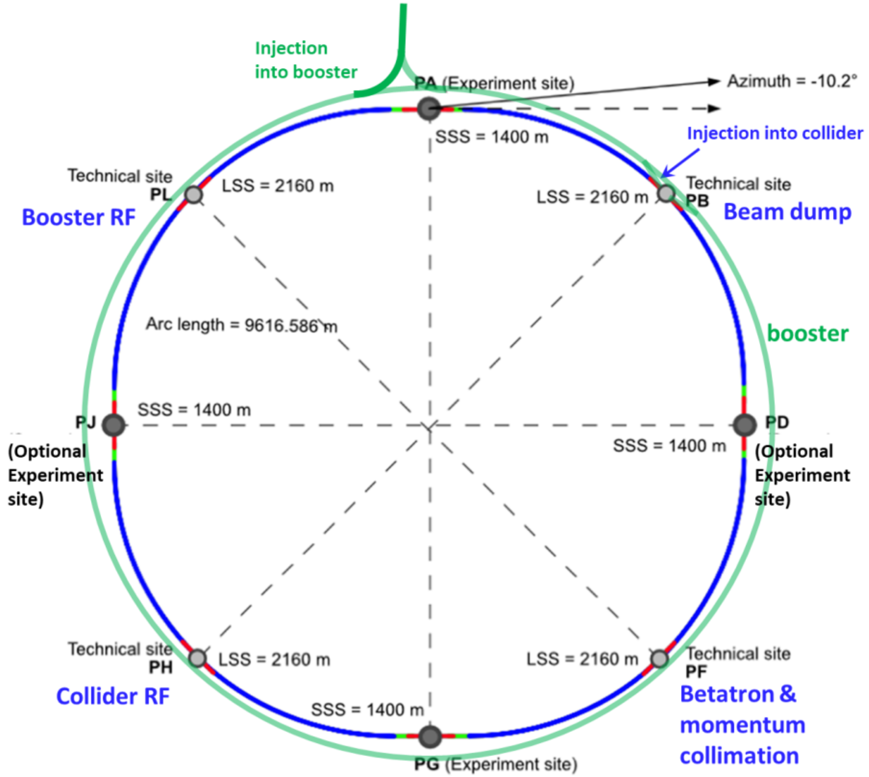
# Optimised Placement and Lay-out for Feasibility Study

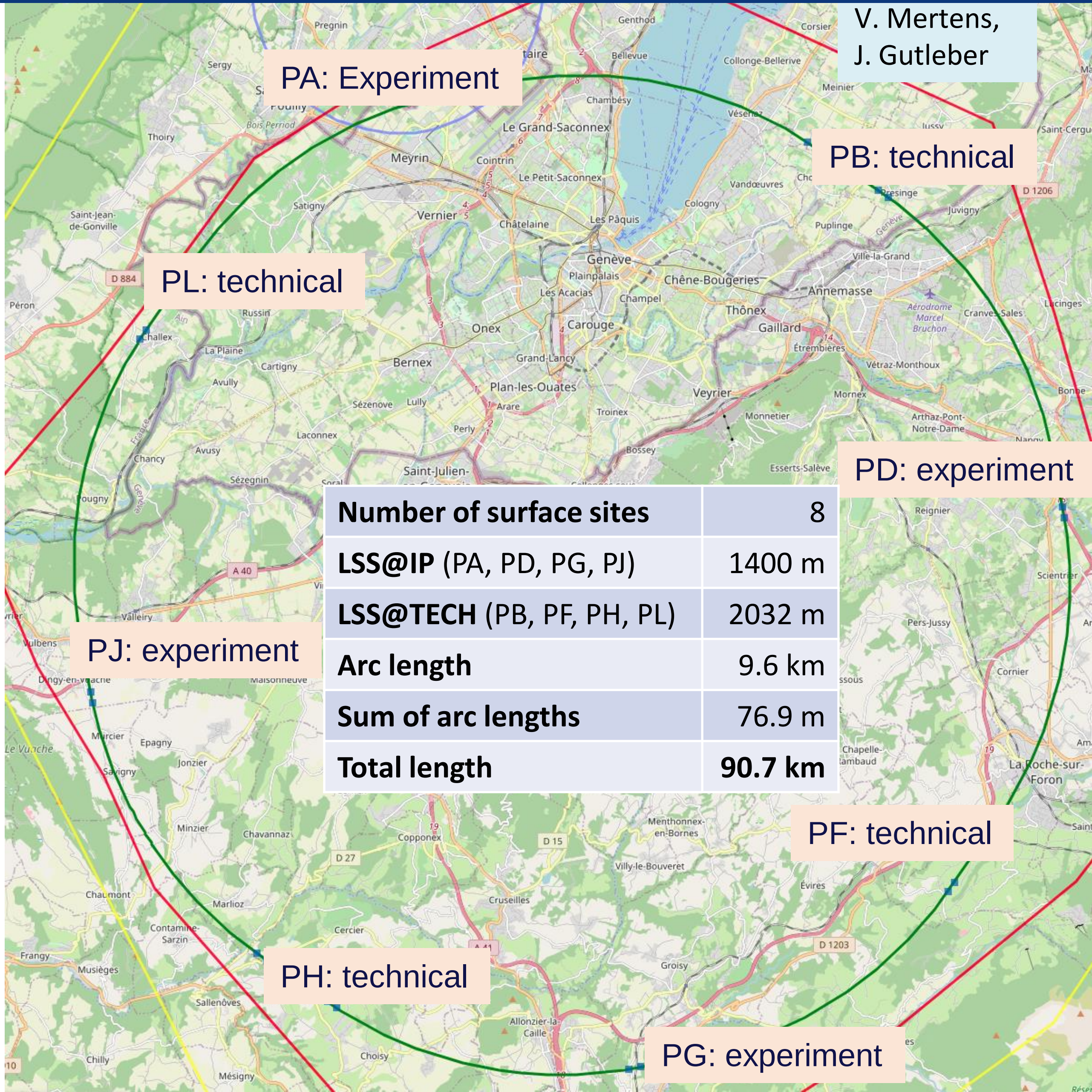
Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

"Avoid-reduce-compensate" principle of EU and French regulations

**Overall lLowest-risk baseline: 90.7 km ring, 8 surface points,**
Whole project now adapted to this placement

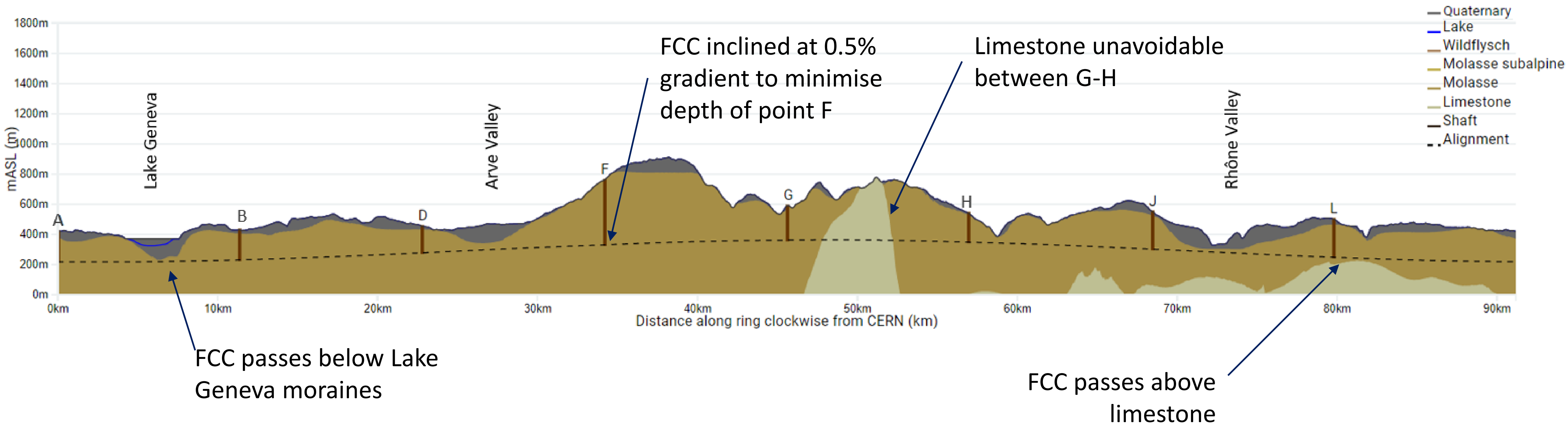



V. Mertens,
J. Gutleber




| Number of surface sites | 8 |
|---|---|
| **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** |

# FCC Long Section – PA31-1.0




## Shaft depth:

A: 202 m B: 200 m D: 177 m F: 399 m G: 228 m H: 139 m J: 251 m L: 253 m

John Osborne

# 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 |

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# Progress with 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 experimental

**PF – Roche sur Foron/Etaux** (FR) – site technique

**PG – Charvonnex/Groisy** (FR) – site experimental

**PH – Cercier** (FR) – site technique

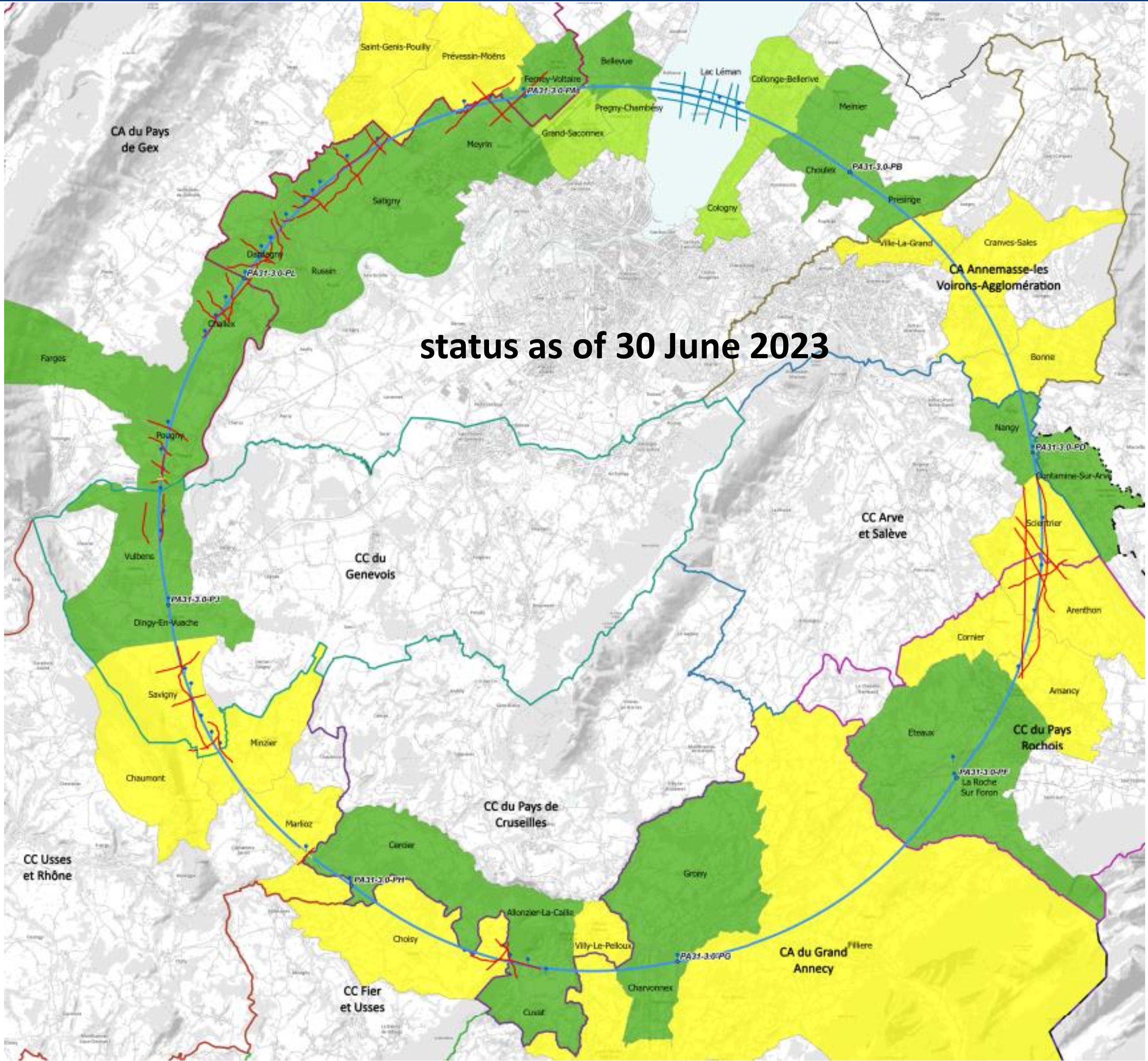
**PJ – Vulbens/Dingy en Vuache** (FR) site experimental

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

Rencontrée individuellement

Rendez-vous proposé / programmé

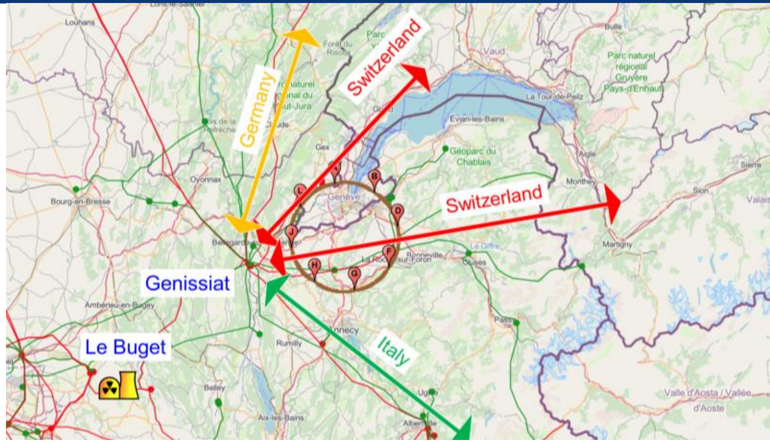
Rencontre collective




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

# Connections to Electrical Grid Infrastructure

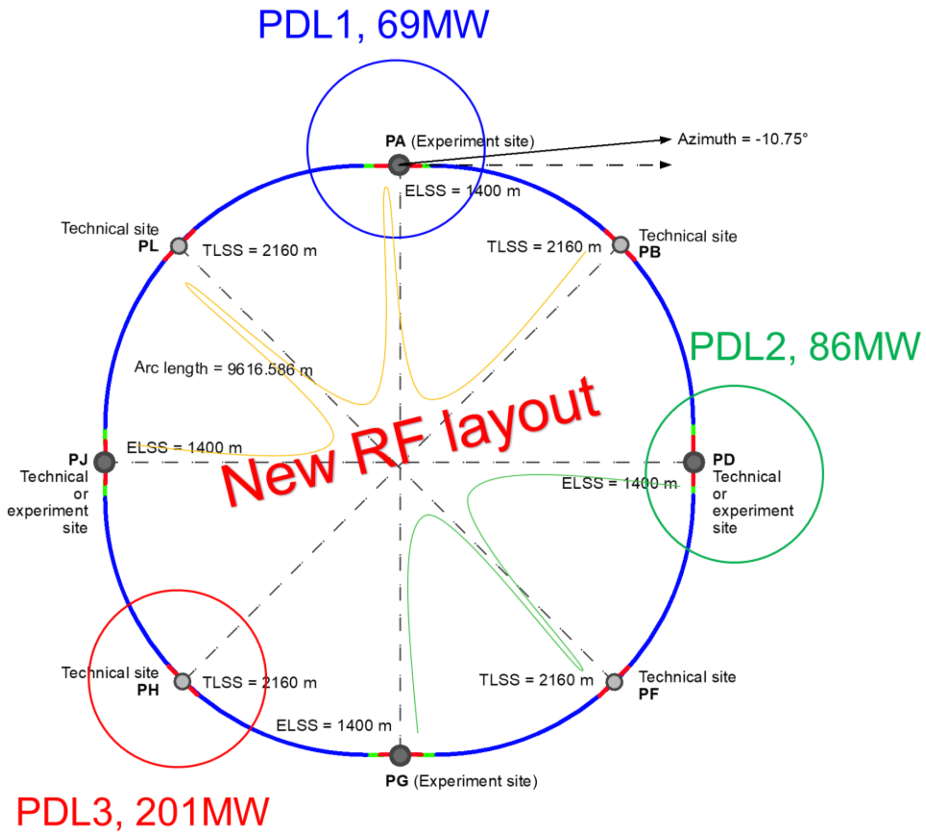
| Updated FCC-ee energy consumption | Z | W | H | TT |
|---|---|---|---|---|
| Beam energy (GeV) | 45.6 | 80 | 120 | 182.5 |
| Max. power during beam operation (MW) | **222** | **247** | **273** | **357** |
| Average power / year (MW) | 122 | 138 | 152 | 202 |
| **Total yearly consumption (TWh)** | **1.07**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




**Powering concept and max power load by sub-stations:**

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

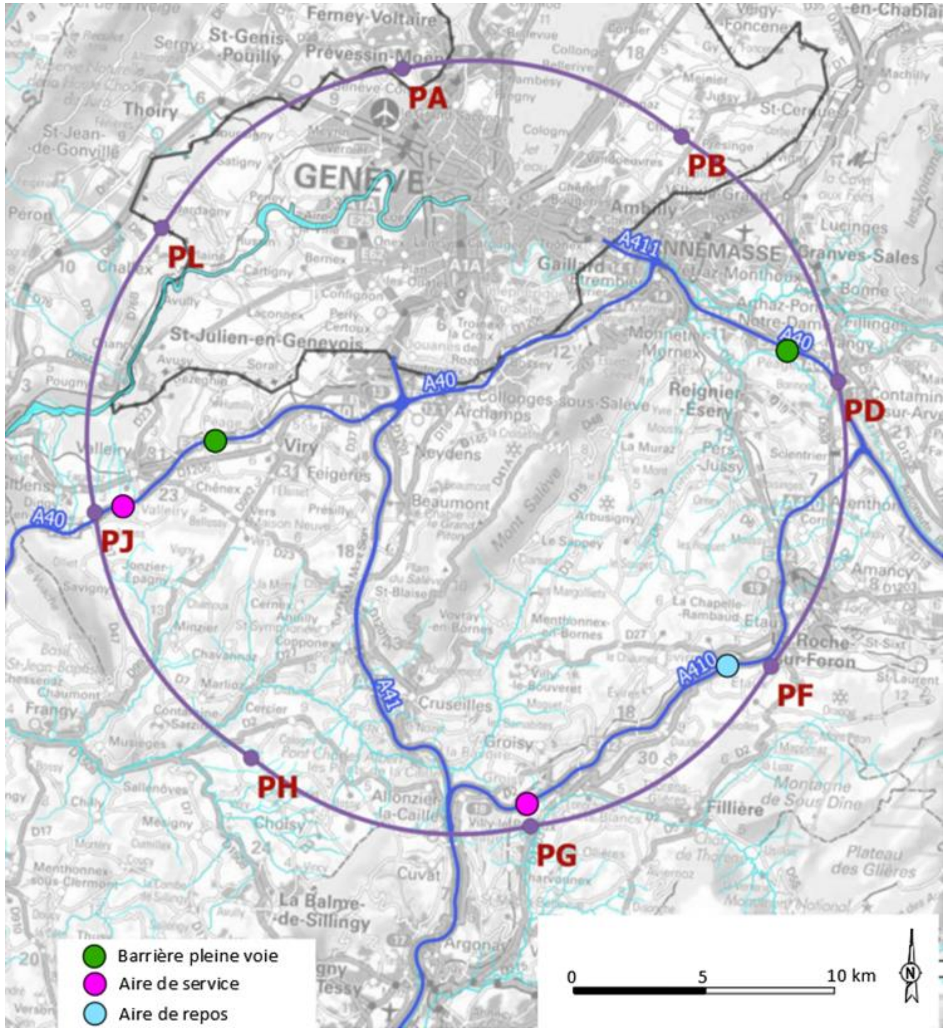
- **Point D with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- **Point A with existing CERN station** covering PB – PL – PJ

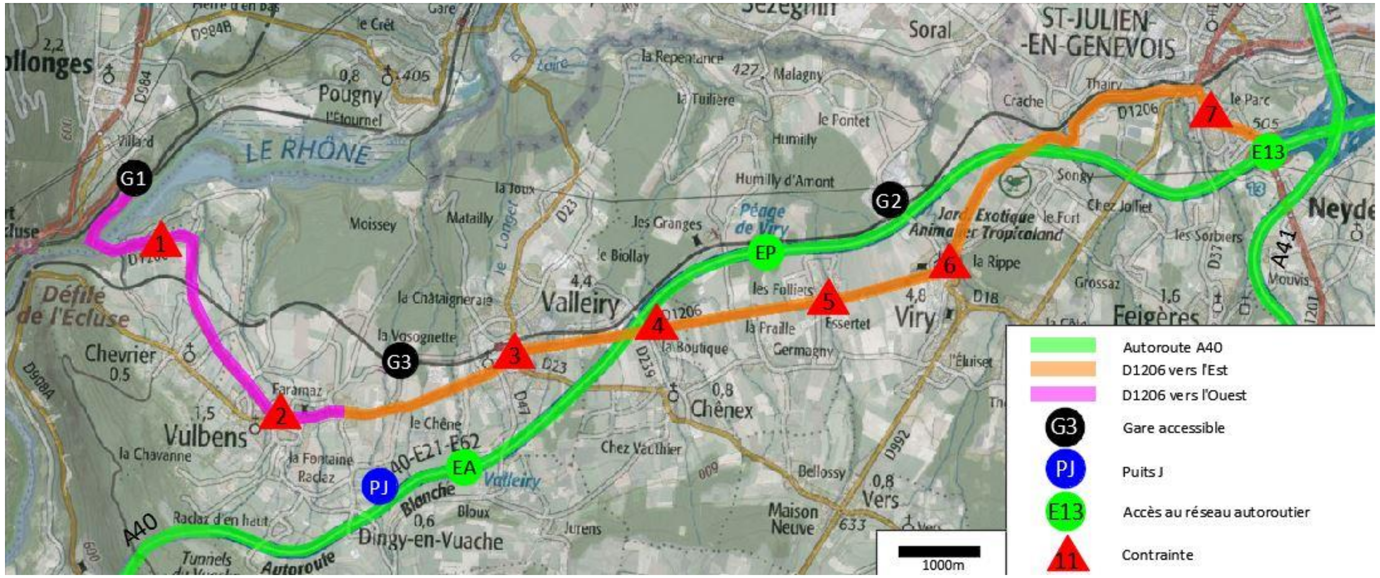


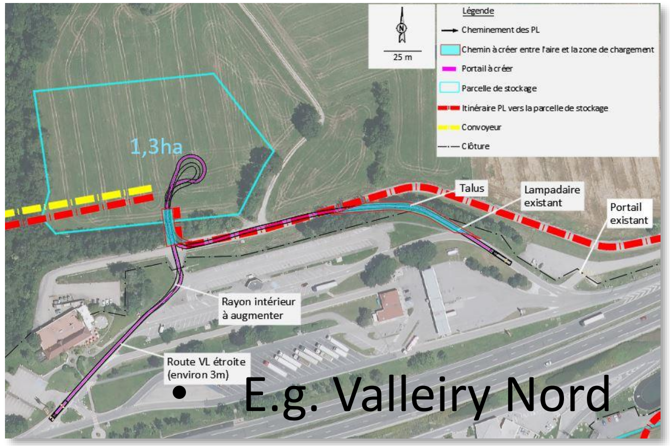

- **Connection concept was studied and confirmed by RTE (French electrical grid operator)**
- **Requested loads have no significant impact on grid**
- **Powering concept and power rating of the three sub-stations compatible with FCC-hh**

# 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)




- E.g. Valleiry Nord

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

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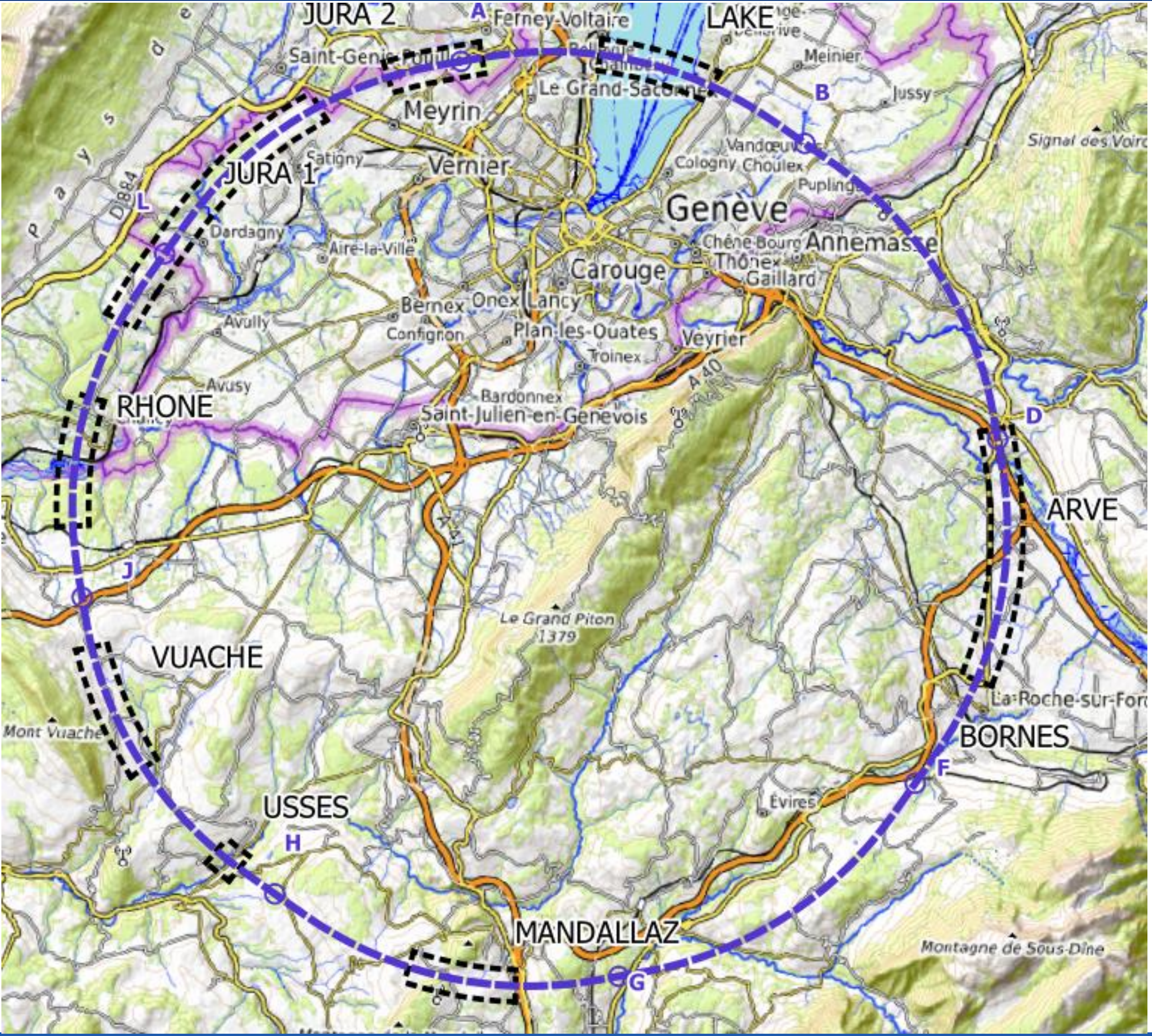
# Plans for High-risk Area Site Investigations




**JURA, VUACHE (3 AREAS)**
Top of limestone
Karstification and filling-in at the tunnel depth
Water pressure

**LAKE, RHÔNE, ARVE AND USSES VALLEY (4 AREAS)**
Top of the molasse
Quaternary soft grounds, water bearing layers

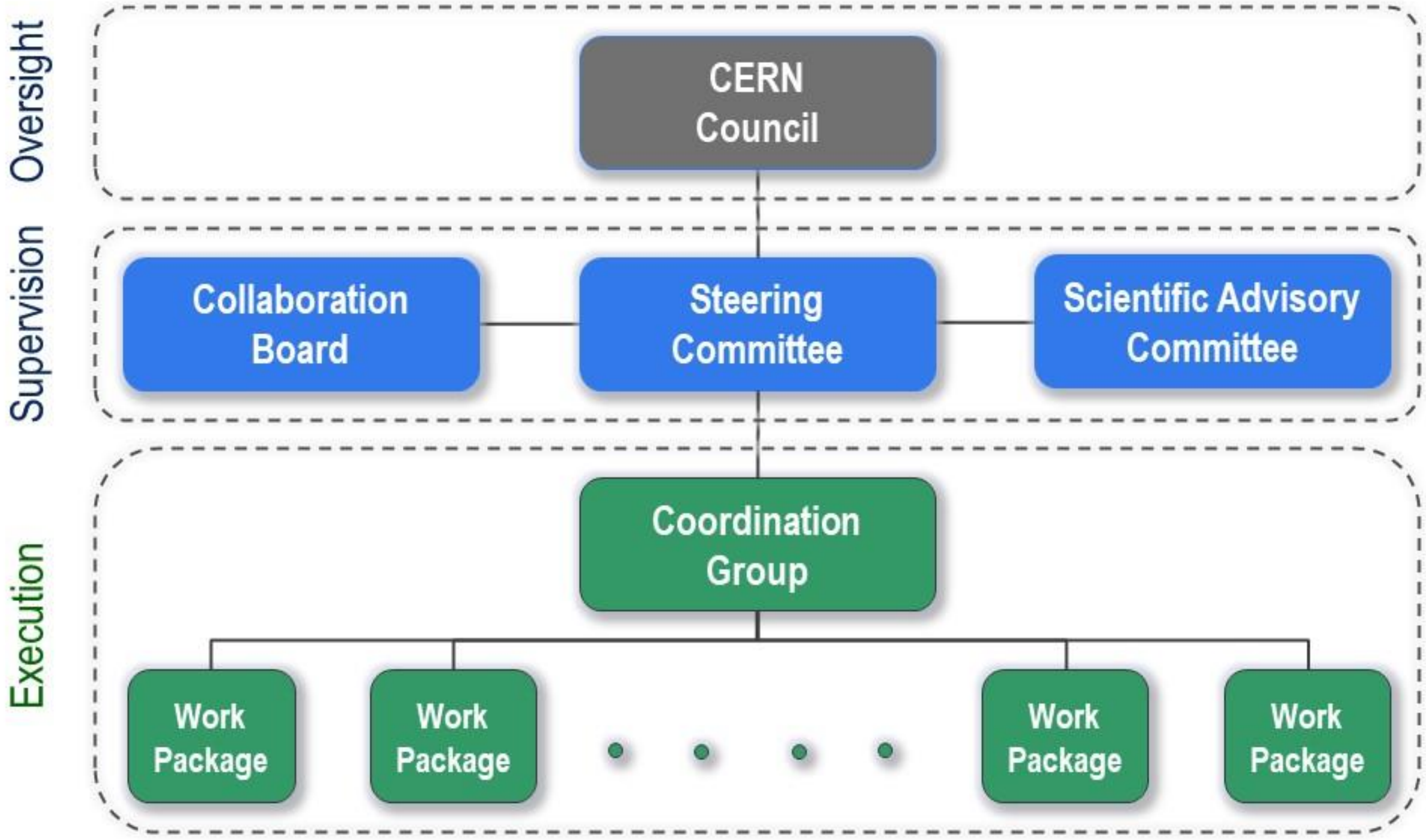
**MANDALLAZ (1 AREA)**
Water pressure at the tunnel level
Karstification

**BORNES (1 AREA)**
High overburden molasse properties
Thrust zones

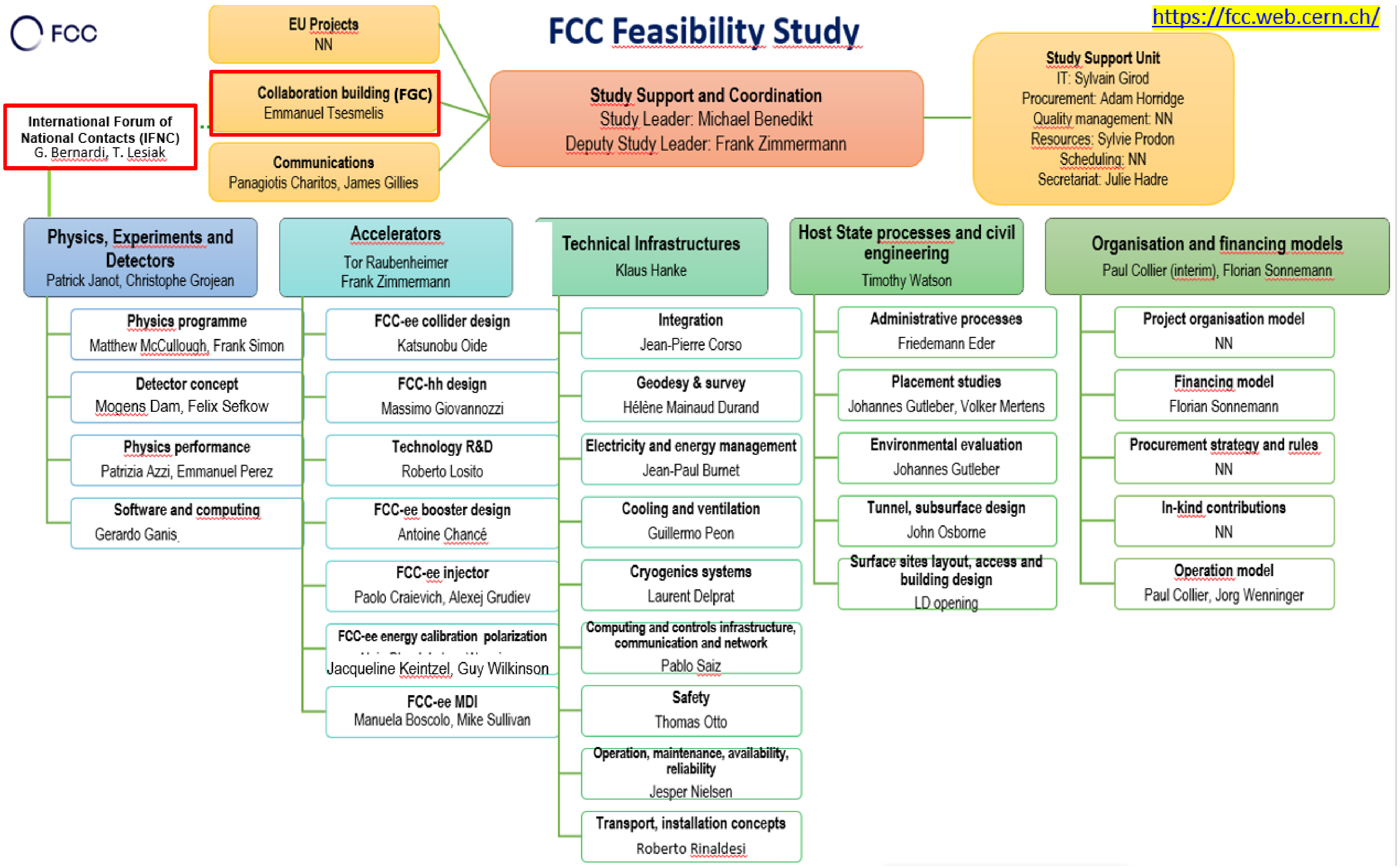
**Site investigations planned for 2024 – 2025:**
**~40-50 drillings, 100 km of seismic lines**

# FCC Feasibility Study Organisational Structure

- **Ownership** of the Feasibility Study by the Council.
- Effective and timely **supervision**.
- Integration of scientific and technical **advice**.
- **Participation of stakeholders** that can potentially make significant financial and technical contributions to a possible future project.
- **Execution** of Feasibility Study.



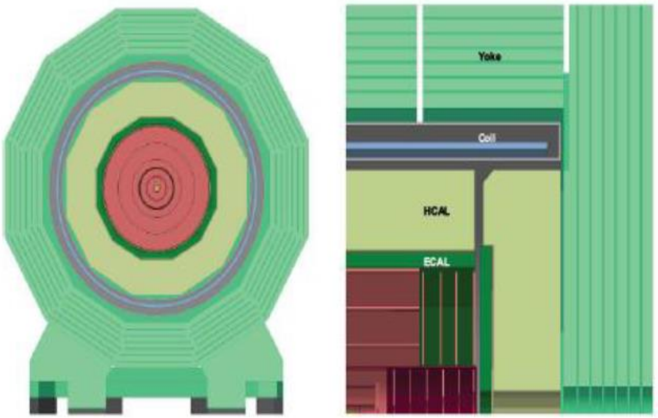
# FGC and IFNC



FCC
EU Projects
NN
Collaboration building (FGC)
Emmanuel Tsesmelis
Communications
Panagiotis Charitos, James Gillies
International Forum of National Contacts (IFNC)
G. Bernardi, T. Lesiak
FCC Feasibility Study
https://fcc.web.cern.ch/
Study Support and Coordination
Study Leader: Michael Benedikt
Deputy Study Leader: Frank Zimmermann
Study Support Unit
IT: Sylvain Girod
Procurement: Adam Horridge
Quality management: NN
Resources: Sylvie Prodon
Scheduling: NN
Secretariat: Julie Hadre
Physics, Experiments and Detectors
Patrick Janot, Christophe Grojean
Physics programme
Matthew McCullough, Frank Simon
Detector concept
Mogens Dam, Felix Sefkow
Physics performance
Patrizia Azzi, Emmanuel Perez
Software and computing
Gerardo Ganis
Accelerators
Tor Raubenheimer
Frank Zimmermann
FCC-ee collider design
Katsunobu Oide
FCC-hh design
Massimo Giovannozzi
Technology R&D
Roberto Losito
FCC-ee booster design
Antoine Chancé
FCC-ee injector
Paolo Craievich, Alexej Grudiev
FCC-ee energy calibration polarization
Jacqueline Keintzel, Guy Wilkinson
FCC-ee MDI
Manuela Boscolo, Mike Sullivan
Technical Infrastructures
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, Volker Mertens
Environmental evaluation
Johannes Gutleber
Tunnel, subsurface design
John Osborne
Surface sites layout, access and building design
LD opening
Organisation and financing models
Paul Collier (interim), Florian Sonnemann
Project organisation model
NN
Financing model
Florian Sonnemann
Procurement strategy and rules
NN
In-kind contributions
NN
Operation model
Paul Collier, Jorg Wenninger

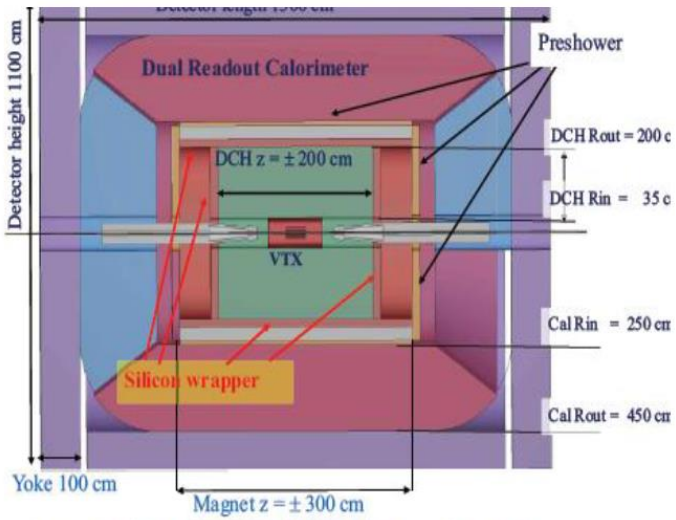
# Detectors Under Study for FCC-ee

## CLD



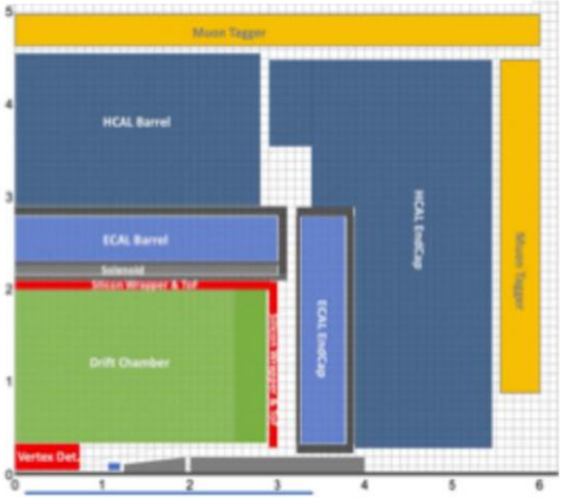

conceptually extended from the CLIC detector design
- full silicon tracker
- 2T magnetic field
- high granular silicon-tungsten ECAL
- high granular scintillator-steel HCAL
- instrumented steel-yoke with RPC for muon detection

## IDEA




- explicitly designed for FCC-ee/CepC
  - silicon vertex
  - low $X_0$ drift chamber
  - drift-chamber silicon wrapper
  - MPGD/magnet coil/lead preshower
  - dual-readout calorimeter: lead-scintillating/ cerenkhov fibers

## Noble Liquid ECAL



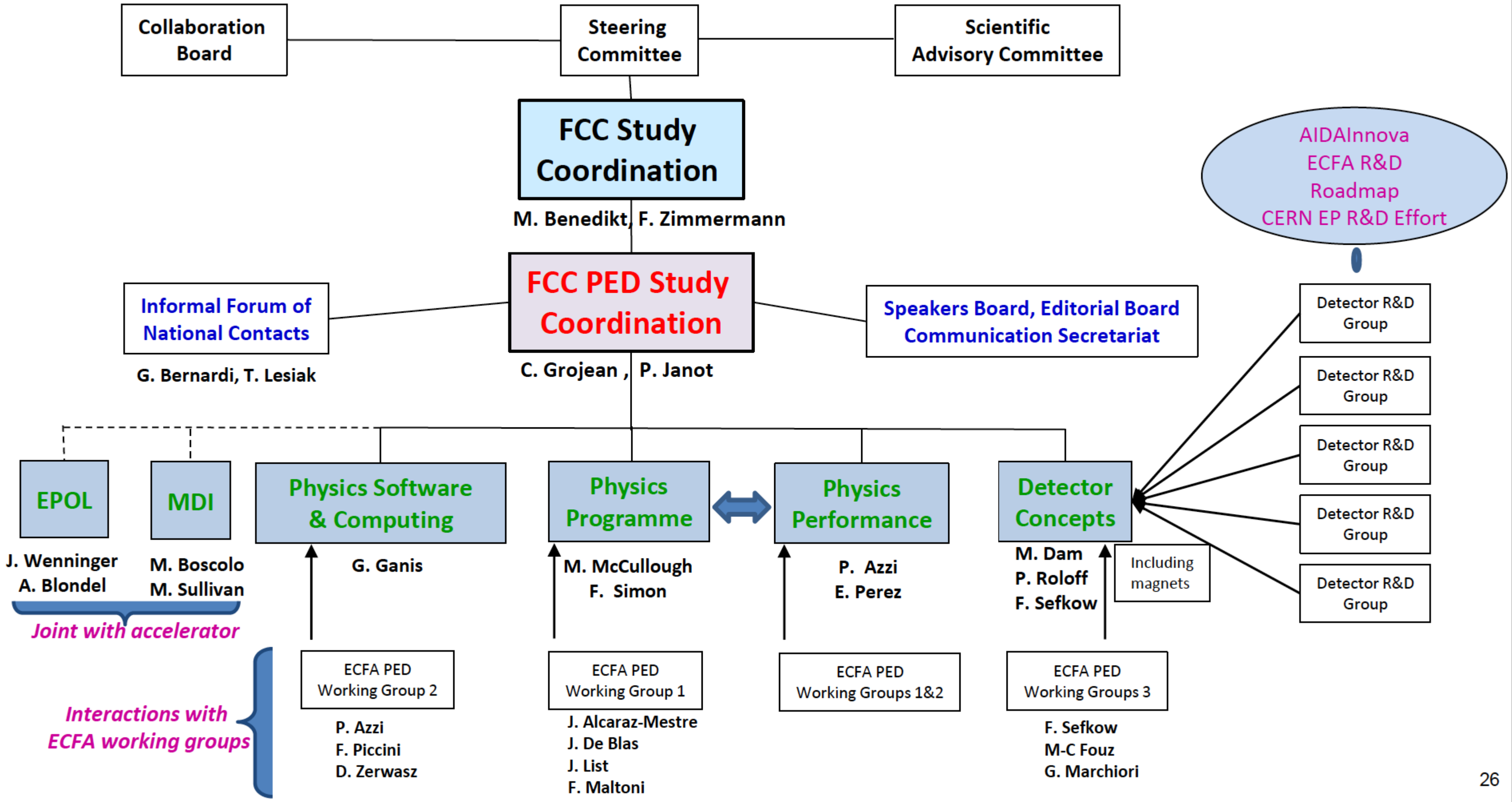

- explicitely designed for FCC-ee, recent concept, under development
- silicon vertex
- Low $X_0$ drift chamber
- Thin Solenoid before the Calorimeter
- High Granularity Liquid Argon Calorimetry

But several other options like Crystal Calorimetry (active in US, Italy), are under study (similarly for tracking, muons and particle ID)

With potentially 4 experiments, many complementary options will be implemented, Definitely a place to contribute

# PED Organisation and Convenors

PED = Physics, Experiments and Detectors



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# Timeline of the FCC Integrated Programme

Technical schedule

1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | ………………… | 19 | 20 | FCC-ee ~ 15 years operation | 10 years | FCC-hh ~ 25 years operation | 70

Feasibility Study

ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

| | √s | L /IP ($cm^{-2} s^{-1}$) | Int. L /IP($ab^{-1}$) | Comments |
|---|---|---|---|---|
| $e^+e^-$ FCC-ee | ~90 GeV Z<br>160 WW<br>240 H<br>~365 top | 230 $x10^{34}$<br>28<br>8.5<br>1.5 | 75<br>5<br>2.5<br>0.8 | 2-4 experiments<br>Total ~ 15 years of operation |
| pp FCC-hh | 100 TeV | 5 x $10^{34}$<br>30 | 20-30 | 2+2 experiments<br>Total ~ 25 years of operation |
| PbPb FCC-hh | $\sqrt{s_{NN}}$ = 39TeV | 3 x $10^{29}$ | 100 $nb^{-1}$/run | 1 run = 1 month operation |
| ep Fcc-eh | 3.5 TeV | 1.5 $10^{34}$ | 2 $ab^{-1}$ | 60 GeV e- from ERL<br>Concurrent operation with pp for ~ 20 years |
| e-Pb Fcc-eh | $\sqrt{s_{eN}}$ = 2.2 TeV | 0.5 $10^{34}$ | 1 $fb^{-1}$ | 60 GeV e- from ERL<br>Concurrent operation with PbPb |

- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~2045-2060
- ❑ FCC-hh operation 2070-2090++

F. Gianotti

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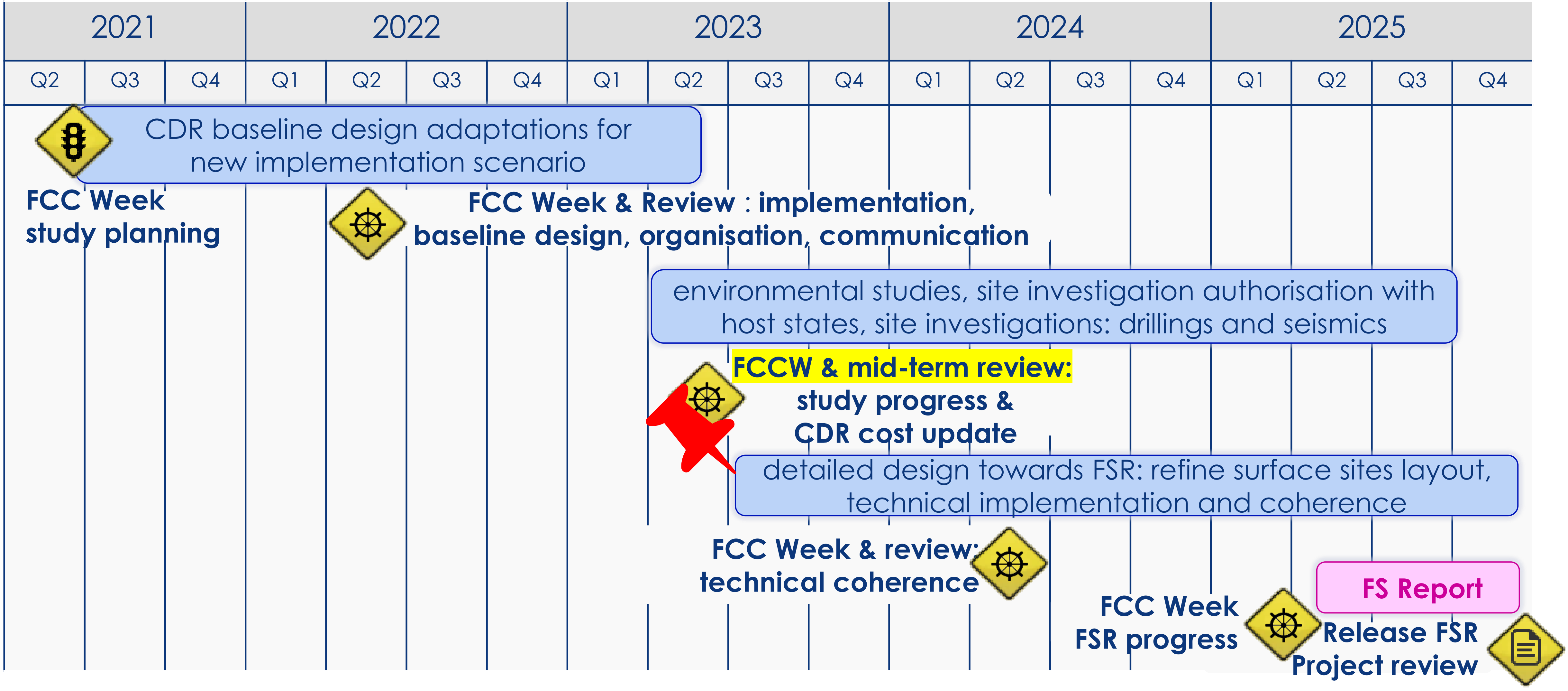
# Feasibility Study Timeline and main activities/milestones



# Mid-Term Review & Cost Review, Autumn '23

**Mid-term review report, supported by additional documentation on each deliverable, will be submitted to review committees and to Council and its subordinate bodies, as input for the review.**

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

### 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 a 10-20 GeV linac
- Key technologies and status of technology R&D program
- FCC-hh overall layout & injection lines from LHC and SC-SPS

### 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

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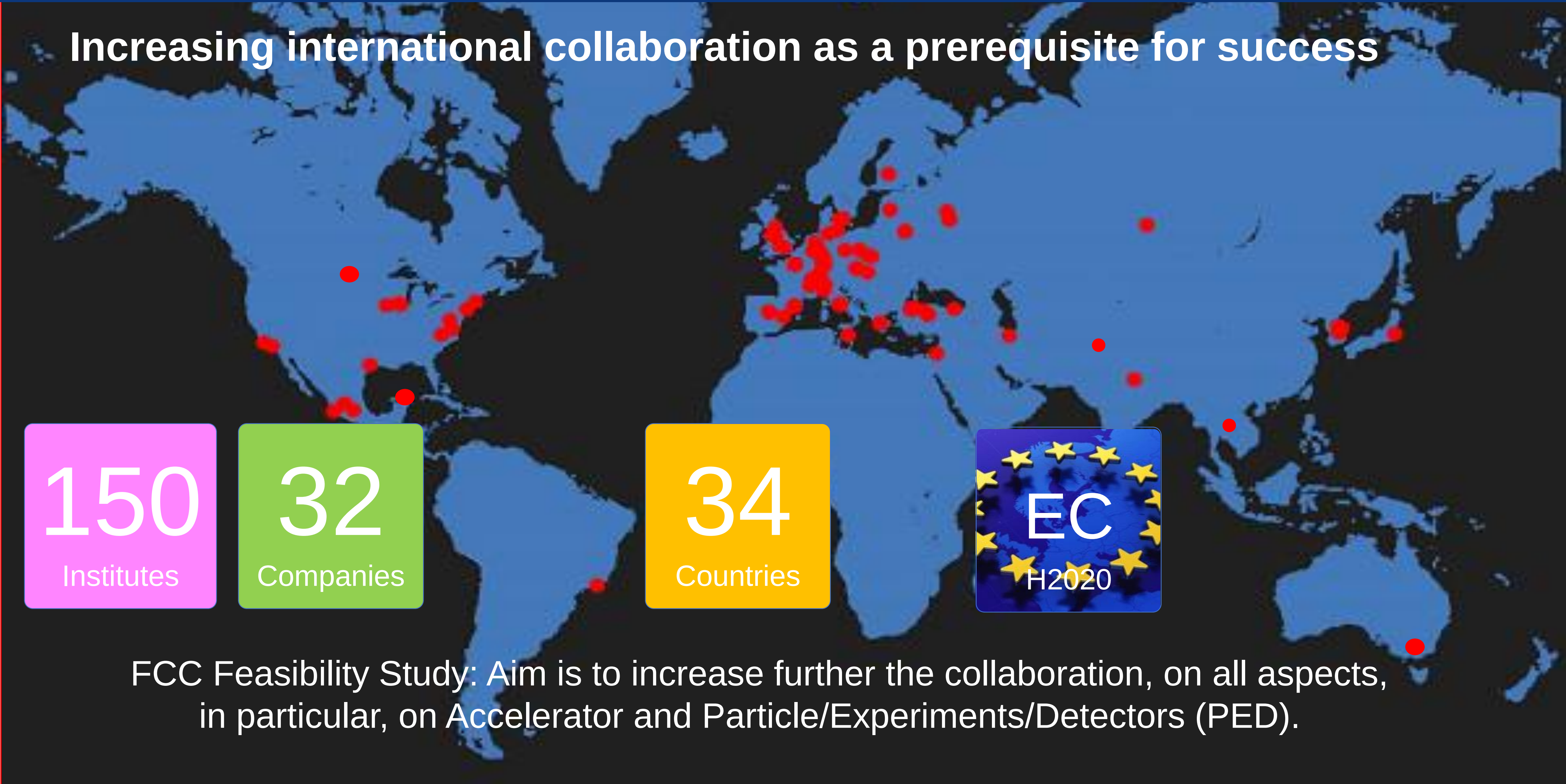
# Status of FCC global collaboration

## Increasing international collaboration as a prerequisite for success



**150** Institutes

**32** Companies

**34** Countries

EC H2020

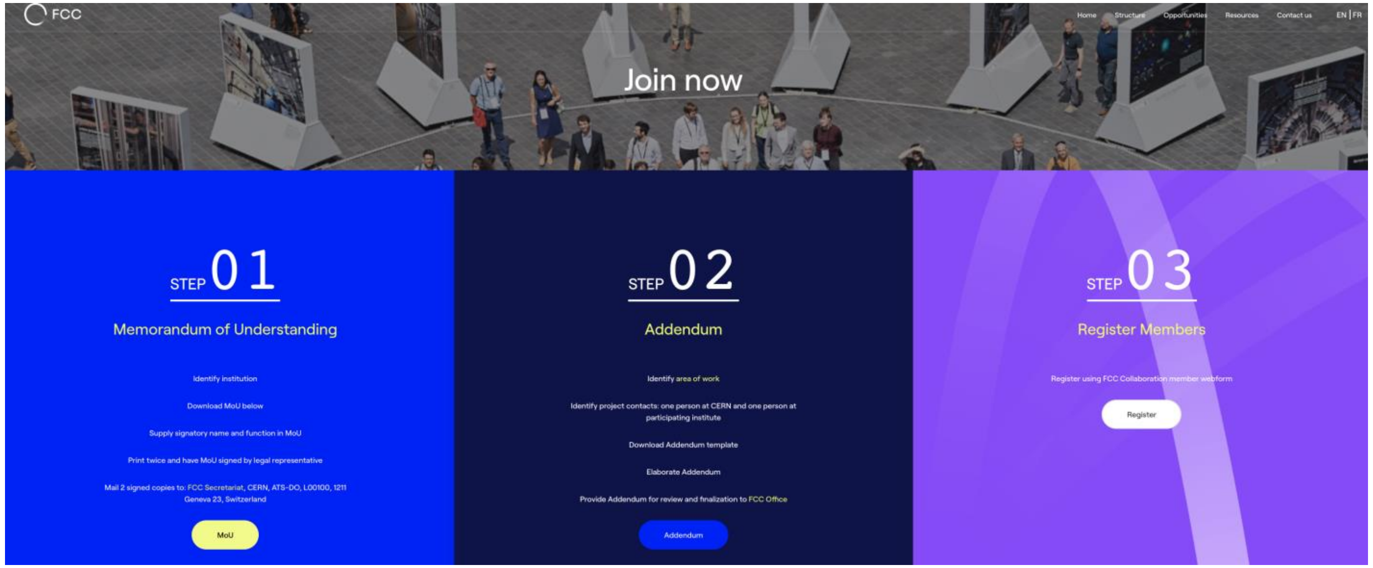
FCC Feasibility Study: Aim is to increase further the collaboration, on all aspects, in particular, on Accelerator and Particle/Experiments/Detectors (PED).

# FCC Feasibility Study Collaboration Membership

Participation in FCC through **MoU and Addenda**.

The FCC MoU for the first phase of the study is being **updated to cover the Feasibility Study**.

The current participating institutes who wish to take part in the Feasibility Study can continue to participate on the basis of the previously signed MoU until the updated MoU is signed.




https://fccis.web.cern.ch/join-now

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FCC Week 2023
London, UK

473 participants

362 in person and
111 remote

Courtesy P. Charitos

# Outlook

Comprehensive R&D programme and implementation preparation is presently being carried out in the frameworks of **FCC FS**, the EU co-financed **FCC Innovation Study**, the **Swiss CHART** programme, and the **CERN High-Field Magnet Programme**.
**Goal: demonstrate FCC feasibility by 2025/26.**

**Plenty of opportunities for collaborations** and for **joint innovative developments** with international partners !

The **first stage of FCC could be approved within a few years after the 2027 European Strategy Update**, if the latter is supportive. **Tunnel construction could then start in the early 2030s** and **FCC-ee physics programme could begin in the second half of the 2040s**, a few years after the completion of the HL-LHC physics runs, expected by 2041.

Long-term goal: **world-leading HEP infrastructure for 21$^{st}$ century** to push particle-physics **precision and energy frontiers** far beyond present limits.

# FCC Summary

- The European Strategy Update in 2020 issued the **request for a feasibility study of the FCC integrated programme to be delivered by end 2025.**
- **The main activities of the FCC Feasibility Study are:**
  - **Local/regional implementation scenario** in collaboration **with Host State authorities.**
  - Accompanied by **machine optimisation, physics studies and technology R&D.**
  - Performed **via global collaboration** and supported by **EC H2020 Design Study FCCIS.**
  - In parallel **High-Field Magnet R&D programme** as separate line, to prepare for FCC-hh.
- Long term goal: **world-leading HEP infrastructure for 21st century** to push the particle-physics **precision and energy frontiers** far beyond present limits.
- **Success of FCC relies on strong global participation. Everybody interested is warmly welcome to join the effort!**

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**Thank you**