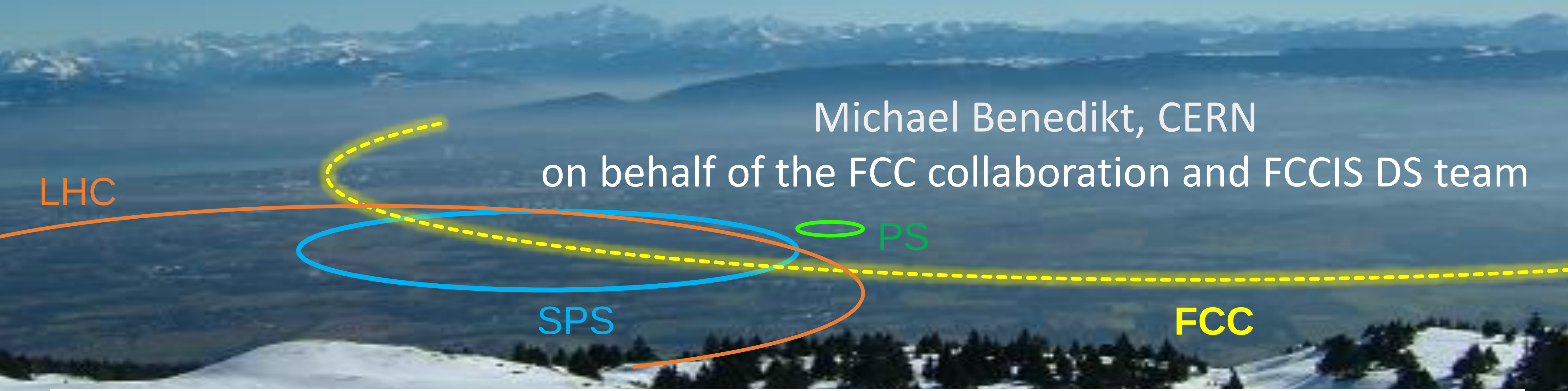
FCC Feasibility Study Status

FCC-EIC Joint MDI workshop, 17 October 2022

Michael Benedikt, CERN
on behalf of the FCC collaboration and FCCIS DS team



FUTURE CIRCULAR COLLIDER Innovation Study

http://cern.ch/fcc

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **ARIES**, grant agreement 730871, **FCCIS**, grant agreement 951754, and **E-JADE,** contract no. 645479*

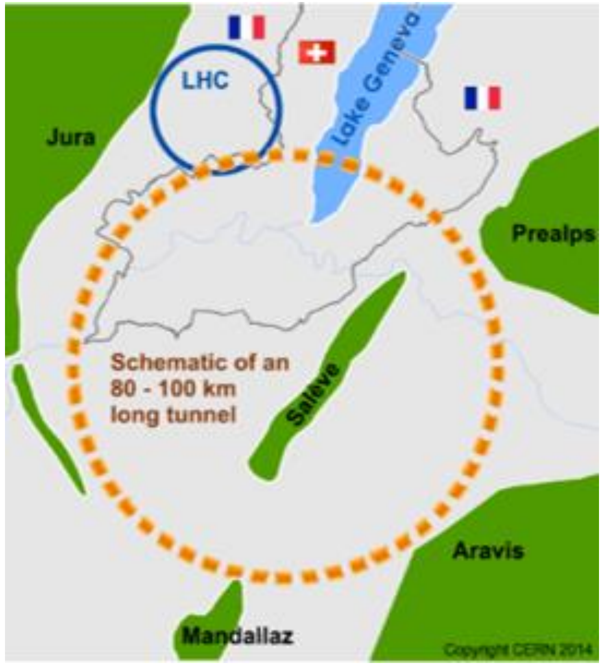
European Commission | Horizon 2020 European Union funding for Research & Innovation

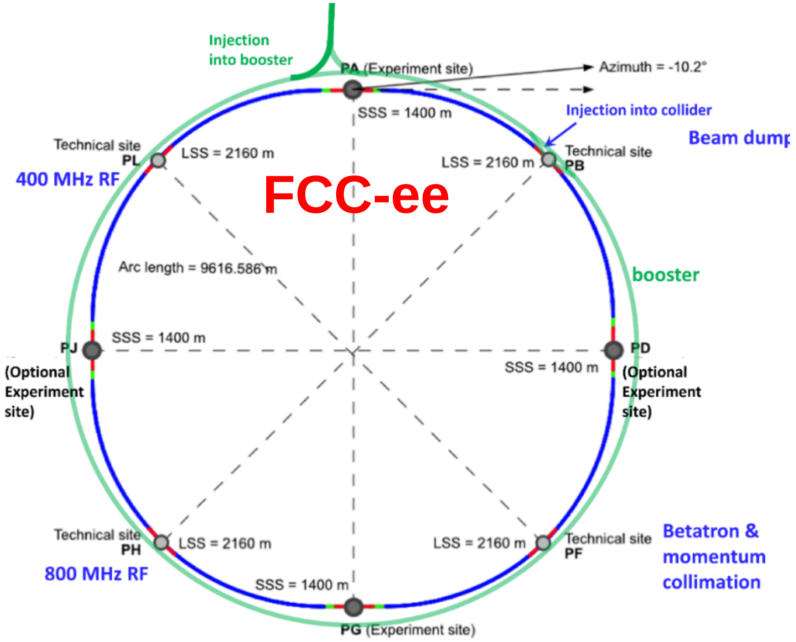
photo: J. Wenninger

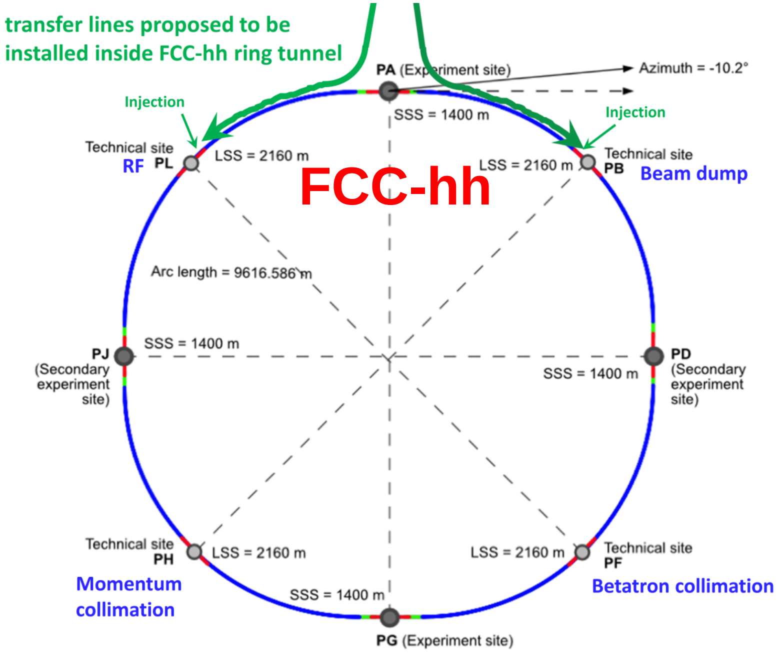
The FCC integrated program inspired by successful LEP – LHC programs at CERN

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, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program



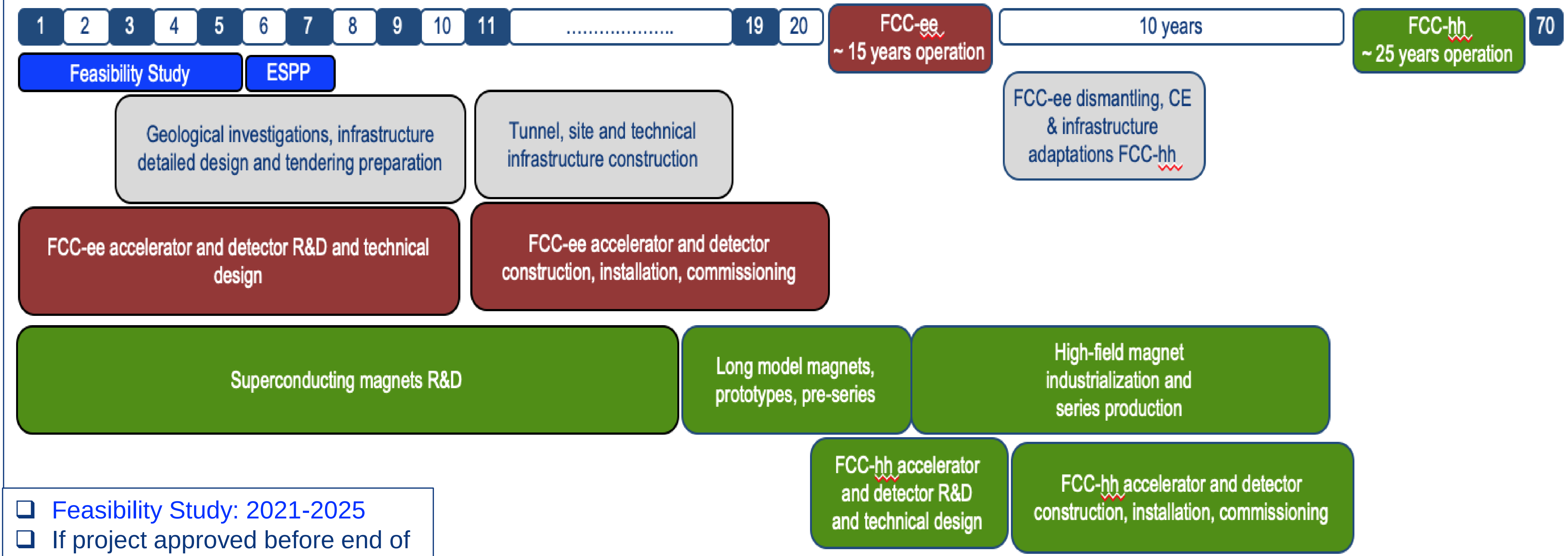




2020 - 2040 | 2045 - 2060 | 2065 - 2090

a similar two-stage project CEPC/SPPC is under study in China

technical timeline of FCC integrated programme



- 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

FCC Feasibility Study (FS)

FUTURE CIRCULAR COLLIDER

2013 ESPPU requested FCC Conceptual Design four-volume report → 4 volumes delivered in 2018/19,
describing the physics cases, the design of the lepton and hadron colliders, and the underpinning technologies and infrastructures. Fol-

2020 ESPPU→ 2021 Launch of FCC Feasibility Study (FCC FS) by CERN Council

- Feasibility Study Report (FSR) expected by the end of 2025 , not only the technical design, but also numerous other key feasibility aspects, including tunnel construction, financing, and environment
- FSR will be an important input to the next ESPPU expected in 2026/27.

FCC FS is organized as an international collaboration.
The FCC FS and a possible future project will profit from CERN's decade-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.

Organisational Structure of the FCC Feasibility Study
http://cds.cern.ch/record/2774006/files/English.pdf

Main Deliverables and Timeline of the FCC Feasibility Study
http://cds.cern.ch/record/2774007/files/English.pdf

CERN/SPC/1155/Rev.2
CERN/3566/Rev.2
Original: English
21 June 2021

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

Action to be taken		Voting Procedure
For decision	RESTRICTED COUNCIL 203rd Session 17 June 2021	Simple majority of Member States represented and voting

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:
PROPOSED ORGANISATIONAL STRUCTURE

This document sets out the proposed organisational structure for the Feasibility Study of the Future Circular Collider, to be carried out in line with the recommendations of the European Strategy for Particle Physics updated by the CERN Council in June 2020. It reflects discussi[ons] at, and feedback received from, the Council in March 2021 and is now submitted for the latte[r's] approval.

CERN/SPC/1161
CERN/3588
Original: English
21 June 2021

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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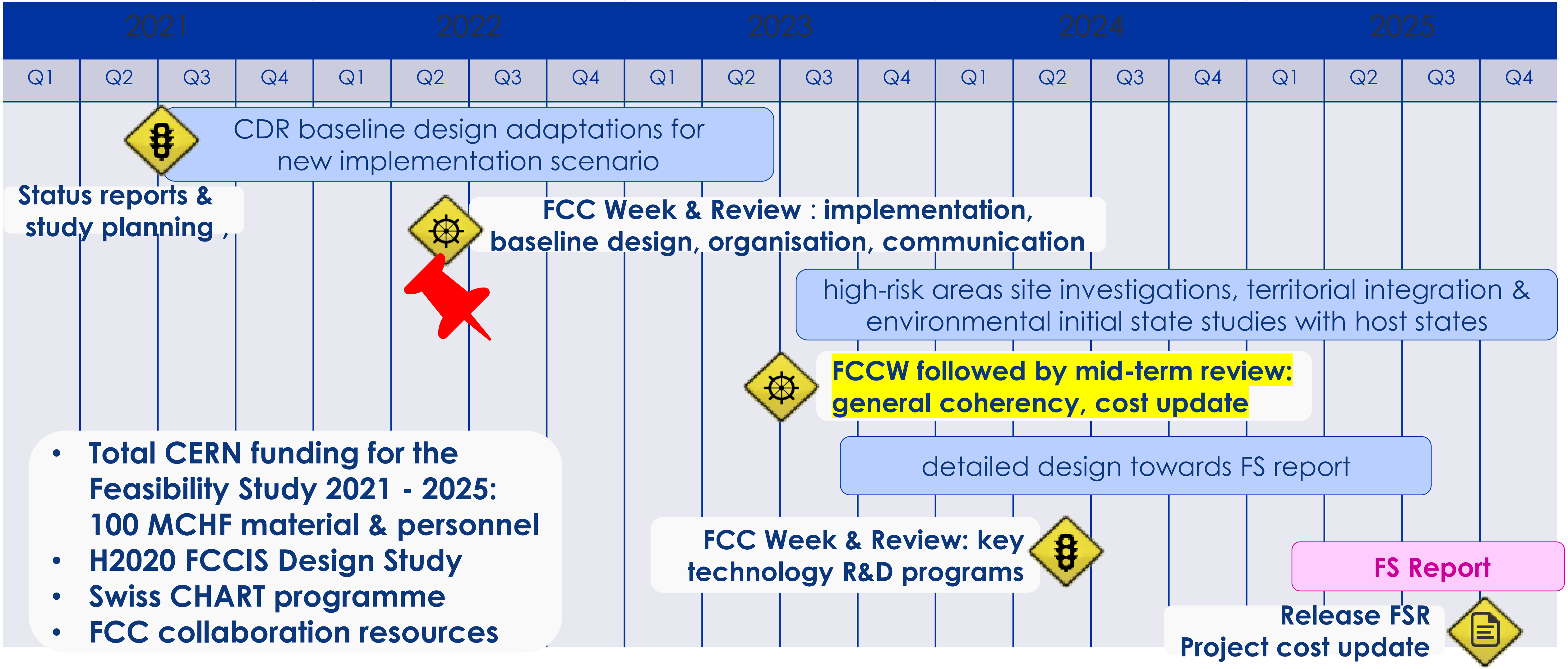
Action to be taken		Voting Procedure
For information	RESTRICTED COUNCIL 203rd Session 17 June 2021	-

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:
MAIN DELIVERABLES AND MILESTONES

This document describes the main deliverables and milestones of the study being carried out to assess the technical and financial feasibility of a Future Circular Collider at CERN. The results of this study will be summarised in a Feasibility Study Report to be completed by the end of 2025.

Feasibility Study Timeline



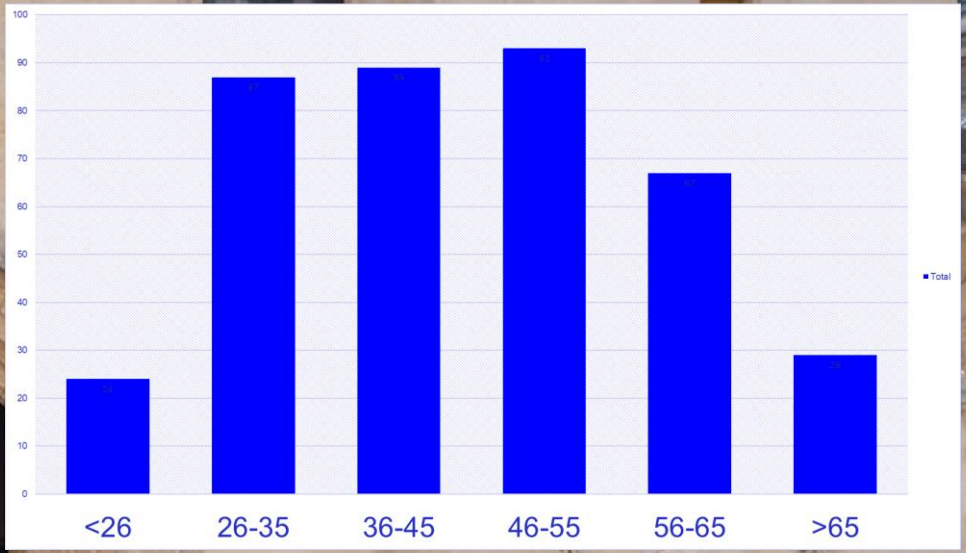
- **Total CERN funding for the Feasibility Study 2021 - 2025: 100 MCHF material & personnel**
- **H2020 FCCIS Design Study**
- **Swiss CHART programme**
- **FCC collaboration resources**

FCC Week 2022, Sorbonne, Paris, 30 May – 3 June 2022

483 participants
269 in person and 214 remote

45 sessions,
202 presentations,
+ 20 posters

Distribution of participants by age group



FUTURE CIRCULAR COLLIDER

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

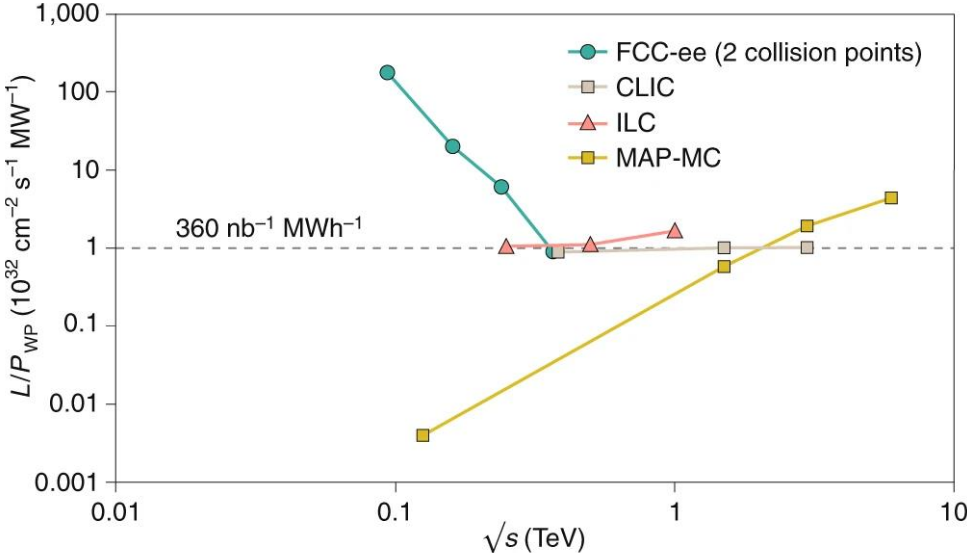
Environmental impact, socio-economic impact:

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

sustainability and carbon footprint studies

highly sustainable Higgs factory

luminosity vs. electricity consumption



Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

optimum usage of excavation material

int'l competition "mining the future®"

https://indico.cern.ch/event/1001465/

FCC-ee annual energy consumption ~ LHC/HL-LHC

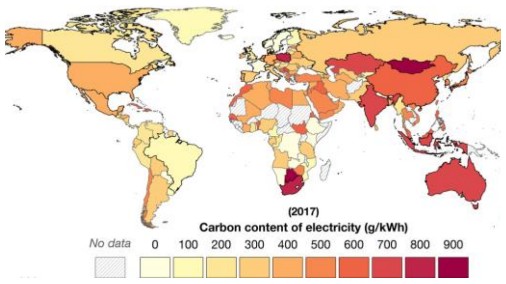
120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

J.-P. Burnet, FCC Week 2022

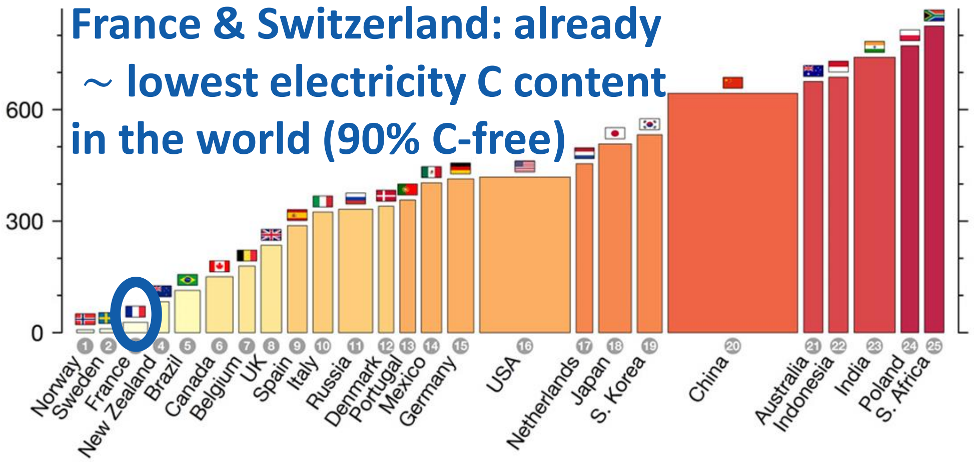
incl. CERN site & SPS

CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

powered by mix of renewable & other C-free sources



https://www.carbonbrief.org/



France & Switzerland: already ~ lowest electricity C content in the world (90% C-free)

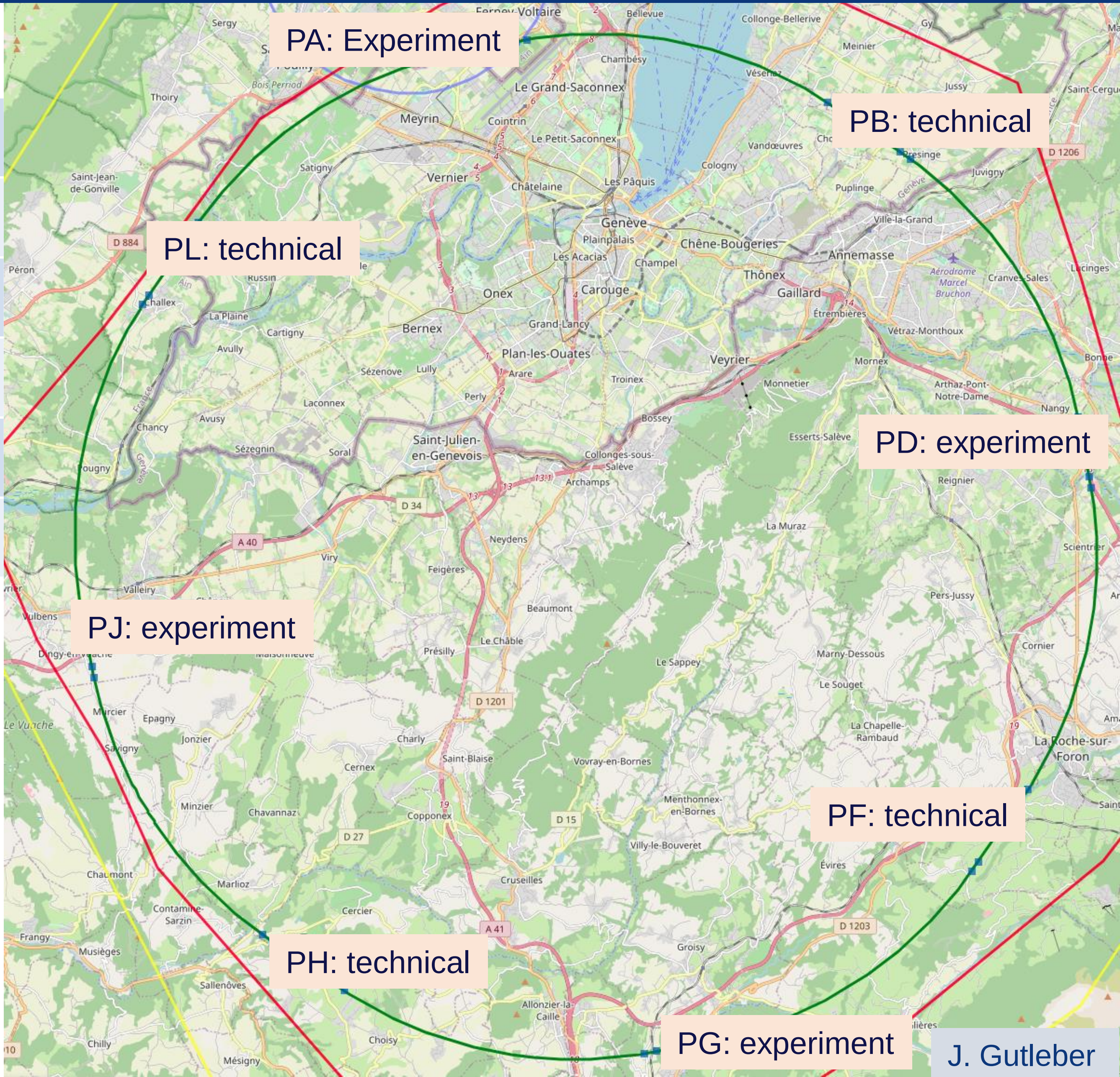
FUTURE CIRCULAR COLLIDER

optimized placement and layout

8-site baseline "PA31"

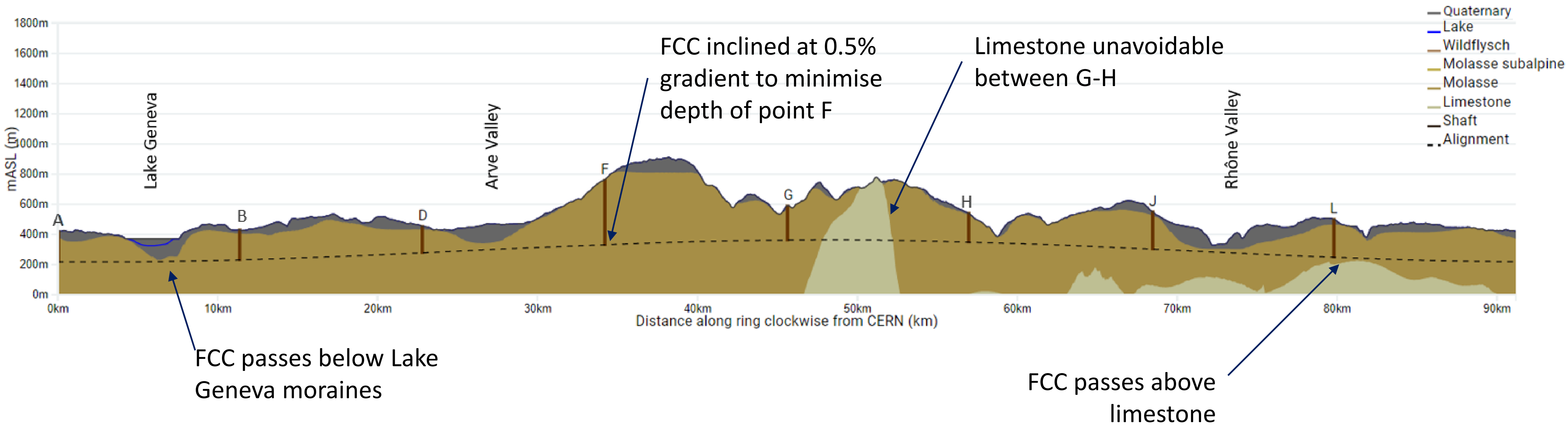
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP
- **Exchanges with ~40 local communes in preparation**



J. Gutleber

FCC Long Section – PA31-1.0

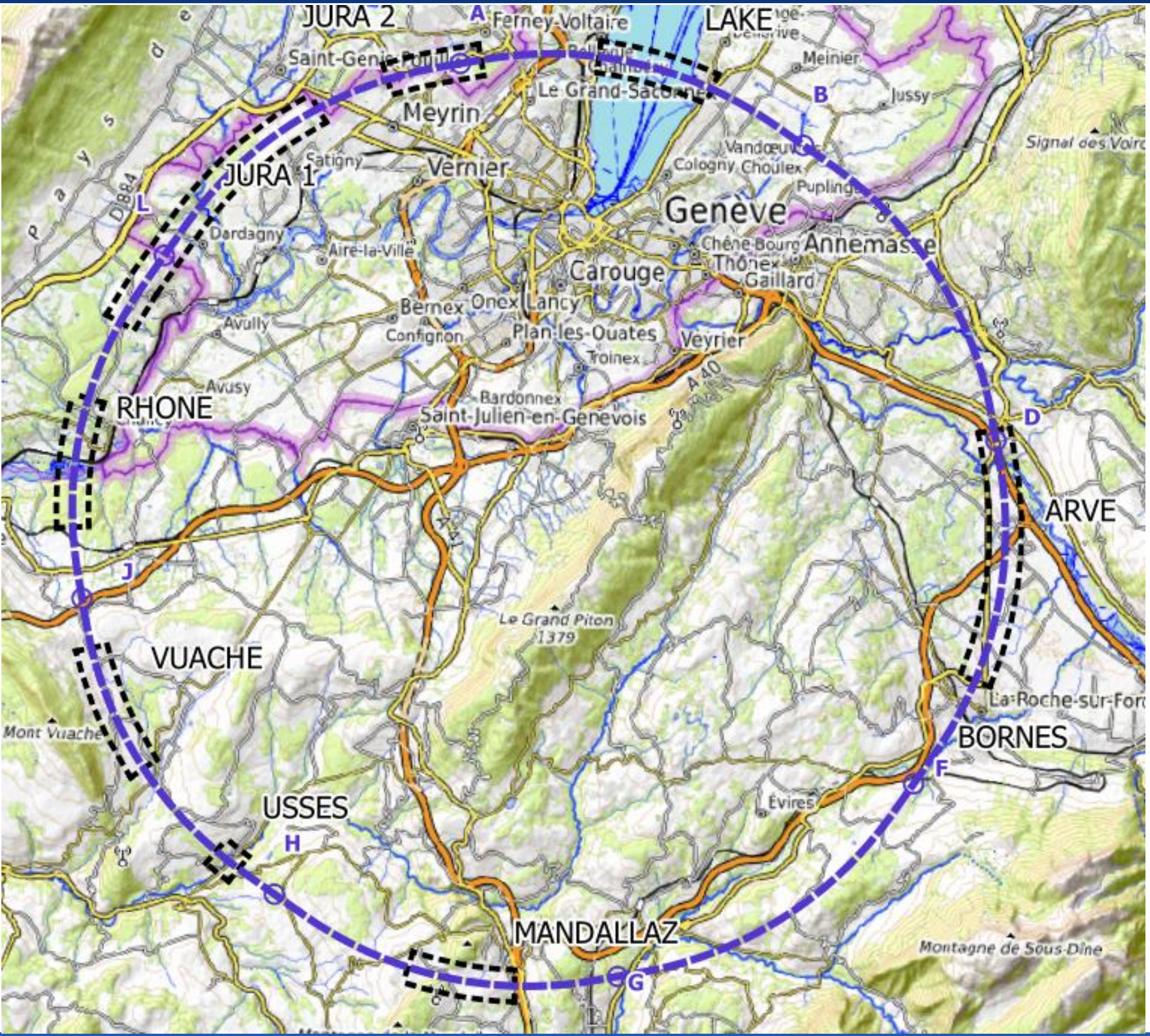


Shaft depth:

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

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 AREAS)
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, some 100 km of seismic lines

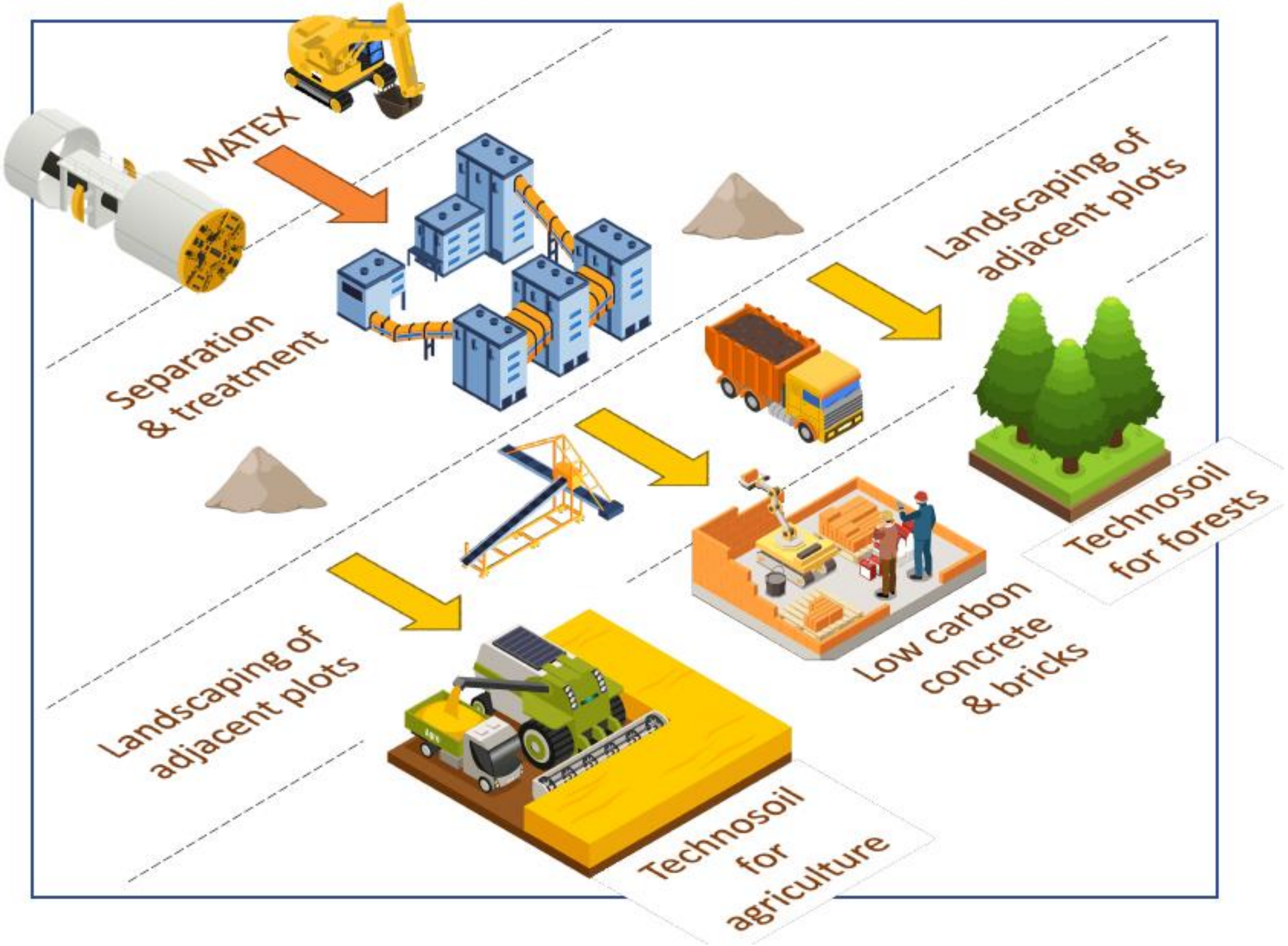
Mining the future – excavation material reuse

AMBERG Konsortium: In-situ characterisation (Crossbelt elemental analyzer) and preparation for use as construction material on site (Spritzbeton, Bindemittel aus Bio-Mineralstoffen), Production of construction elements withouth cement/concrete.

BG Konsortium: Online-analysis and preparation of Molasse for construction elements from sandstone, sabd, filing material for concrete, low-carbon concrete, terra cotta bricks, etc.

ARCADIS Konsortium: Molasse combined with some stabilisation material for production of construction bricks via high mechanical pressure. Replacing high-carbon construction materials. Mobile production plants directly on site.

EDAPHOS Konsortium: Combining mineral (Molasse) material and organic material to produce fertile soil with on-site production plants by using mikrobiology to accelerate humus creation. Fertile soil as top layer for agricultural use, recultivation.

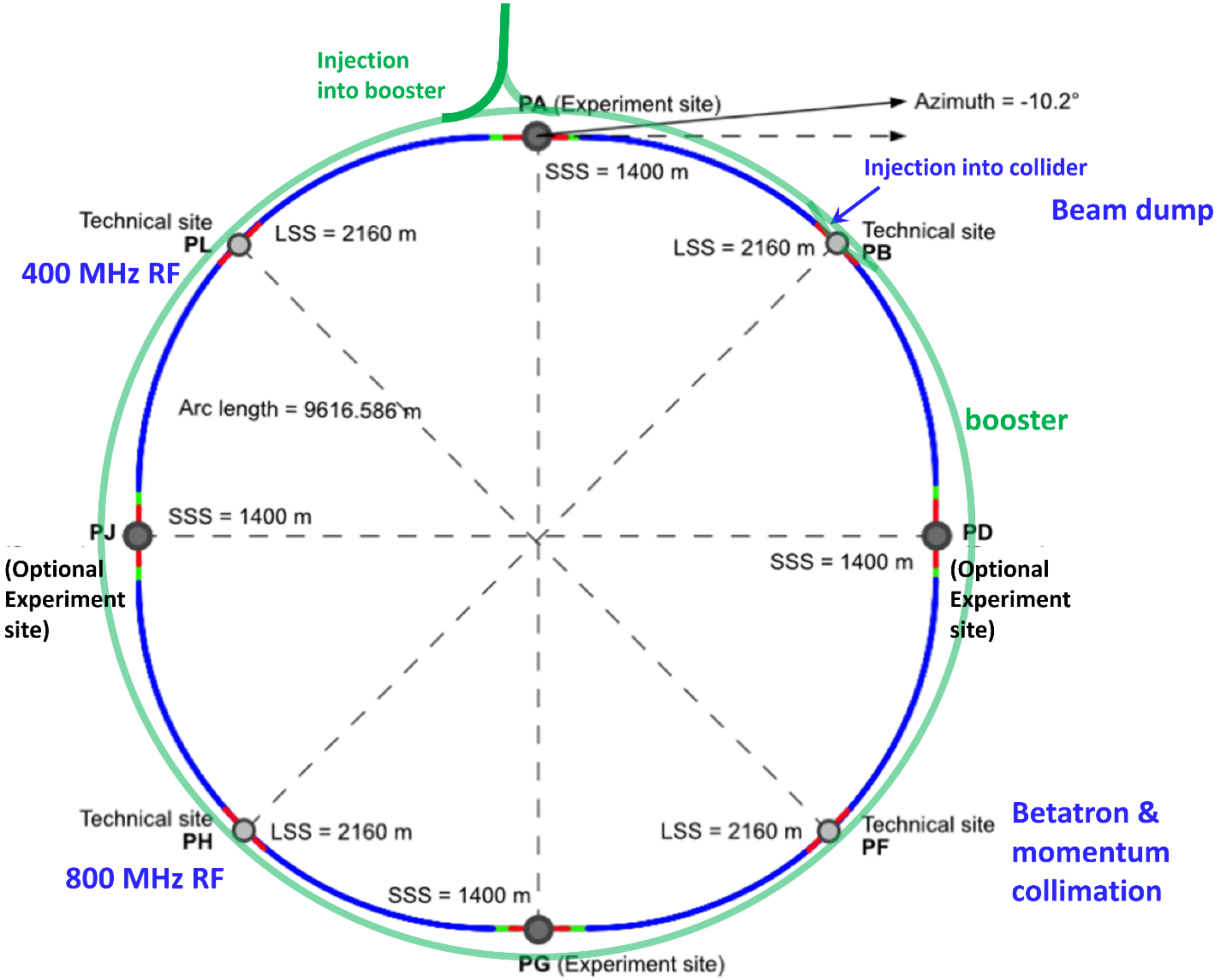


new layouts & preliminary assignments of straight sections

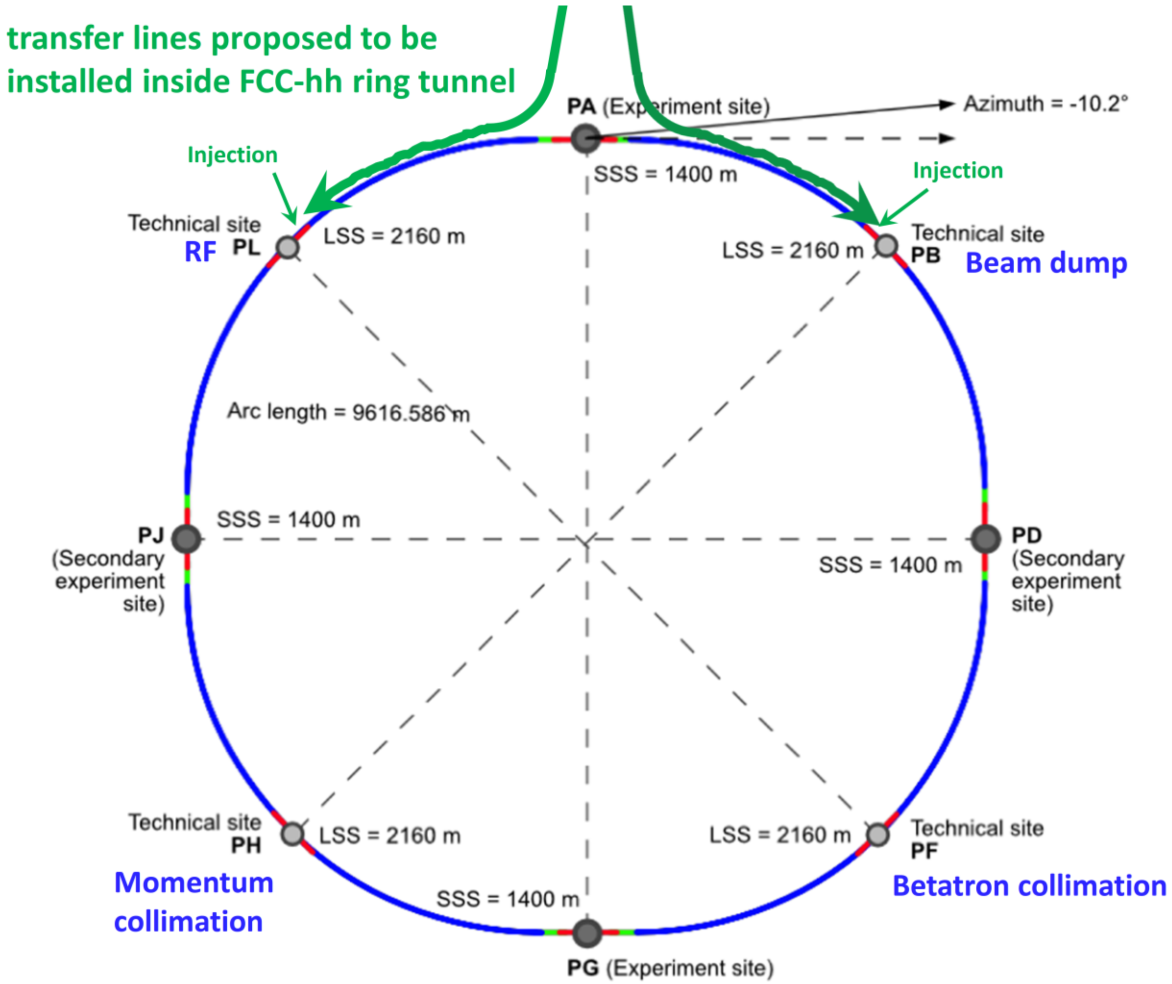
injection-tunnel near PA; 400 MHz RF in PL; 4 exp. caverns for both

4-fold periodicity, synergies ee & hh

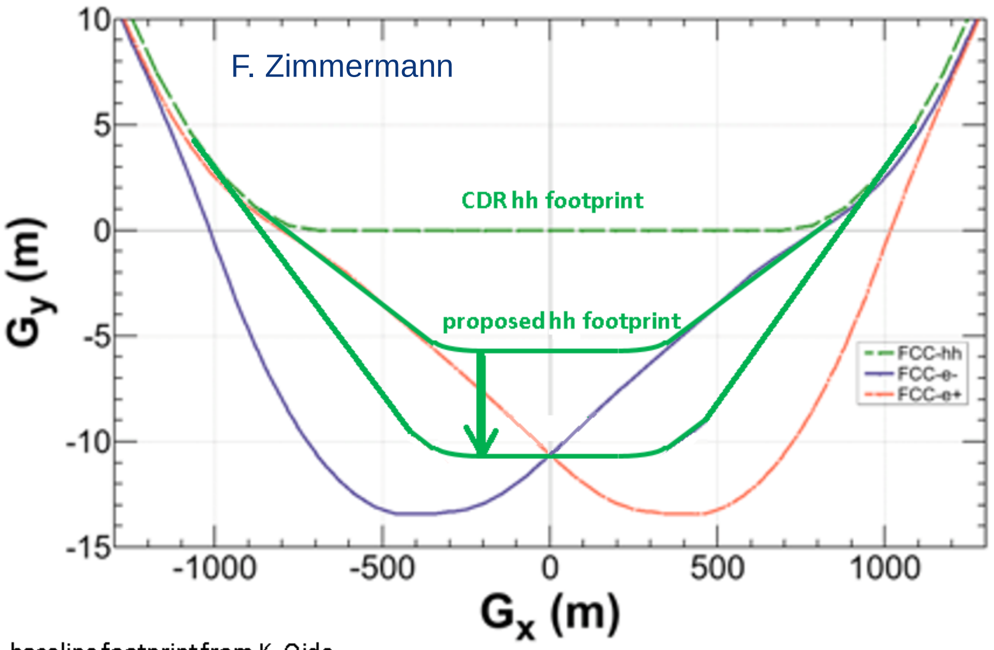
FCC-ee



FCC-hh



layout optimisation of high-luminosity insertions

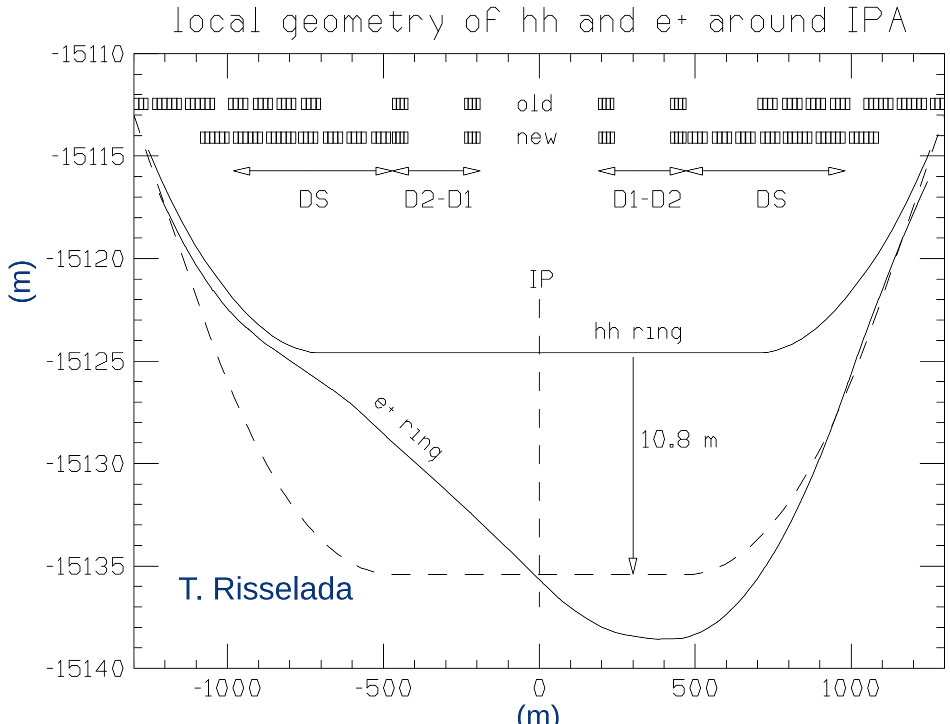


baseline footprint from K. Oide

In CDR:

- Due to FCC-ee asymmetric IR layout, transverse displacement of IPs for FCC-ee and FCC-hh.
- FCC-hh footprint compatible with FCC-ee injector

Massimo Giovannozzi & Thys Risselada



Implementation of an improved layout with FCC-ee & FCC-hh IPs with same transverse positions

<u>Advantages:</u>

- **Transverse size of detector cavern reduced**
- **Tunnel width reduced over 2 x 500 m**
- **Potential re-use of FCC-ee detector magnets for FCC-hh**

FCC-ee in a nutshell

- **High luminosity precision study of Z, W, H, and $t\bar{t}$** 2×10^{36} cm^{-2}s^{-1}/IP at Z (or total $\sim10^{37}$ cm^{-2}s^{-1} with 4 IPs), 7×10^{34} cm^{-2}s^{-1} at ZH, 1.3×10^{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

FUTURE CIRCULAR COLLIDER

Stage 1: updated parameters

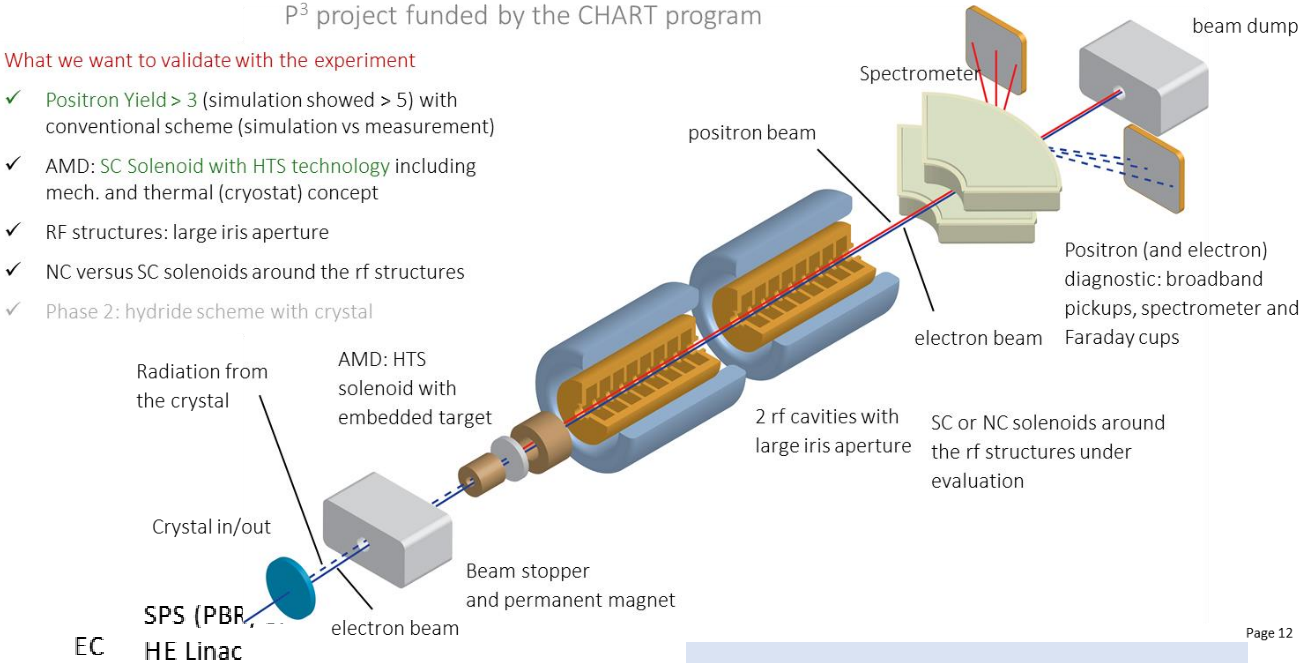
K. Oide, D. Shatilov,

Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

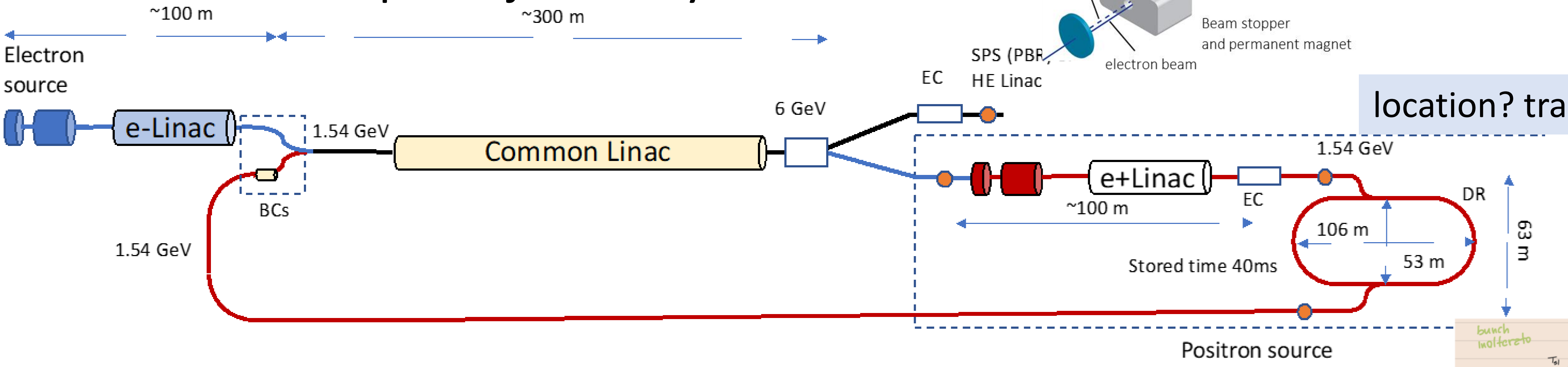
FCC-ee Pre-Injector - Swiss CHART 2 program

Collaboration between PSI and CERN with external partners: CNRS-IJCLab (Orsay), INFN-LNF (Frascati), KEK/SuperKEKB as observer, INFN-Ferrara – radiation from crystal

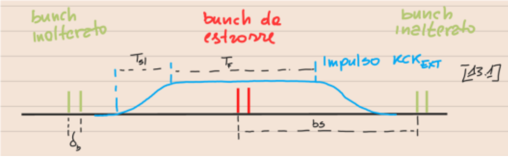
P^3: PSI e^+ production experiment with HTS solenoid at SwissFEL planned for 2024/25



Latest FCC-ee pre-injector layout



location? transfer lines?

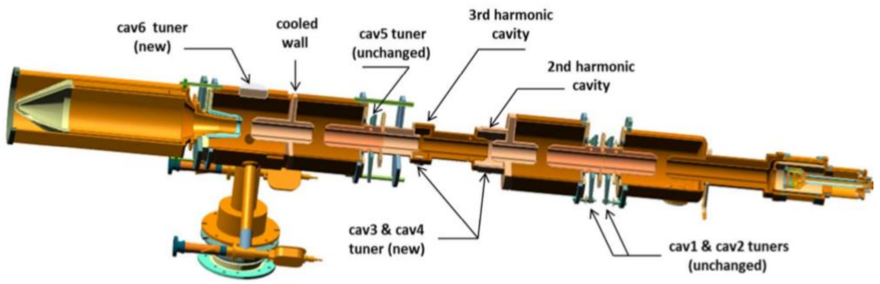


P. Craievich, A. Grudiev, C. Milardi, A. De Santis, et al.

accelerator R&D examples

efficient RF power sources (400 & 800 MHz)

I. Syratchev



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

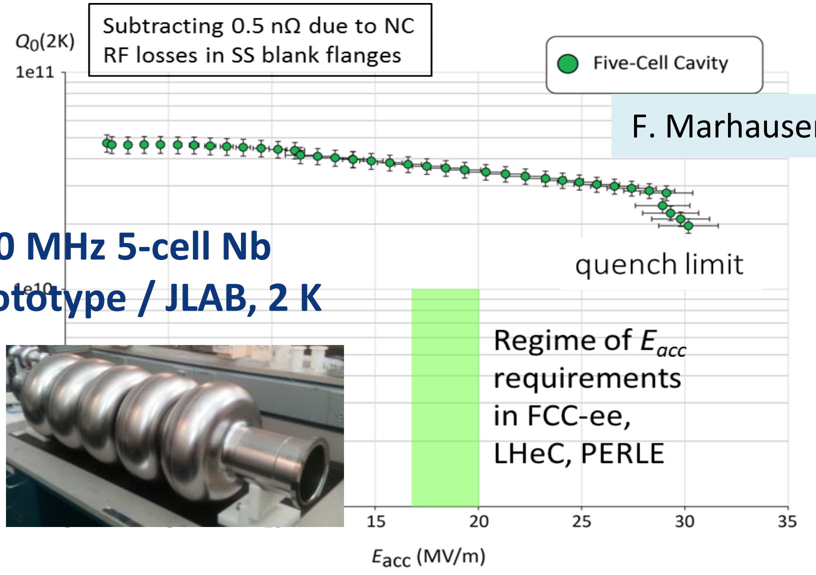
efficient SC cavities

Jefferson Lab

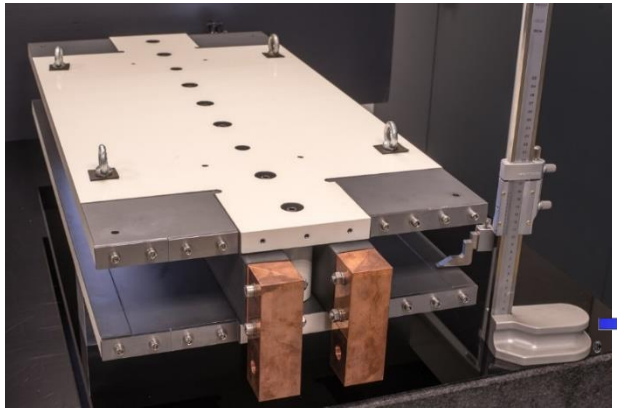
400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

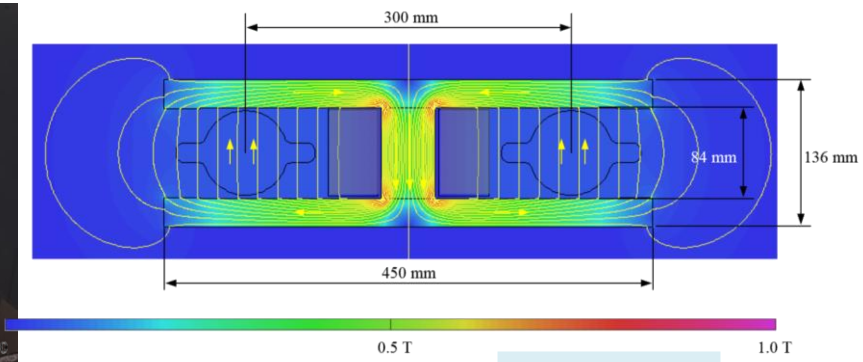
800 MHz 5-cell Nb prototype / JLAB, 2 K

F. Marhauser



energy **efficient** twin aperture **arc dipoles**

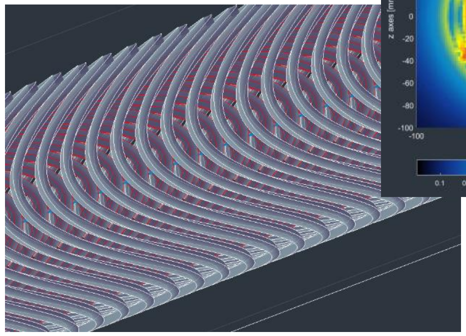


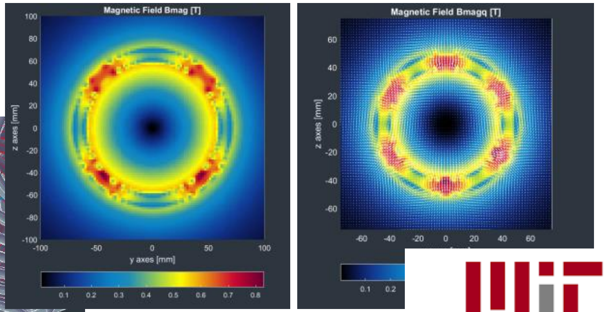


A. Milanese

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

PAUL SCHERRER INSTITUT PSI





Massachusetts Institute of Technology

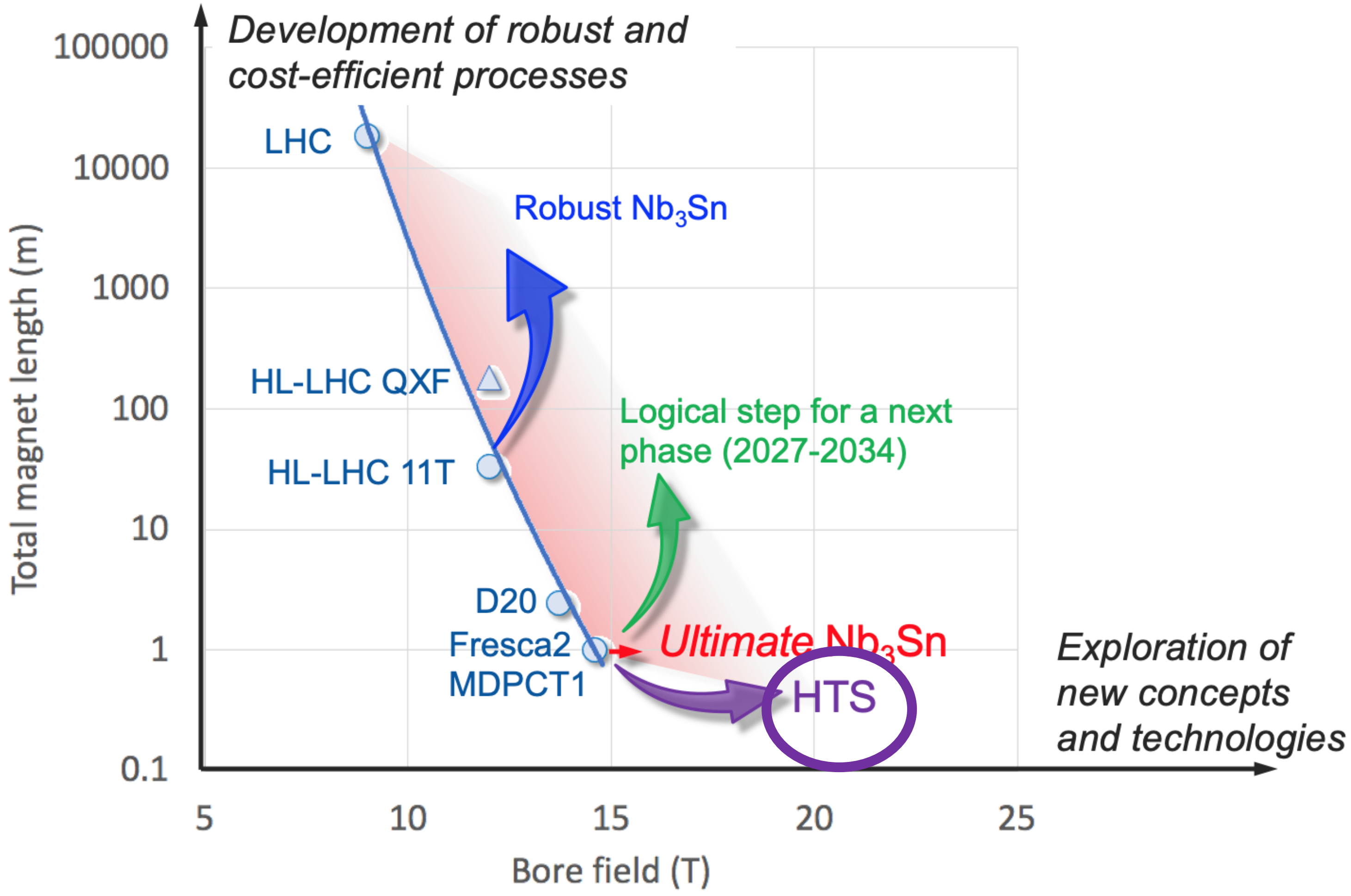
M. Koratzinos

Stage 2: FCC-hh (pp) collider parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb.function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

preparing for FCC stage 2 (FCC-hh)

In parallel to FCC studies,
High Field Magnet development program as long-term separate R&D project



CERN budget for high-field magnets doubled in 2020 Medium-Term Plan (~ 200 MCHF over ten years)

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

Detailed deliverables and timescale being defined through Accelerator R&D roadmap under development

L. Bottura, F. Gianotti, A. Siemko

FCC

FCC Feasibility Study

EU Projects
NN

Collaboration building
Emmanuel Tsesmelis

Communications
Panagiotis Charitos, James Gillies

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
- **Physics performance** – Patrizia Azzi, Emmanuel Perez
- **Software and computing** – Gerardo Ganis, Clément Helsens

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** – Alain Blondel, Jorg Wenninger
- **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

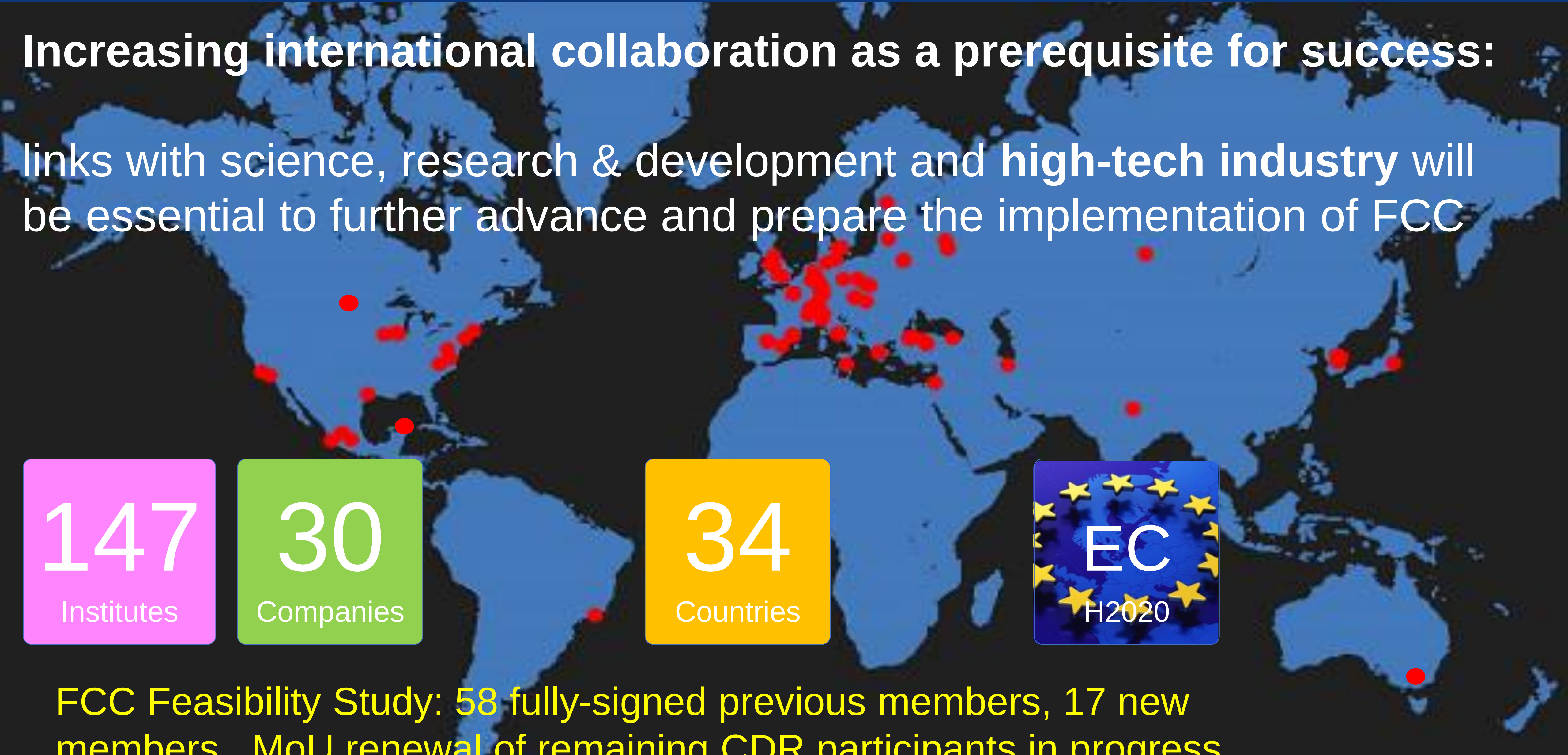
- **Project organisation model** – NN
- **Financing model** – Florian Sonnemann
- **Procurement strategy and rules** – NN
- **In-kind contributions** – NN
- **Operation model** – Paul Collier, Jorg Wenninger

FUTURE CIRCULAR COLLIDER

Status of Global FCC 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



147 Institutes

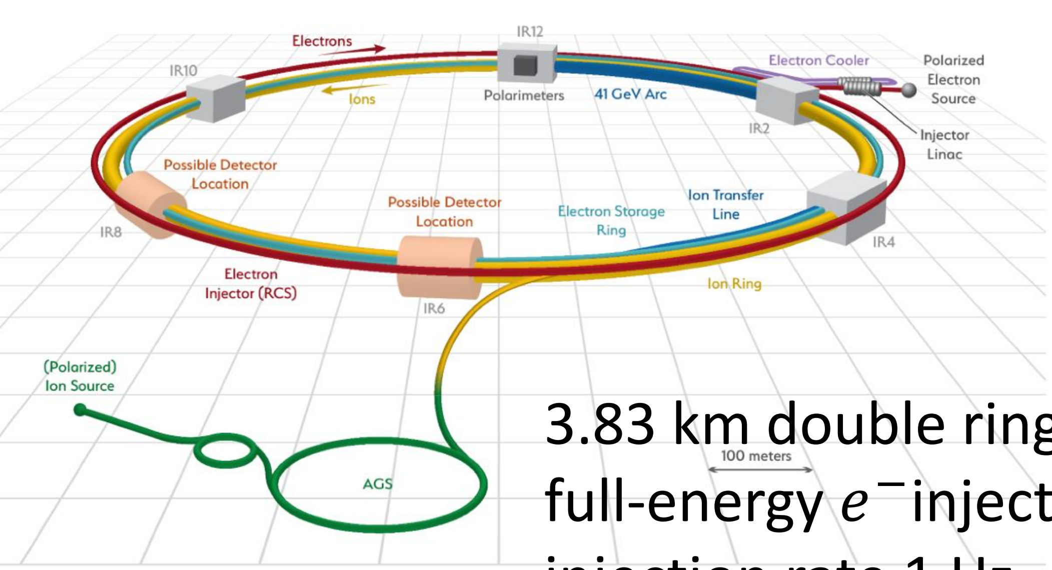
30 Companies

34 Countries

EC H2020

FCC Feasibility Study: 58 fully-signed previous members, 17 new members. MoU renewal of remaining CDR participants in progress

Electron Ion Collider (EIC)



US EIC Electron Storage Ring similar to, but more challenging than, FCC-ee

beam parameters almost identical, but twice the maximum electron beam current, or half the bunch spacing, and lower beam energy

3.83 km double ring, full-energy e^{-}injection, injection rate 1 Hz, every 2 min into same bucket

~10 areas of common interest identified by the FCC and EIC design teams, addressed through joint EIC-FCC working groups.

EIC will start beam operation about a decade prior to FCC-ee

The EIC will provide another invaluable opportunity to train the next generation of accelerator physicists on an operating collider, to test hardware prototypes, beam control schemes, etc.

	EIC	FCC-ee-Z
Beam energy [GeV]	10 (18)	45.6 (80)
Bunch population [10^{11}]	1.7	1.7
Bunch spacing [ns]	10	15, 17.5 or 20
Beam current [A]	2.5 (0.27)	1.39
SR power / beam /meter [W/m]	7000	600
Critical photon energy [keV]	9 (54)	19 (100)

Outlook

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

Plenty of opportunities for collaborations (incl. DAFNE, EIC, SuperKEKB/Belle II,…) and for **joint innovative developments** with int'l 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 program 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 21st century** to push particle-physics **precision and energy frontiers** far beyond present limits

FCC FS status summary

Following 2020 European Strategy Update, **organisation structure and major milestones & deliverables for the FCC Feasibility Study (FCC FS) approved by CERN Council in June 2021.** Entire **FCC government structure (**members of **SC, CB, SAC, CG) established by now (summer 2022).**

Main activities: **developing & confirming concrete implementation scenario,** in collaboration **with host state authorities**, including **environmental impact analysis**, and accompanied by **machine optimisation, physics studies and technology R&D** - **via global collaboration,** supported by **EC H2020 Design Study FCCIS and Swiss CHART. Goal: demonstrate feasibility by 2025/26**

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


FCC
WEEK
2023
5 – 9 June
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TUNED