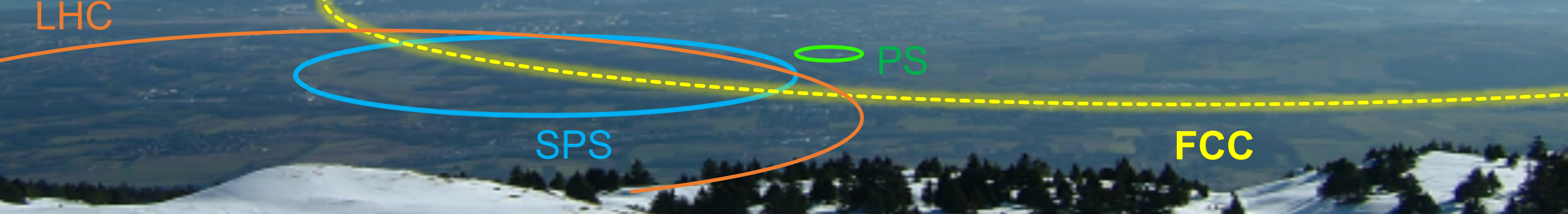
The e^-e^+ Future Circular Collider FCC-ee

Frank Zimmermann, CERN
Michael Benedikt, CERN ; Tor Raubenheimer, SLAC
Katsunobu Oide, KEK & U. Geneva

NAPAC 2022

on behalf of the FCC collaboration and FCCIS DS team



FCC hh ee he
EuroCirCol A key to New Physics
EASITrain
iFAST
FUTURE CIRCULAR COLLIDER Innovation Study
E-JADE
http://cern.ch/fcc
CERN

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

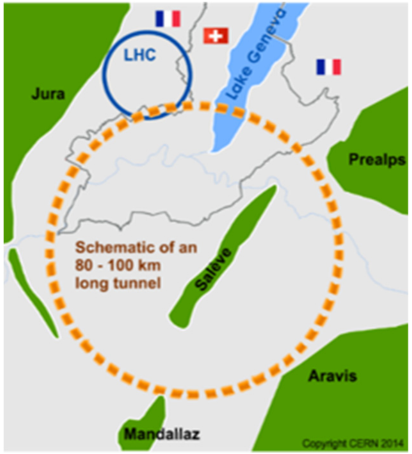
European Commission | Horizon 2020 European Union funding for Research & Innovation

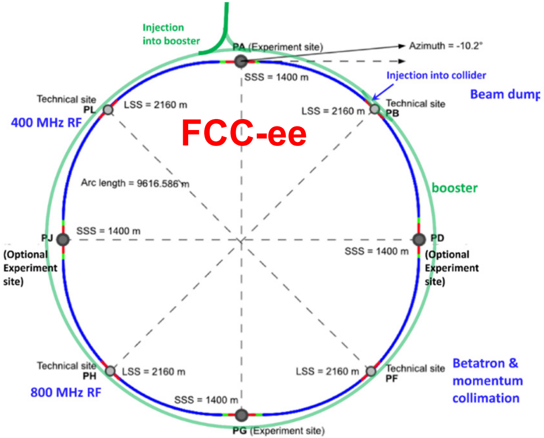
photo: J. Wenninger

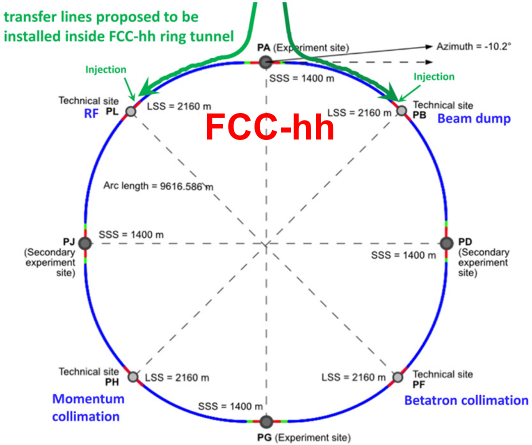
The FCC integrated program inspired by successful LEP – LHC programs at CERN

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



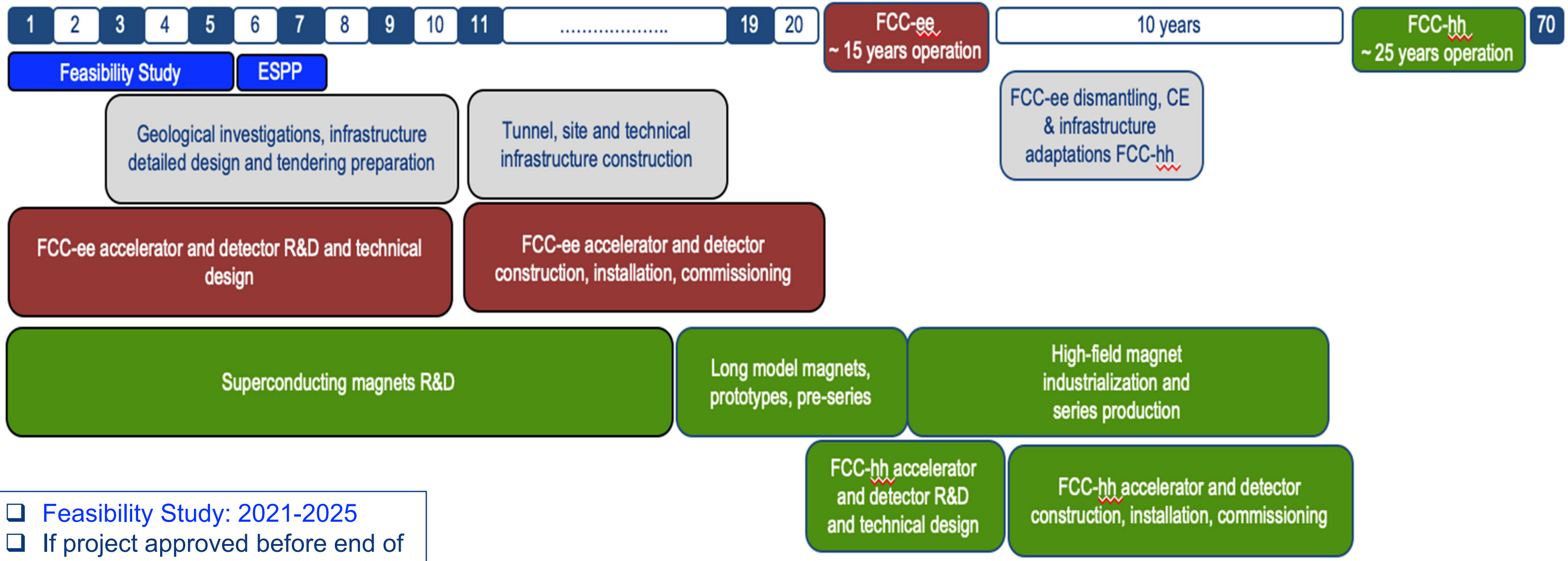




2020 - 2040 | **2045 - 2060** | **2065 - 2090**

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-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 ~10^{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-mm, 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*

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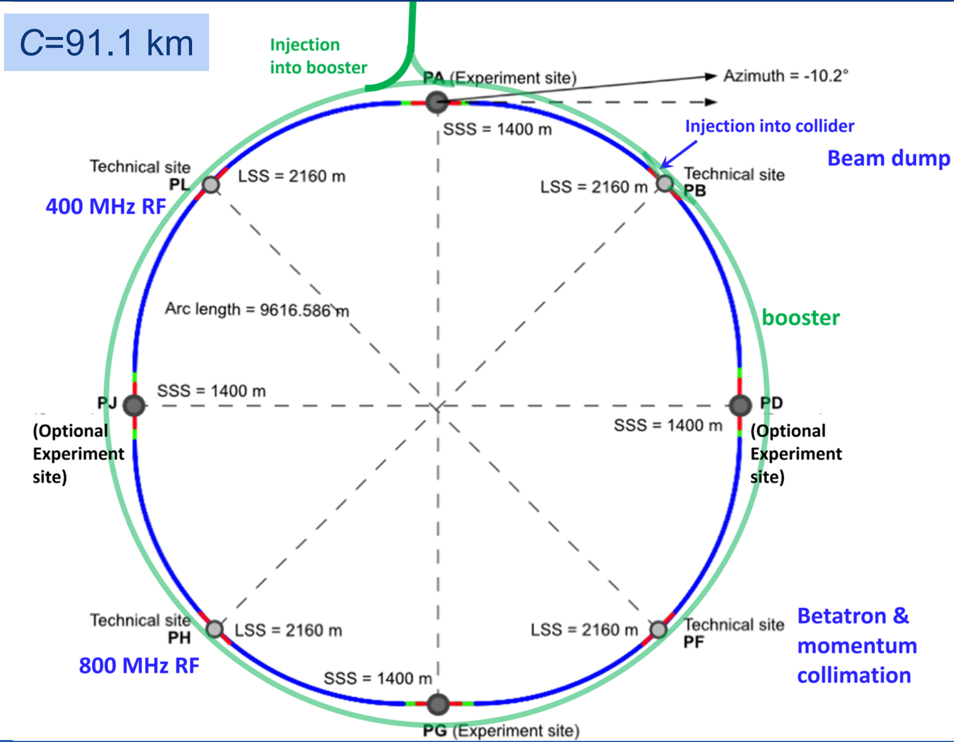
FCC-ee parameters

Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1400	135	26.7	5.0
number bunches/beam	8800	1120	336	42
bunch intensity [10^{11}]	2.76	2.29	1.51	2.26
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	2.1/0	2.5/8.8
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.15	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]	10	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]	4.32 / 15.2	3.55 / 7.02	2.5 / 4.45	1.67 / 2.54
luminosity per IP [10^{34} cm^{-2}s^{-1}]	181	17.3	7.2	1.25
tot. integr. luminosity / yr [ab^{-1}/yr]	86	8	3.4	0.6
beam lifetime rad Bhabha / BS [min]	19 / ?	20 / ?	10 / 19	12 / 46

FCC-ee Design Outline



Double ring e^+e^- collider

Common footprint with FCC-hh

Asymmetric IR layout and optics to limit SR towards the detector

Large crossing angle **30 mrad, “virtual” crab-waist collision**, **four-fold superperiodicity**: 2 or 4 IPs

SR power 50 MW/beam

Top-up injection requires **booster synchrotron in collider tunnel**

a case for four IPs & experiments

Four different FCC-ee detectors to optimally address:

(1) Higgs factory program; (2) Ultraprecise electroweak & QCD physics; (3) Heavy Flavour physics; (4) Search for feebly coupled particles

For FCC-hh, two high-luminosity general-purpose experiments and two specialized experiments are foreseen, similar to present LHC detectors

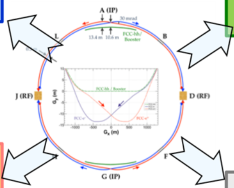
FCC-ee & hh would share the 4 experimental caverns

M. Dam, ECFA Det. R&D Roadmap, 2021, https://indico.cern.ch/event/994685/

Detector Requirements in Brief

"Higgs Factory" Programme
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme
- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6}: stability of √s meast.



Heavy Flavour Programme
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

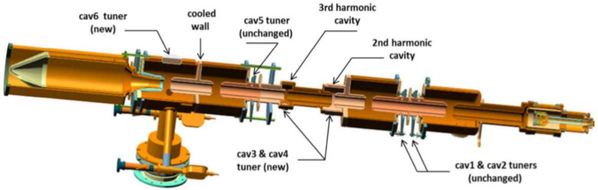
Benchmark signature: Z → νN, with N decaying late
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

accelerator R&D examples

efficient RF power sources

(400 & 800 MHz)

I. Syratchev

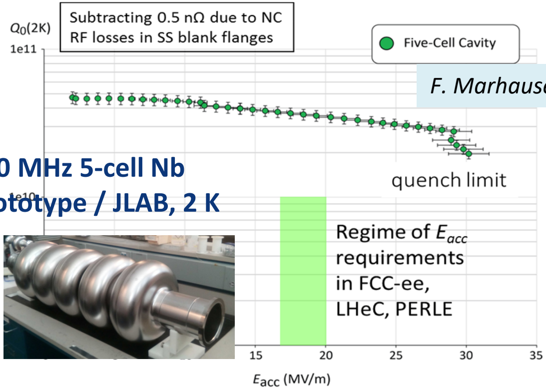


FPC & HOM coupler, cryomodule, thin-film coatings…

efficient SC cavities

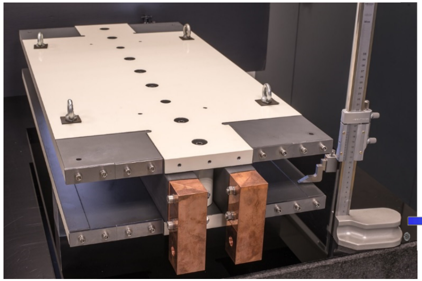
400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

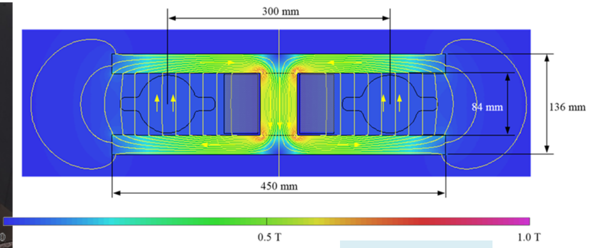
800 MHz 5-cell Nb prototype / JLAB, 2 K



F. Marhauser

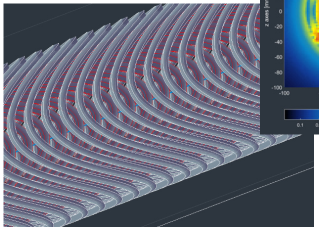
energy efficient *twin aperture* arc dipoles

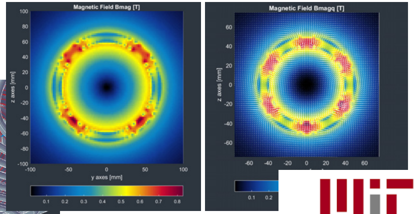




A. Milanese

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



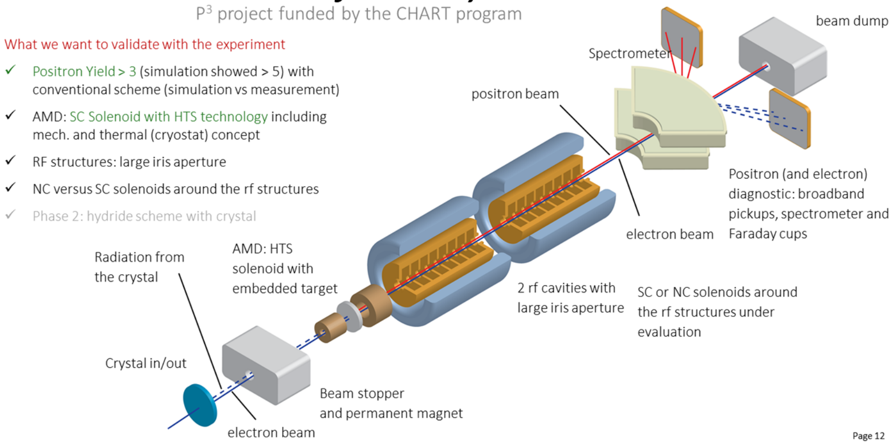


M. Koratzinos

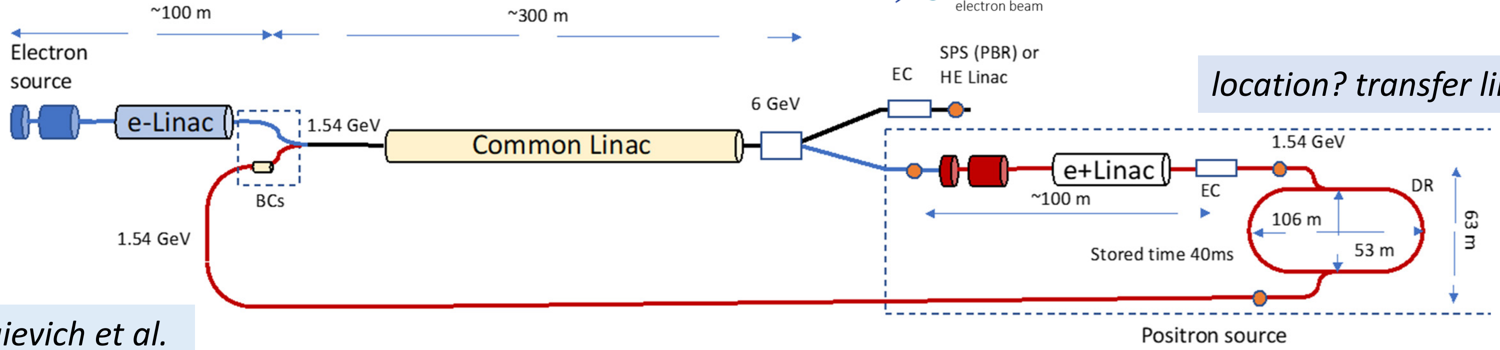
FCC-ee Pre-Injector - Swiss CHART 2 program

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 et al.

FCC-ee mock-ups for arcs and IR

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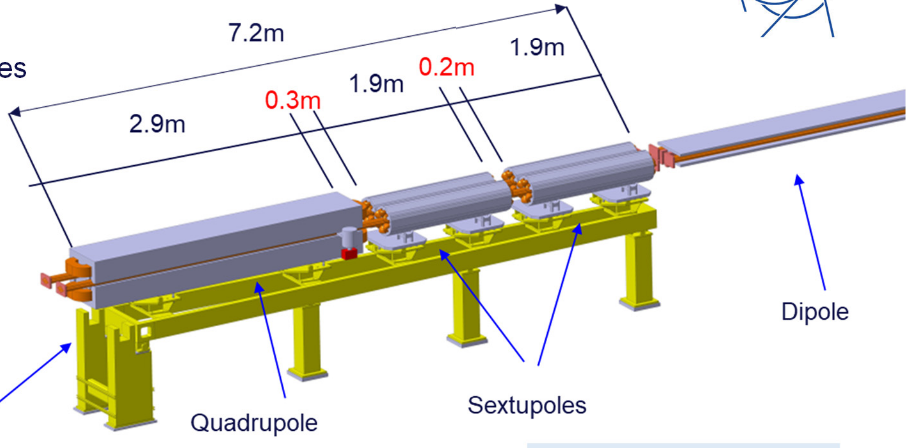
SLAC NATIONAL ACCELERATOR LABORATORY

F. Cara et al.

CERN

Arc half-cell mock-up

- **Arc half-cell**: most recurrent assembly of mechanical hardware in the accelerator (~1500 similar FODO)
- **Mock-up** → Functional prototype(s) → Pre-series → Series
- Building a mock-up allows optimizing and testing **fabrication, integration, installation, assembly, transport, maintenance**
- Working with structures of equivalent volumes, weights, stiffness

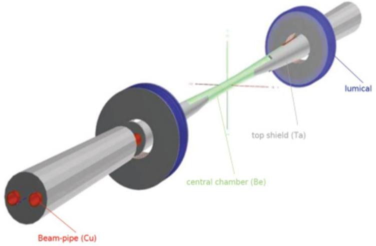


IR mock-up

Step 1: Central IP vacuum chamber (test the cooling system and the vacuum system), **AlBeMet162 & steel transition** (study the shape of the transition, EBW process), **Bellows** (vacuum and thermal tests), **Welding** (EBW for elliptical geometry)

Step 2: Trapezoidal vacuum chamber with remote vacuum connection, **first quadrupole QC1, cryostat,** beam pipe and quadrupole and **cryostat support**, **vibration & alignment sensors**

M. Boscolo et al.



SLAC NATIONAL ACCELERATOR LABORATORY

INFN LNF Istituto Nazionale di Fisica Nucleare

LAPP Laboratoire d'Annecy de Physique des Particules

International FCC-ee R&D | focus on US

European Strategy Update '20, **CERN Council**, **European Commission** *(EuroCirCol, EasiTrain, FCC Innovation Study – FCCIS)*, **Switzerland** *(CHART program)*, **partners** → **strong support for FCC**

"Addendum III to Accelerator Protocol III for Participation by the U.S. Department of Energy in the Future Circular Collider Feasibility Study" *agreed by* **CERN & DOE Office of Science** *in 2020*

Unique expertise at US national labs & universities *(SLAC, FNAL, BNL, JLAB, LBNL, ANL, Cornell, U. Hawaii, etc.)*: **collider beam physics** *(PEP-II, SLC, Tevatron, CESR, SuperKEKB, KEKB, …)*, **SRF, magnets, polarised beams, low-e rings, beam diagnostics, collimation, machine-detector interface, …**

Substantial synergies with the EIC *(highly similar beam parameters and challenges for FCC-ee & EIC ESR !) ; presently setting up joint working groups in various domains*

Synergies with SuperKEKB / BELLE II *addressed with help of U. Hawaii, BNL, and other US BELLE II members*

Europe-America-Japan Accelerator Development and Exchange Programme (EAJADE), *recently approved by the EC with highest rating, addresses key technical challenges for future Higgs factories, through collaboration with partner institutes in US and Japan, including FCC-ee R&D*

Ex. themes: **Nb_3Sn/Cu … HTS magnets** *for FCC-ee & FCC-hh,* **C^3 linac** *for FCC-ee injector*

SuperKEKB / Belle II

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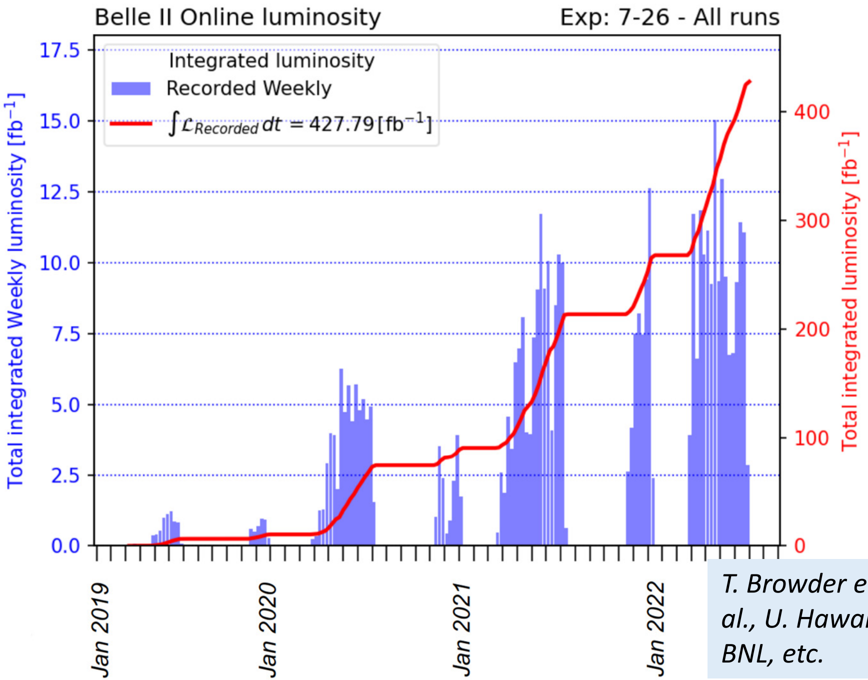
Design: double ring e^+e^- collider as *B*-factory *at 7(e^-) & 4(e^+) GeV; target* luminosity ~6 x 10^{35} $cm^{-2}s^{-1}$; b_y^* ~ 0.3 mm; beam lifetime ~5 min; top-up *inj.*; e^+ rate up to ~ 2.5 10^{12} /s ; under commissioning



T. Browder et al., U. Hawaii, BNL, etc.

$\mathcal{L}_{peak}$ = 4.7 x 10^{34}/cm^2/sec
nanobeams: vertical beam spot size 300nm (design 50nm)

This is four-times PEP-II peak with much lower beam currents.

>2 x higher than KEKB

Not easy:
ran throughout the two years of the COVID-pandemic with social distancing.

Integrated a BaBar size data sample, 428 fb^{-1}. Need more running time.

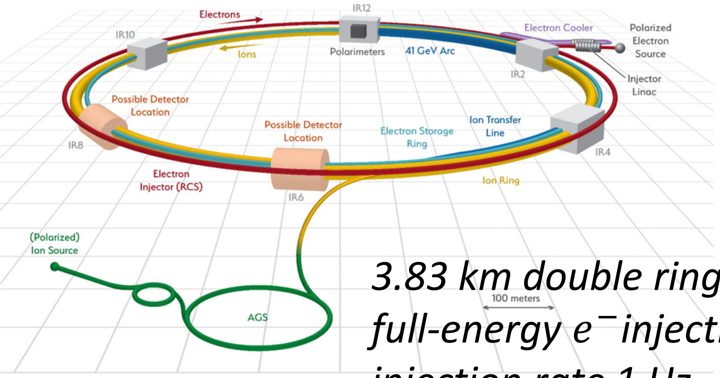
world record luminosity of 4.71x10^{34} cm^{-2}s^{-1} on 22 June 2022, b_y^* = 1.0 mm in routine operation, also b_y^* = 0.8 mm demonstrated in both rings – with FCC-ee-style "virtual" crab-waist collision scheme originally developed for FCC-ee (K. Oide)

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

~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.



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

	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)

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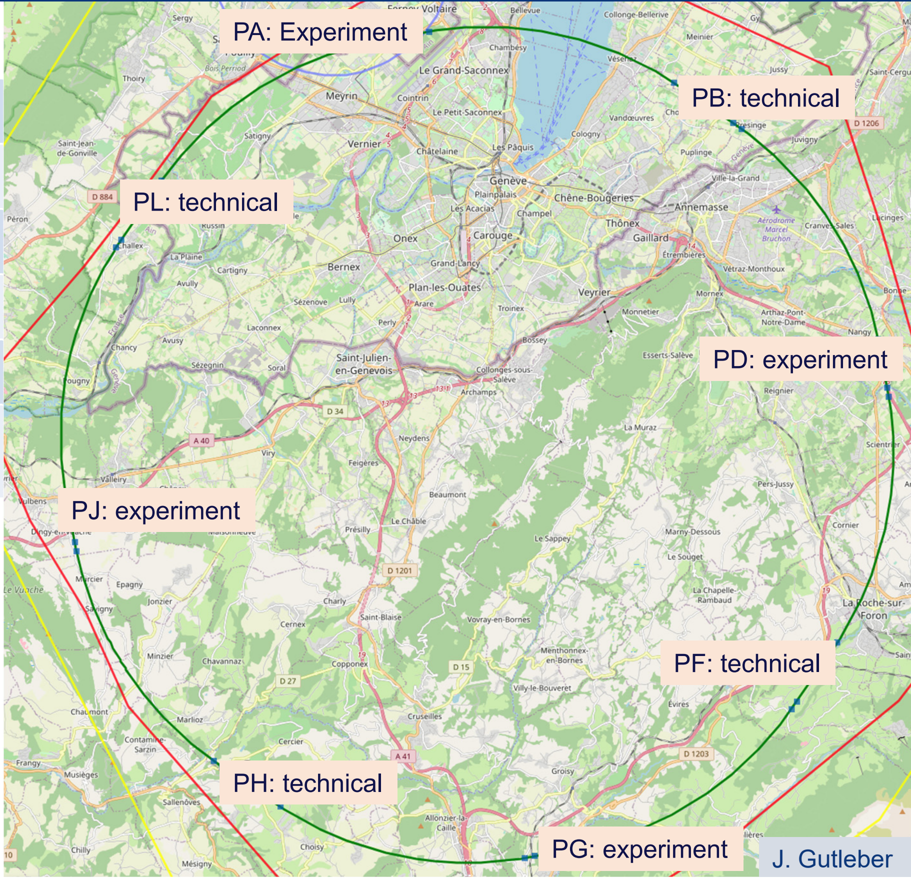
optimized placement and layout

8-site baseline “PA31”

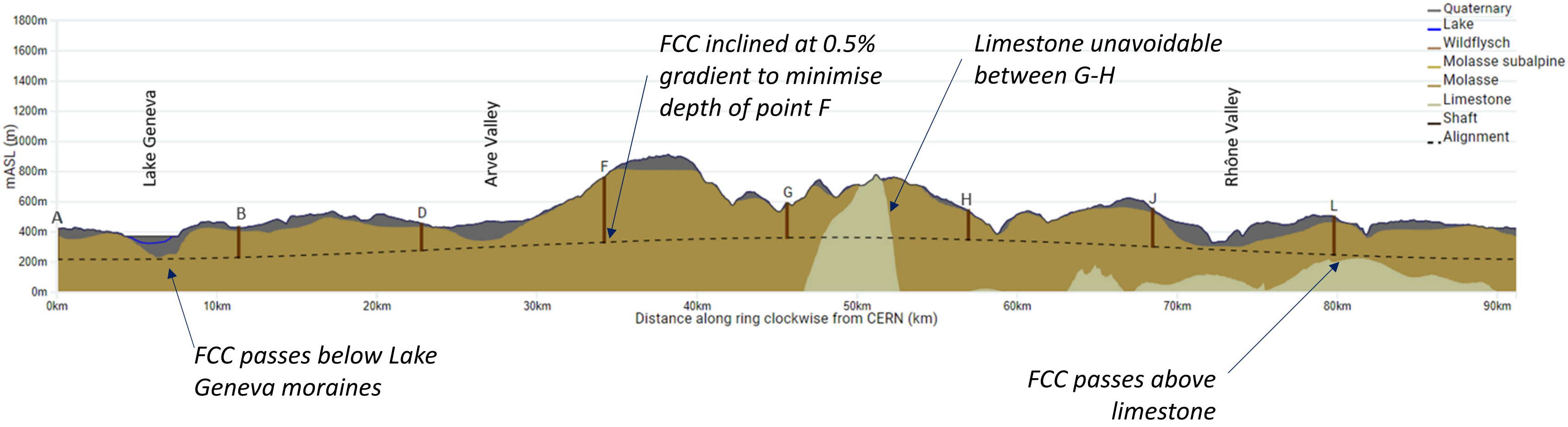
Number of surface sites	*8*
LSS@IP *(PA, PD, PG, PJ)*	*1400 m*
LSS@TECH *(PB, PF, PH, PL)*	*2143 m*
Arc length	*9.6 km*
Sum of arc lengths	*76.9 m*
Total length	**91.1 km**

- *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*



J. Gutleber

FCC Long Section – PA31-1.0

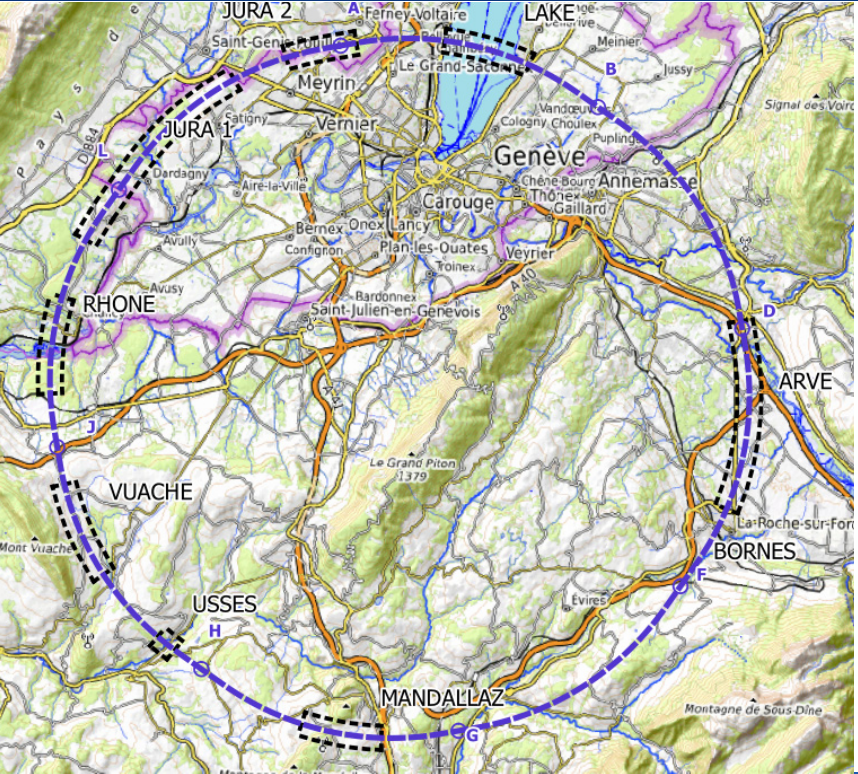


Shaft depth:

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

sustainability and carbon footprint studies

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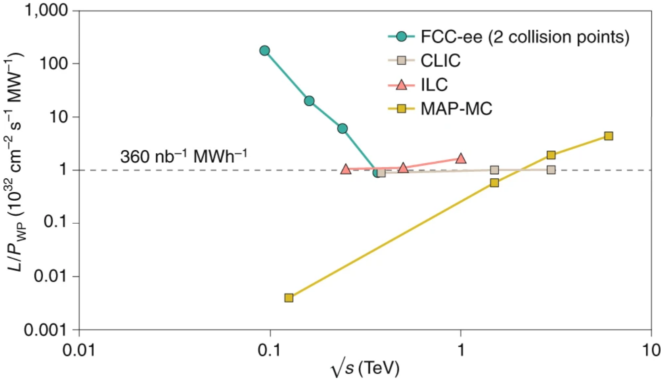
highly sustainable Higgs factory

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

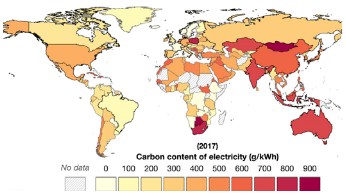
120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880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

J.-P. Burnet, FCC Week 2022

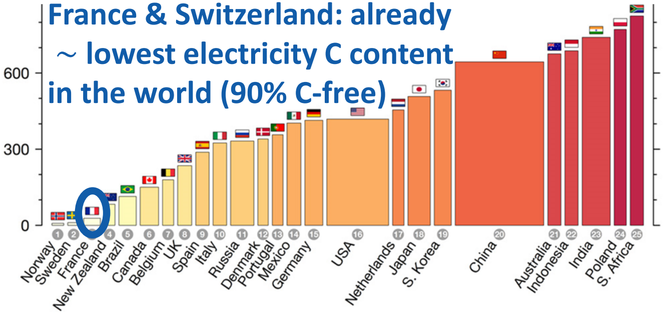
incl. CERN site & SPS

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/



sustainability compared with other Higgs factories

Patrick Janot

https://indico.cern.ch/event/1178975/

TWh / year for the "Higgs factory" centre-of-mass energy

$\sqrt{s}$ = 240 GeV for CEPC/FCC-ee, 250 GeV for ILC/C3, 380 GeV for CLIC

CLIC	ILC	C3	FCC-ee	CEPC
0.8	0.9	0.9	1.1	2.0

Energy consumption in MWh / Higgs

CLIC	ILC	C3	CEPC	FCC-ee
30	20	21	10	3.3

becomes 2 MWh / Higgs for FCC-ee with 4 IPs

Present carbon footprint for electrical energy in tons CO_2 / Higgs

CLIC@CERN	ILC@KEK	C3@FNAL	CEPC@China	FCC-ee@CERN
2.1	7.8	8.5	6.1	0.24

0.14 ton CO_2 / Higgs for FCC-ee with 4 IPs

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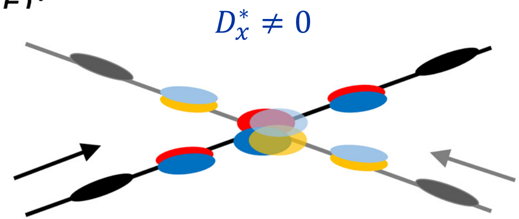
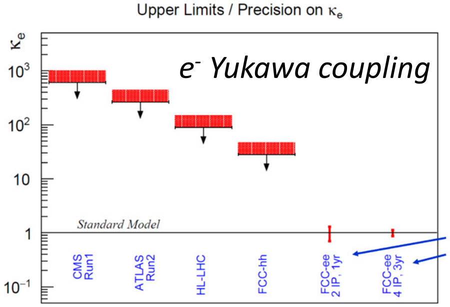
future upgrades and uses

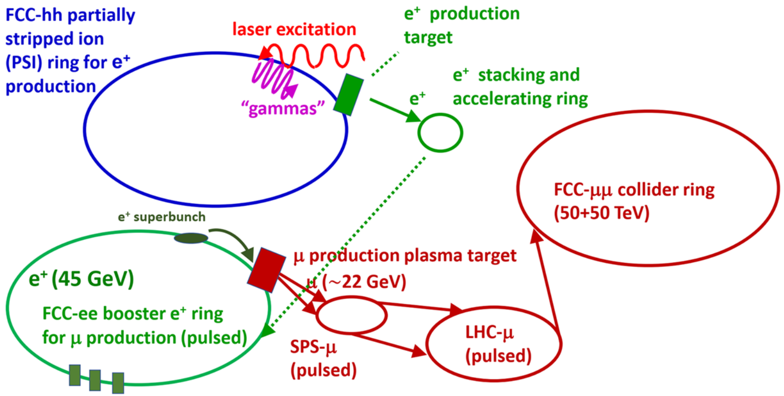
- *FCC-ee: not only Higgs, but* **Z and W factory** *(TeraZ);* **$t\bar{t}$ upgrade** *(~1 BCHF);*
- *optional* **direct *s*-channel Higgs production** *at 125 GeV with* **monochromatization**
- **civil construction & technical infrastructures shared with** *[and prepare] 100 TeV* **hadron collider FCC -hh – stage 2 of FCC integrated program** *(next slide)*
- *numerous other possible extensions (ep/eA/AA, Gamma Factory, LEMMA-type m collider FCC-mm ? …, ERL upgrade ? …)*

A. Faus-Golfe et al., Eur. Phys. J. Plus, 137 (2022) 31



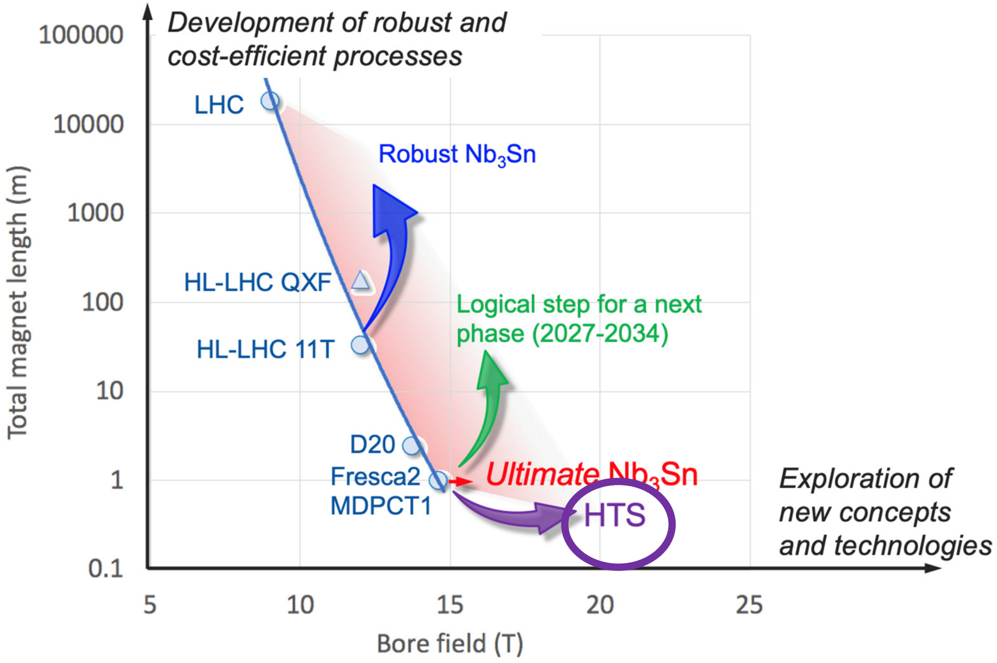


F. Zimmermann et al., PAC'22, Bangkok, WEPOST009



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 Feasibility Study (FS)

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

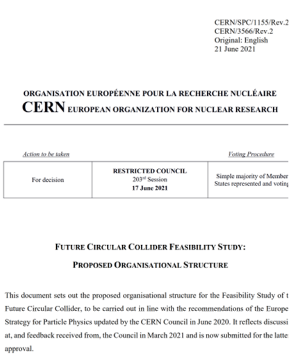
- Feasibility Study Report (FSR) expected by the end of 2025 , not only the technical design, but also numerous other key feasibility aspects, including tunnel construction, financing, and environment
- FSR will be an important input to the next ESPPU expected in 2026/27.

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

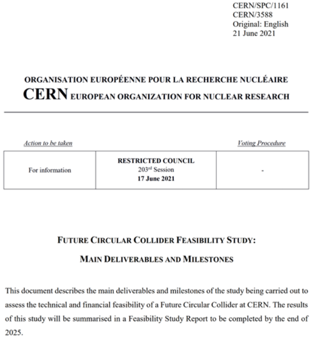

CERN/SPC/1155/Rev.2
CERN/3566/Rev.2
Original: English
21 June 2021

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 t Future Circular Collider, to be carried out in line with the recommendations of the Europe Strategy for Particle Physics updated by the CERN Council in June 2020. It reflects discussi at, and feedback received from, the Council in March 2021 and is now submitted for the latte approval.


CERN/SPC/1161
CERN/3588
Original: English
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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.

Post FS & ESPPU2027: Project Cost & Profile

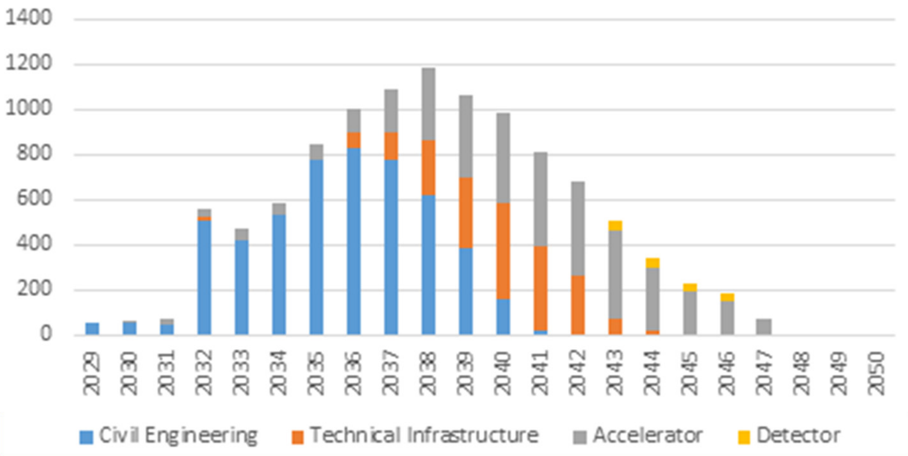
Construction cost estimate for FCC-ee (from CDR 2018, update in 2025)

- Machine configurations for Z, W, H working points included
- Baseline configuration with 2 detectors
- CERN contribution to 2 experiments incl.

cost category	[MCHF]	%
civil engineering	5.400	50
technical infrastructure	2.000	18
accelerator	3.300	30
detector	200	2
total cost (2018 prices)	10.900	100

Spending profile for FCC-ee

- CE construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.



Status of Global FCC Collaboration

FUTURE CIRCULAR COLLIDER

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

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. FCC-EIC, Belle II,…) and for* **joint innovative developments** *with US 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
WEEK
2023
5 – 9 June
STAY
TUNED