FCC FEASIBILITY STUDY – CURRENT STATUS

114th Plenary ECFA Meeting, Frascati, 5 July 2024

Michael Benedikt, Frank Zimmermann, CERN
on behalf of FCC collaboration & FCCIS DS team

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

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain**, grant agreement no. 764879; **iFAST**, grant agreement 101004730, **FCCIS**, grant agreement 951754; **E-JADE**, contract no. 645479; **EAJADE**, contract number 101086276; and by the Swiss **CHART** program*

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

FCC integrated program - timeline

FCC Conceptual Design Study started in 2014 leading to CDR in 2018

2021- 25: Feasibility Study

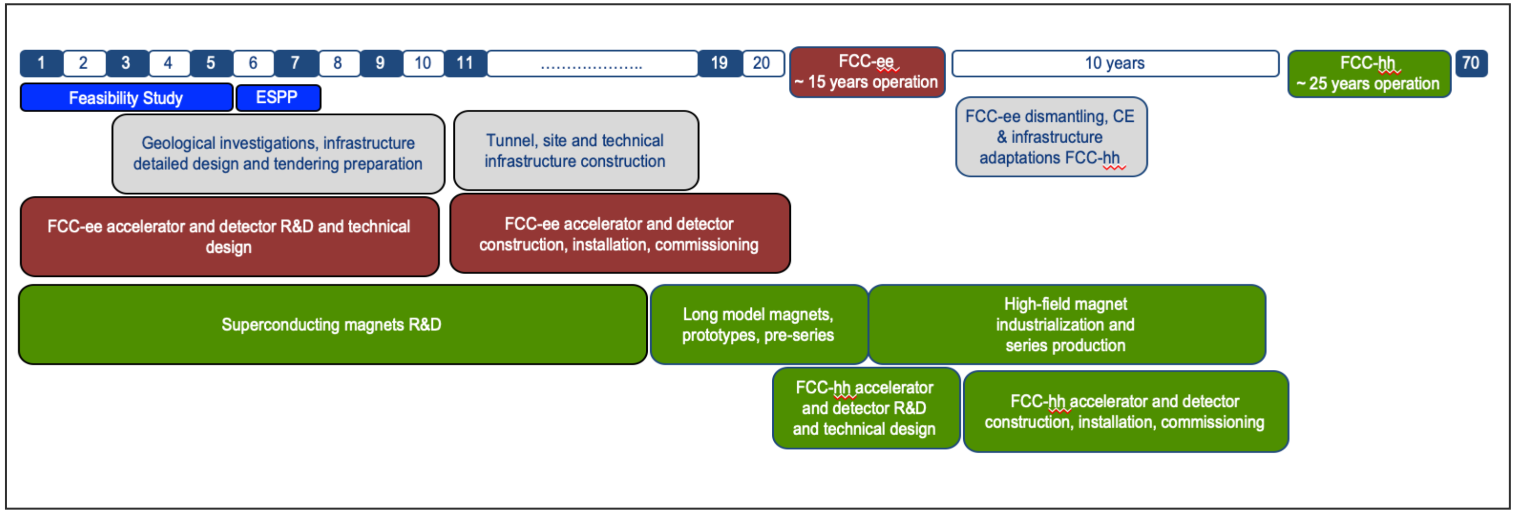
2028: project approval by CERN Council

2032: construction starts

2041: HL- LHC ends

2045: Operation of FCC-ee

2070: Operation of FCC-hh



"Realistic" schedule taking into account:

- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041

Can be accelerated if more resources available

FS Mid-Term Review passed !

Deliverables:

D1 : Definition of the baseline scenario
D2 : Civil engineering
D3 : Processes and implementation studies with the Host States
D4 : Technical infrastructure
D5 : FCC-ee accelerator
D6: FCC-hh accelerator
D7: Project cost and financial feasibility
D8: Physics, experiments and detectors

Documents:

- Mid-term report (all deliverables except D7)
- Executive Summary of mid-term report
- Updated cost assessment (D7)
- Funding model (D7)

Future Circular Collider
Midterm Report

February 2024

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

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

This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

Full Report

8 Chapters/Deliverables

~ 700 pp document

~ 16 editors

~ 500 contributors

Review process:

Oct 2023:
- Scientific Advisory Committee (sci. and tech. aspects)
- Cost Review Panel (ad hoc committee; cost and financial asp.)

Nov 2023:
- SPC and FC

2 Feb 2024:
- Council

Approved deliverables:
https://indico.cern.ch/event/1197445/contributions/5034859/attachments/2510649/4315140/spc-e-1183-Rev2-c-e-3654-Rev2_FCC_Mid_Term_Review.pdf

All deliverables met, no technical showstoppers

→ **70-80 recommendations**

Main goals 2024/ beginning 2025

Completing technical work for Feasibility Study until end 2024

- Implementation of recommendations from the mid-term review
- Focus on “feasibility items” and items with important impact on cost/performance
- Develop a risk register
- Update cost estimate to reach cat 3 level on cost uncertainty.
- Further develop the funding model based on discussions with the Council

Continue work with host states on:

- project definition and responsibilities
- authorization procedures
- excavation material strategy
- regional implementation development

Complete FS by March 2025 as input for ESPP update

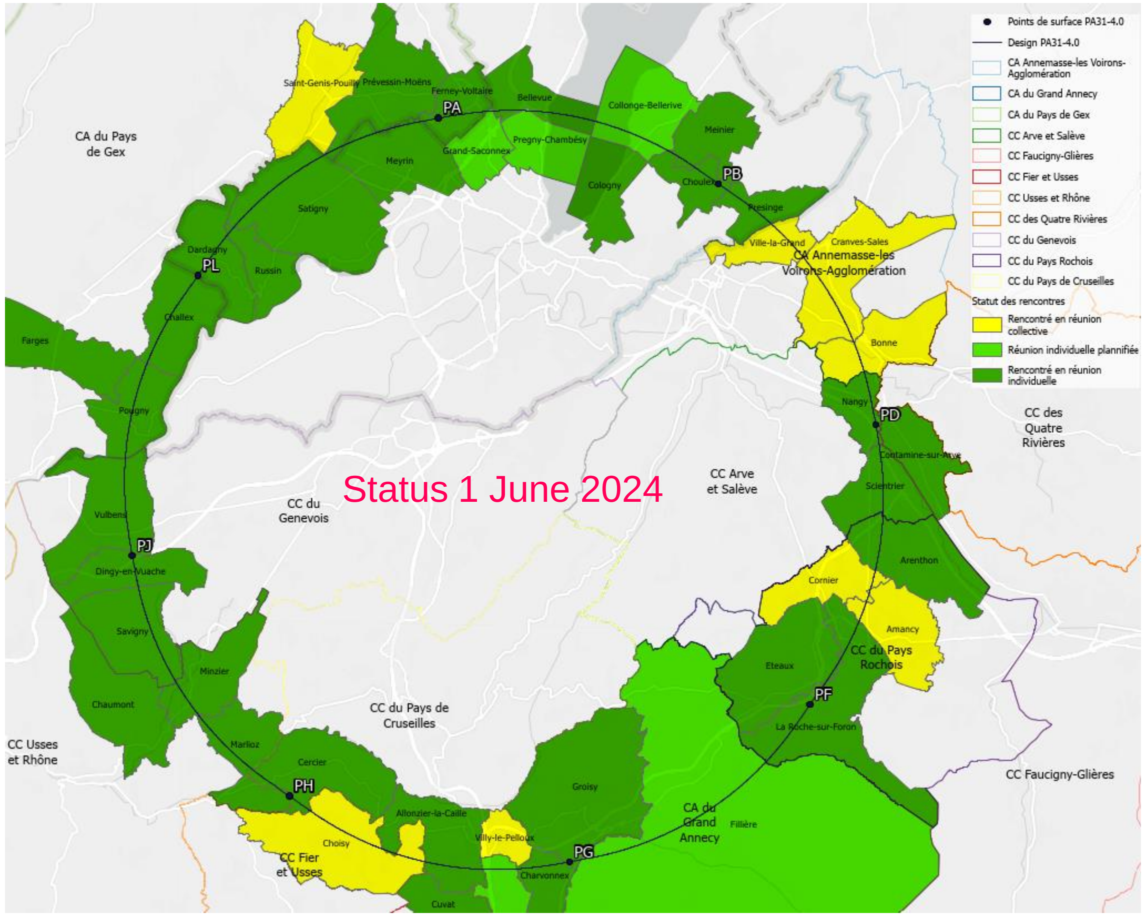
Regional implementation activities

Meetings with municipalities in France (31) and Switzerland (10)

- **PA – Ferney Voltaire** (FR) – experiment site
- **PB – Présinge/Choulex** (CH) – technical site
- **PD – Nangy (FR)** – experiment site
- **PF – Roche sur Foron/Etaux** (FR) – technical site
- **PG – Charvonnex/Groisy** (FR) – experiment site
- **PH – Cercier** (FR) – technical site
- **PJ – Vulbens/Dingy en Vuache** (FR) experiment site
- **PL – Challex (FR)** – technical site

Detailed work with municipalities and host states

- identify land plots for surface sites
- understand specific aspects for design
- identify opportunities (waste heat, techn.)
- reserve land plots until project decision



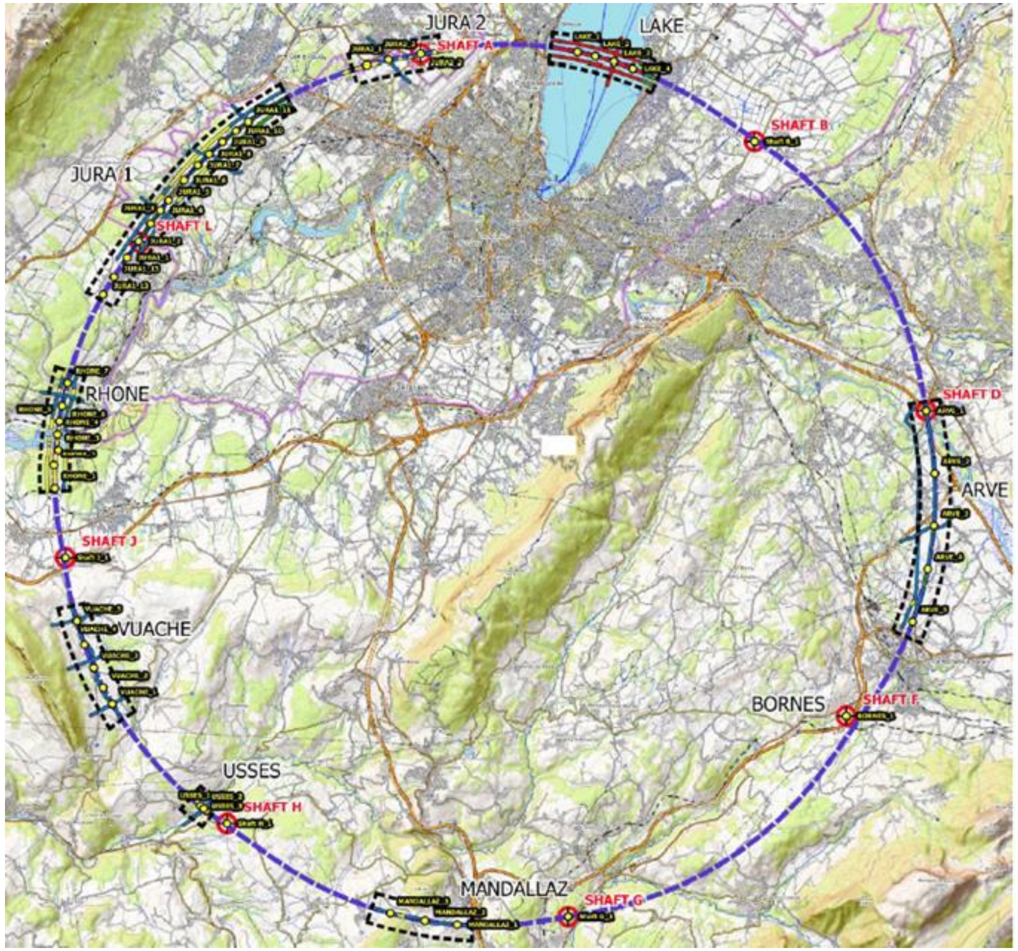
Individual meeting

Individual meeting planned

Collective meeting

→ **The support of the host states is greatly appreciated and essential for the study progress!**

Status site investigations



Site investigations to identify exact location of geological interfaces:

- Molasse layer vs moraines/limestone
- ~30 drillings
- ~100 km seismic lines

→ Start in July/August 2024

→ Vertical position and inclination of tunnel

Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)

Drilling work on the lake

Public information / engaging sessions

First public information and discussion meeting at the Science Gateway on 24 April at CERN

- Meeting for local community (CH, F)
- Discussion about "Progress of the Feasibility Study of the Future FCC circular collider"

La Roche-sur-Foron - Haute Savoie international fair, 27 April to 6 May

Unveiling the science of tomorrow: FCC Study takes centre stage at La Roche-sur-Foron exhibition

The Future Circular Collider team discussed the project's status and aspirations with a large number of attendees

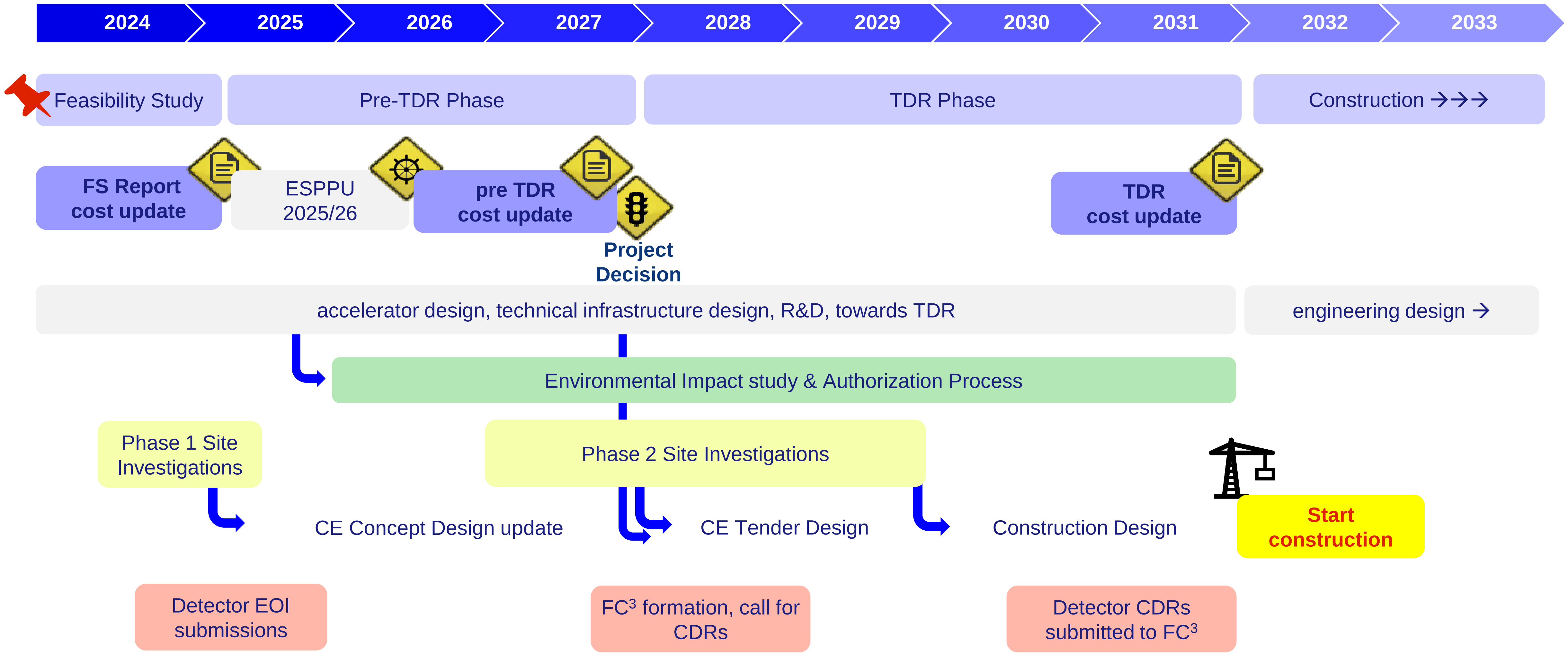
15 MAY, 2024 | By Zoe Nikolaidou

- CERN's participation enhanced by help of volunteers from the FCC team
- Discussions with over 2000 locals
- Various topics (from the required technological. advancements to sustainability measures)

On 15 May, RTS (Radio Télévision Suisse) broadcasted a special program celebrating CERN's 70th anniversary and hosted at CERN's Science Gateway.

- Comprehensive look at CERN's history, achievements, and future ambitions (FCC)
- Study experts interacting with the audience explaining the Future Circular Collider (FCC) project

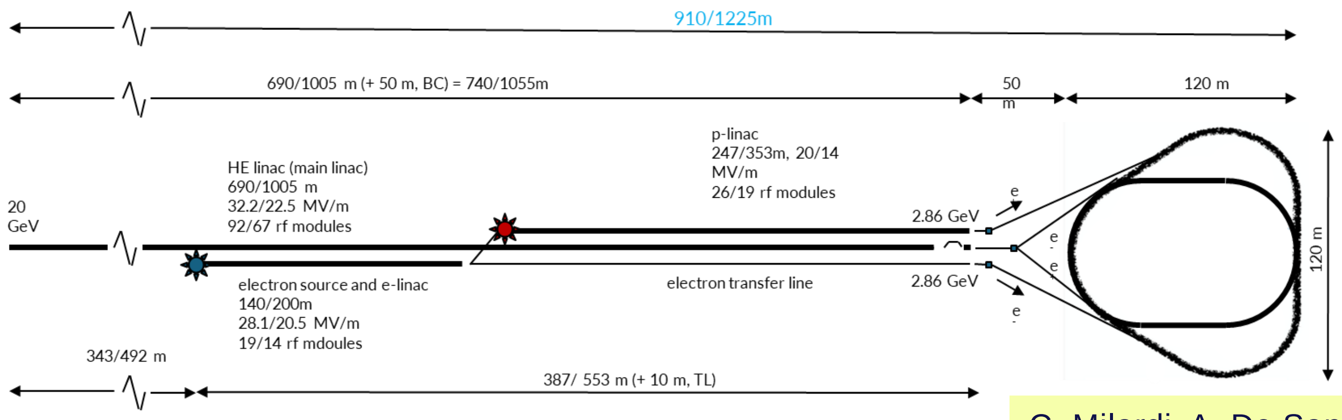
Timeline till start of construction



FCC-ee Injector

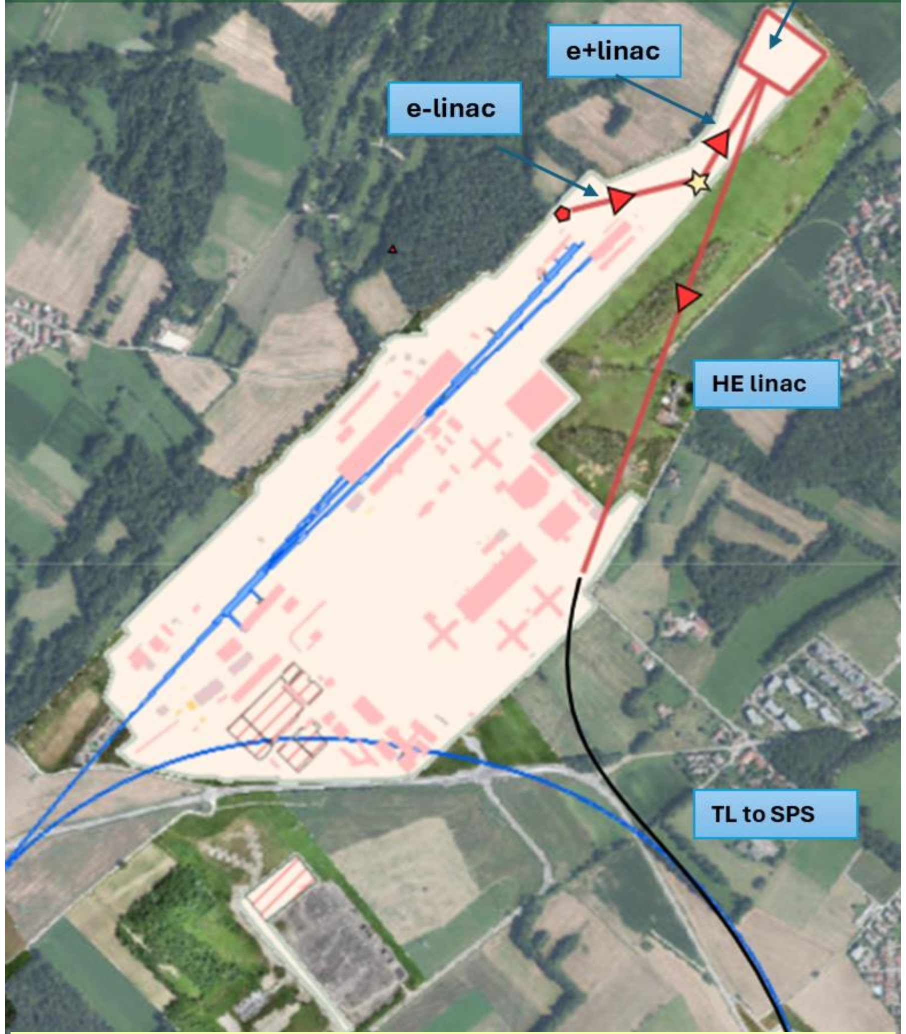
P. Craievich et al

Overall injector parameter optimisation
- Operation frequency, gradient, etc…
- Positron production energy, damping ring energy



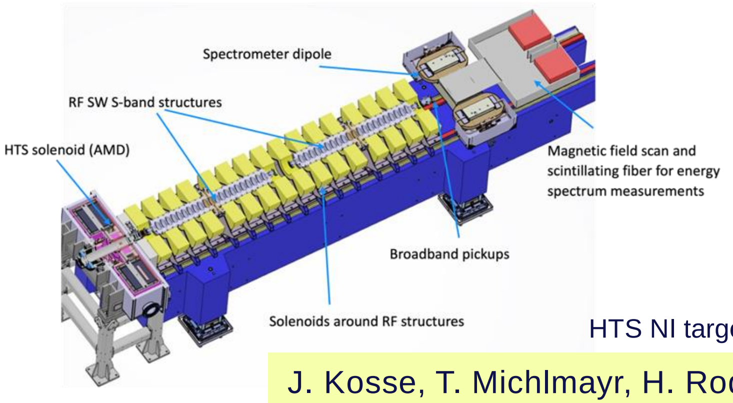
C. Milardi, A. De Santis et al.

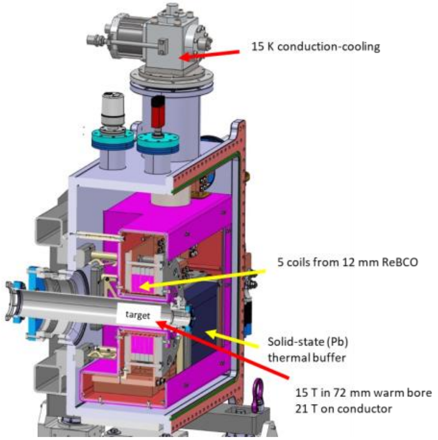
Injector implementation study on CERN Prévessin Site



P. Craievich, W. Bartmann, Y. Papaphilippou, C. Milardi

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





HTS NI target solenoid

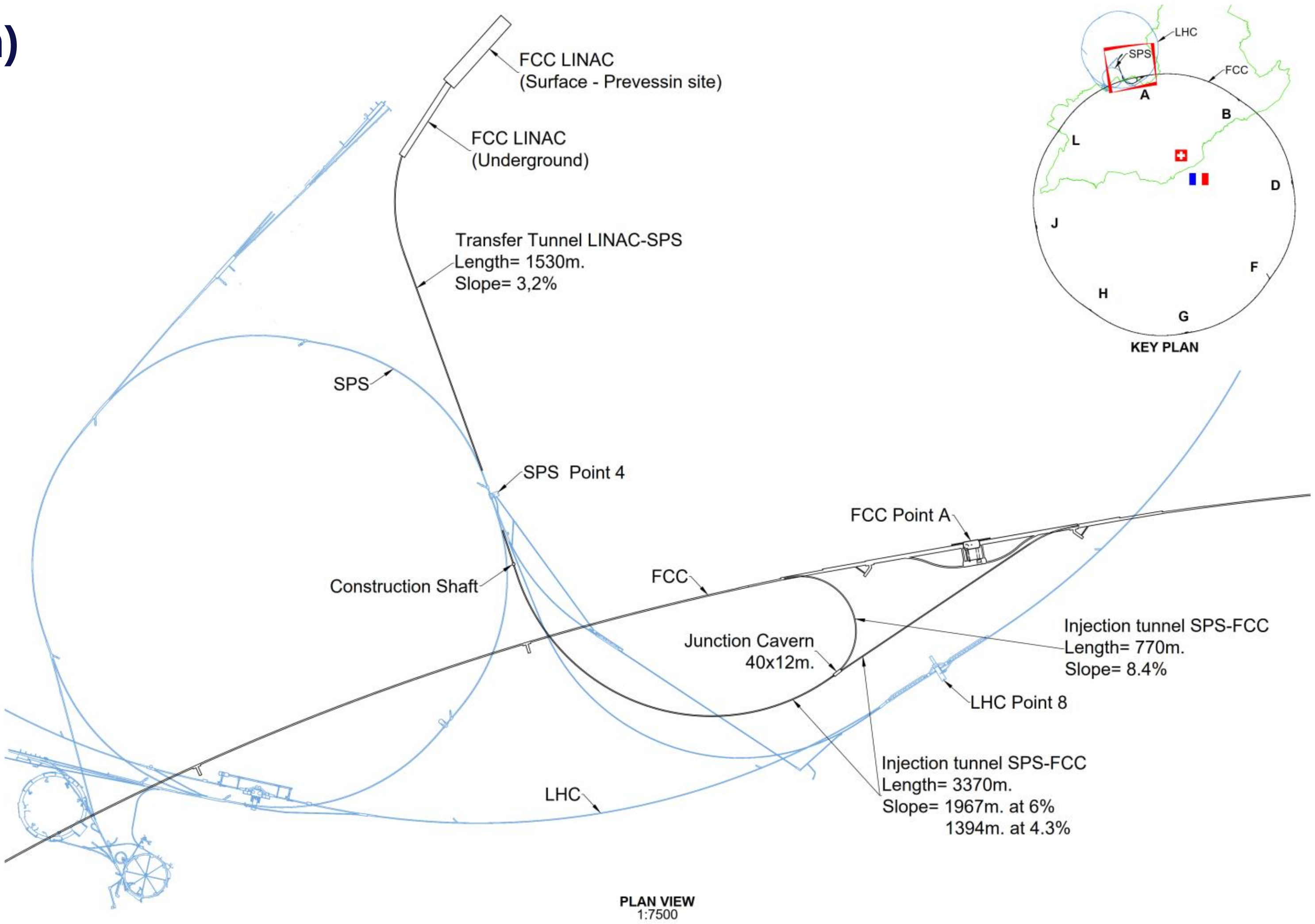
J. Kosse, T. Michlmayr, H. Rodrigues

Transfer line FCC-ee

(option with SPS for FCC-hh)

LINAC and Injection Tunnels

- Enables injection
  - from SPS as pre-booster
  - from a new HE Linac sited at Prevessin
- Single tunnel with spur to enable anticlockwise injection
- Design allows re-use for FCC-hh if injector in the SPS tunnel (SC-SPS option)
  - SPS Point 4 to FCC (clockwise)
  - SPS Point 6 to FCC (counter-c.w.)



W. Bartmann, T. Watson

FCC-ee main machine parameters

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

F. Gianotti

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam
- Independent vacuum systems for electrons and positrons
- full energy booster ring with top-up injection, collider permanent in collision mode

Improvements:

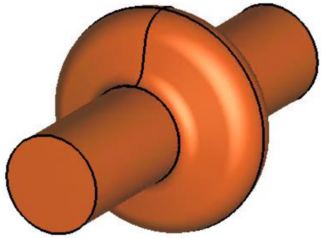
- x10-50 on all EW observables
- up to x 10 on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points

→ robustness, statistics, possibility of specialised detectors to maximise physics output

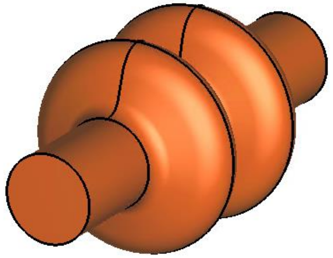
FCC-ee baseline RF configuration so far

Z 1-cell 400 MHz, Nb/Cu



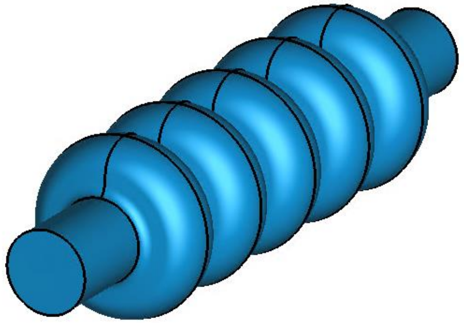
low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H 2-cell 400 MHz, Nb/Cu



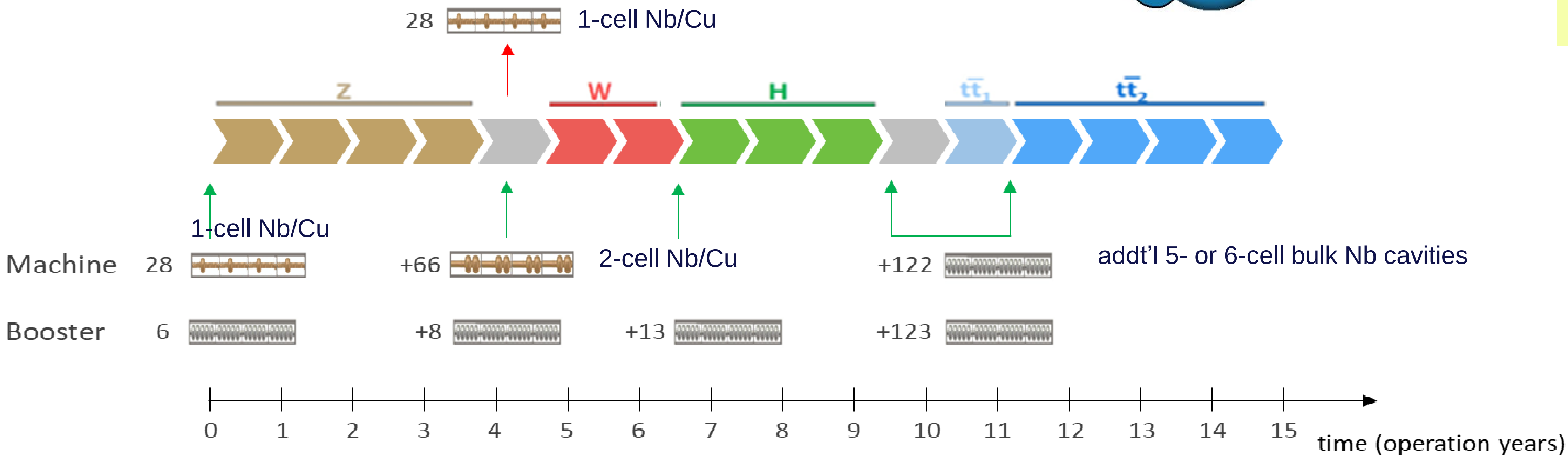
moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

ttbar, booster 5-cell 800 MHz, bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

F. Peauger, O. Brunner



O. Brunner

FCC-ee simplified RF system

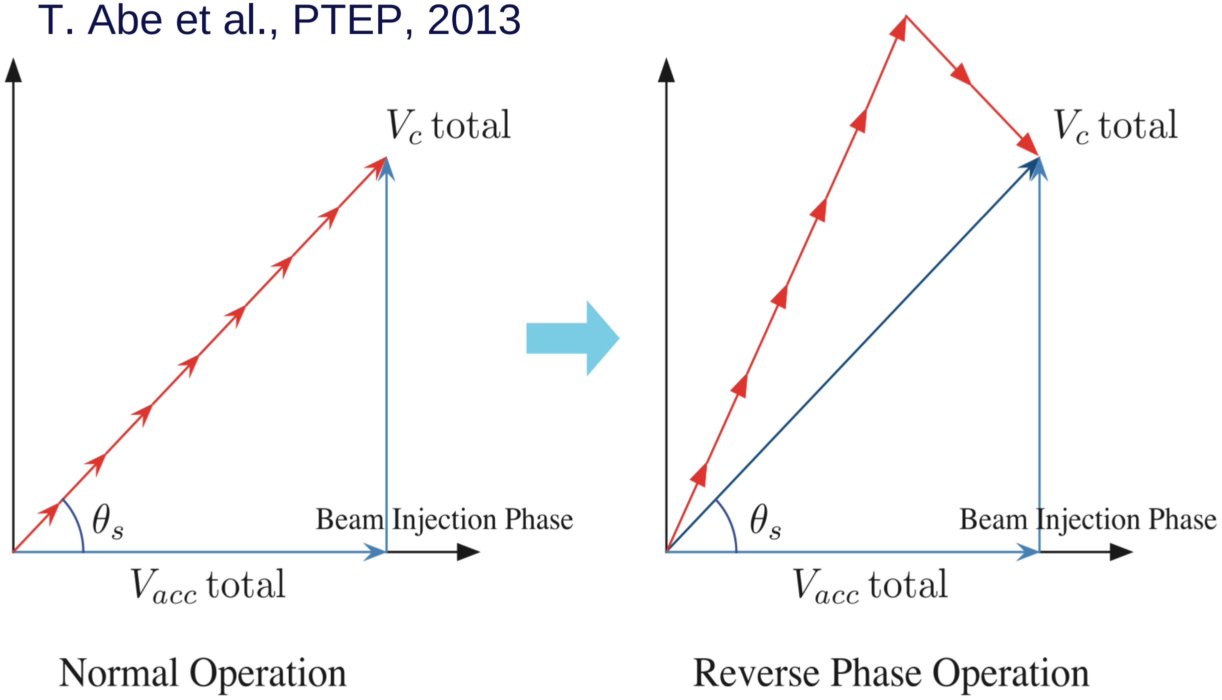
2-cell for all energies

$$Q_{L,opt} = \frac{V_{\mathrm{cav}}^2 N_{\mathrm{cav}}}{2 V_{tot} (R/Q) I_{b,DC} \cos \phi_s}$$

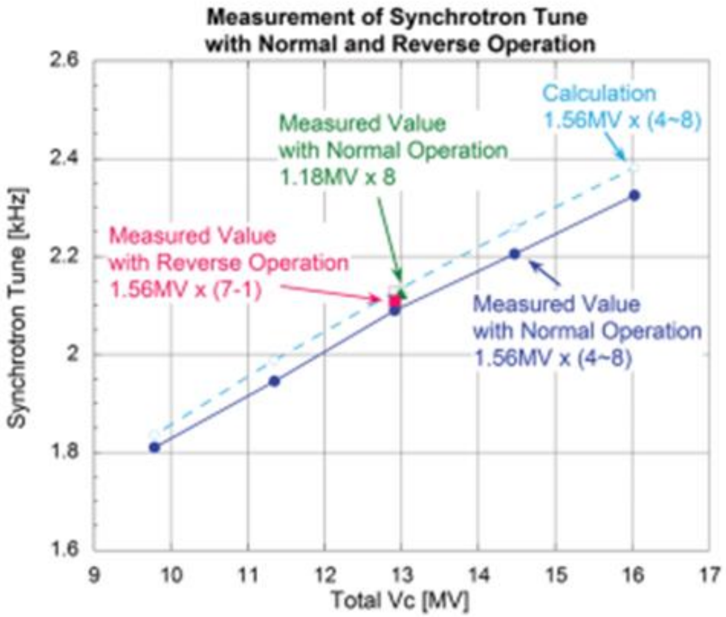
Reverse phase operation (RPO) → higher RF cavity voltage *(Y. Morita et al., SRF, 2009)*

- **Experimentally verified** with high beam loading in KEKB *(Y. Morita et al., IPAC, 2010)*
- **Baseline solution for EIC ESR** *(e.g., J. Guo et al., IPAC, 2022)*

T. Abe et al., PTEP, 2013



KEKB HER synchrotron tune measured for several SC cavity configurations. RPO "(7 - 1)" case with1.56 MV/cavity yielded about the same f_s as for 8 in-phase cavities with 1.18 MV/cavity [T. Abe et al., 2013]



→ RPO potentially allows same optimal quality factor for Z, W, and H modes

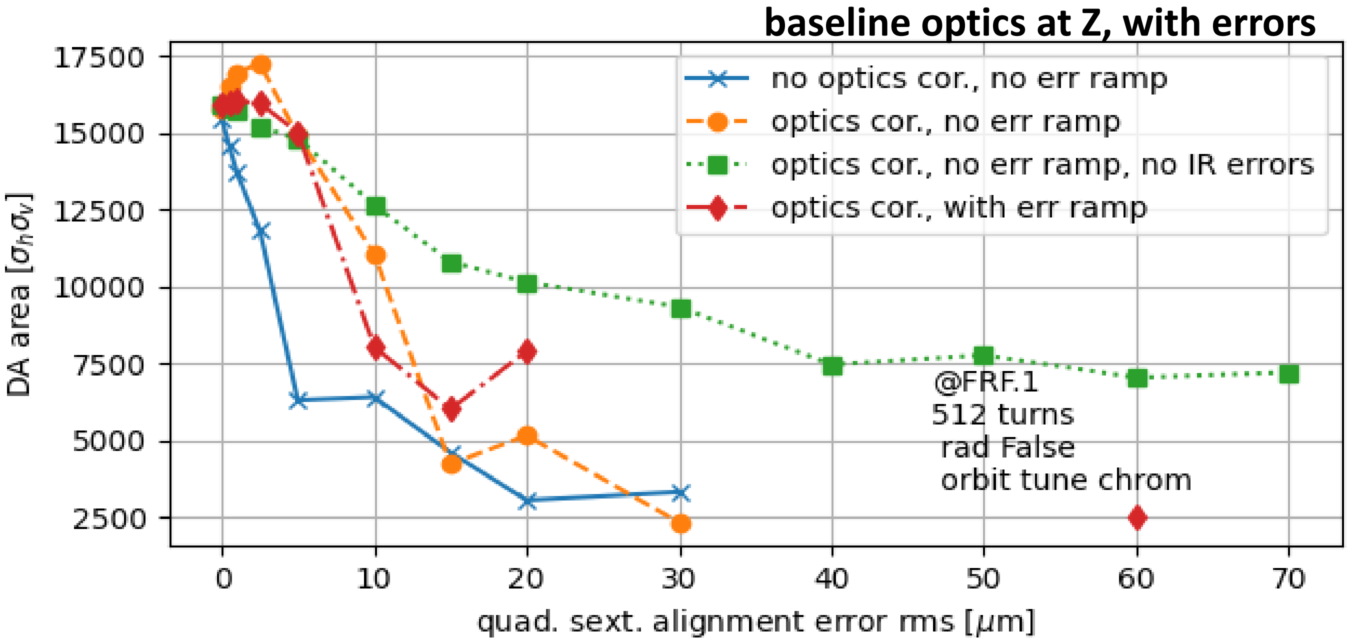
I. Karpov

__Advantages:__

- ❑ Rationalize RF resources during the development process (3 → 2 cavity types)
- ❑ Simplify, shorten the installation sequence (no cryo-module removal)
- ❑ **Great flexibility in physics running modes**
- ❑ Potential savings (cost, manpower, and time)

FCC-ee dynamic aperture with alignment errors

S. Liuzzo, ESRF

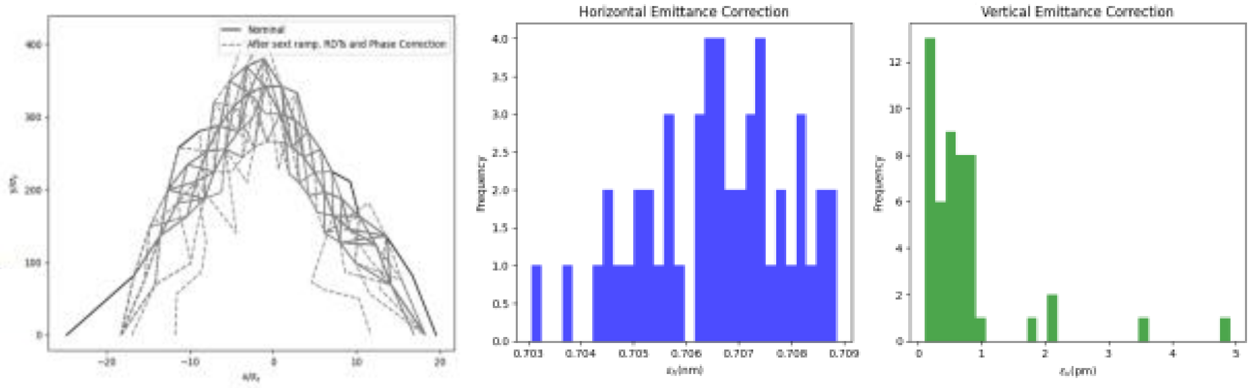


>100 μm alignment errors in the arcs acceptable for present baseline optics

E. Musa, DESY

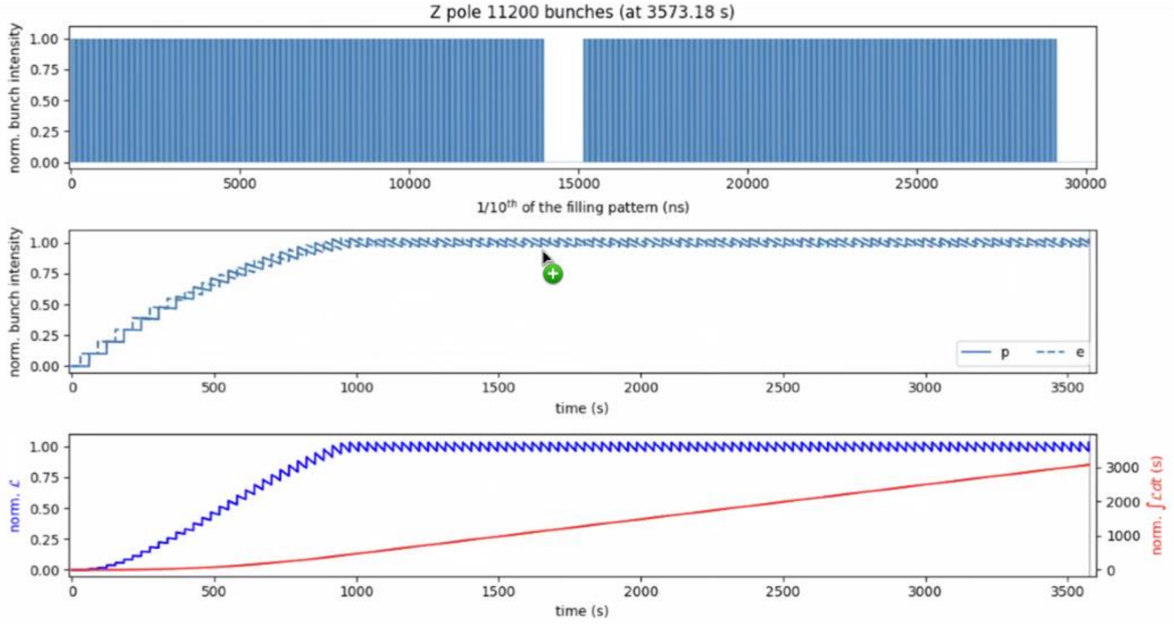
50 seeds (mean values)		rms orbit x (μm)	rms orbit y (μm)	Δβx/βx %	Δβy/βy %	Δ ηx (mm)	Δ ηy (mm)	ε_h (nm)	ε_v (pm)
100 μm on arc quads & sexts	With err	6224.8	7276.7	1e-6	1e-4	11985	73458	-	-
	After Sext ramping	8.55	8.35	5.98	9.91	45.23	45.96	0.71	9.61
	RDTs & ηy Cor	8.58	8.42	6.01	9.94	45.09	4.49	0.71	2.32
	Phase Cor	8.55	8.35	0.35	0.79	2.94	4.36	0.70	0.88
	Final cor. result	8.55	8.35	0.35	0.89	2.94	4.37	0.70	0.73

@FRF.1
Sigma_x =0.000362m
Sigma_y =0.000012m

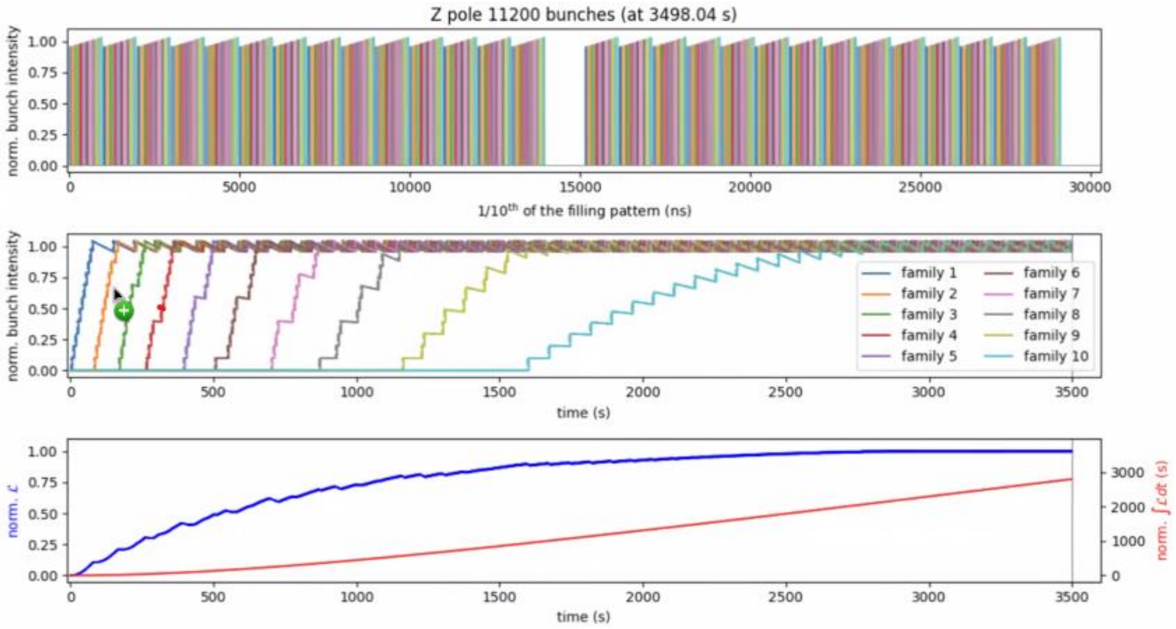


FCC-ee filling scheme & e-cloud mitigation

“CDR scheme”



“Carli-Bartosik scheme”



only 1/10 of intensity per booster cycle
→ vacuum pressure-tolerant
only 1/10 of collider bunches at intermediate intensity
→ anti e-cloud build up

→ yet same integrated luminosity as for CDR scheme !

H. Bartosik, C. Carli, L. Mether, F. Zimmermann

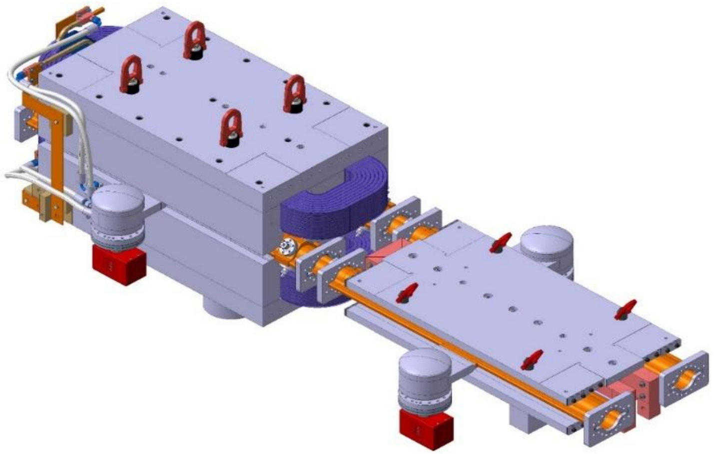
Arc layout and integration optimisation

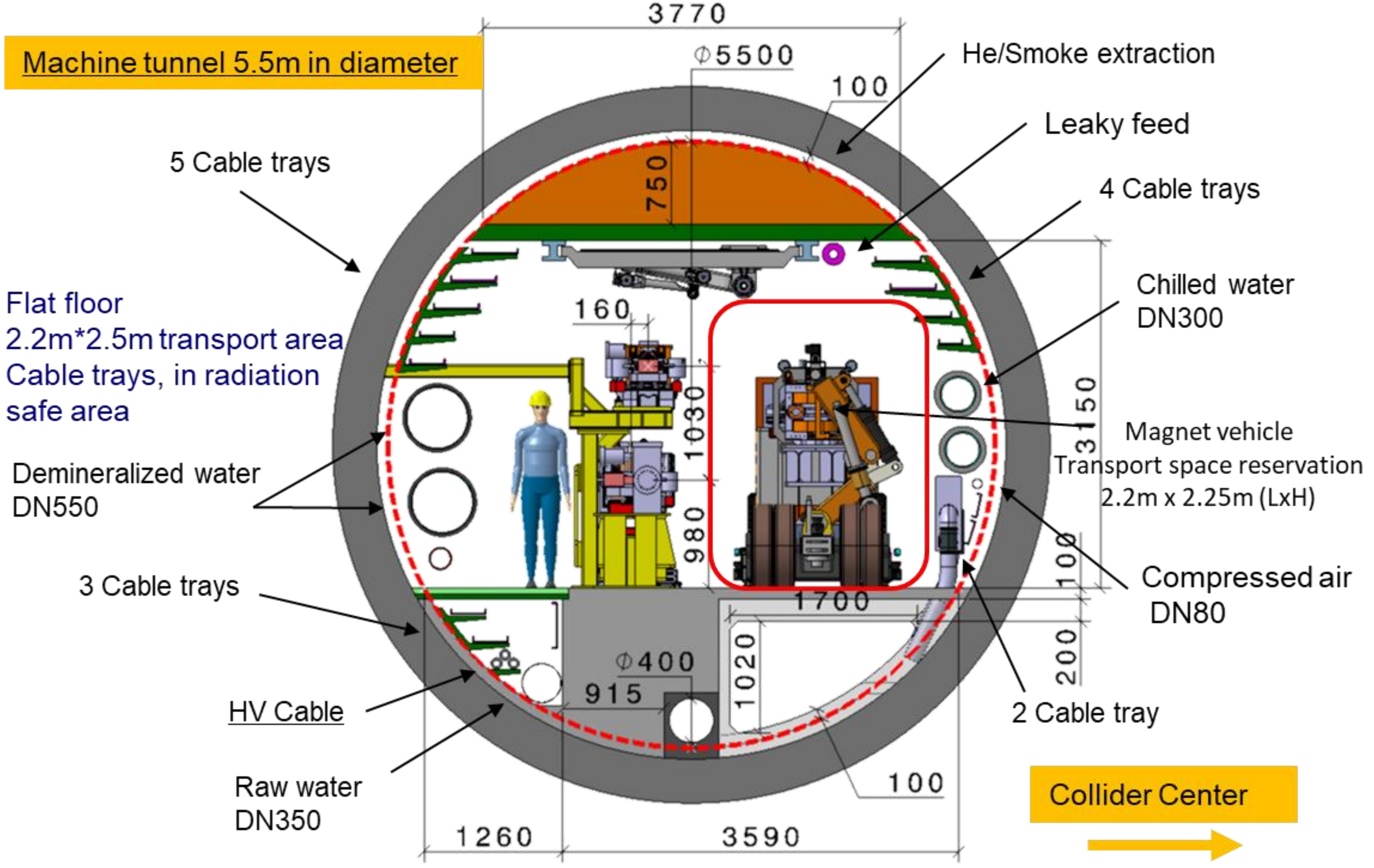
Arc cell optimisation – 80 km total length, dedicated working group active.

- including support, girder and alignment systems, shielding systems
- vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs
- cabling, cooling & technical infrastructure interfaces
- safety aspects, access and transport concept

→ **Confirmation of tunnel diameter**

FCC-ee arc half-cell mock up



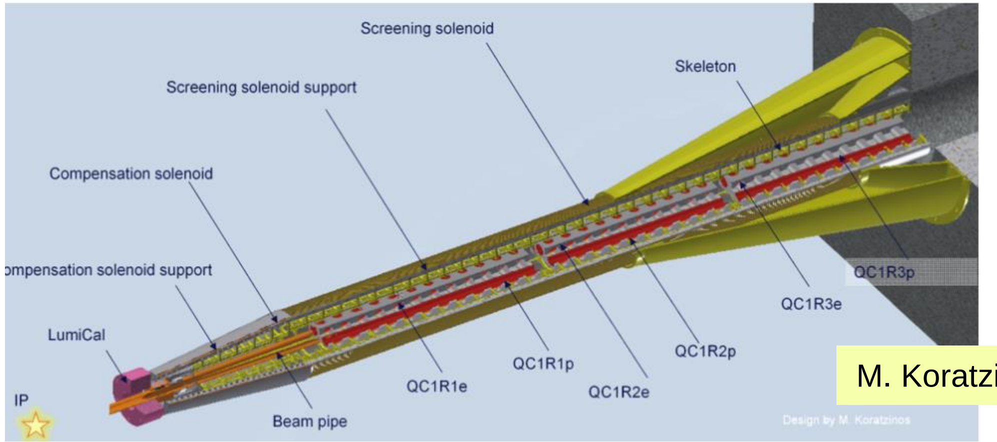


F. Carra, CERN; F. Valchkova

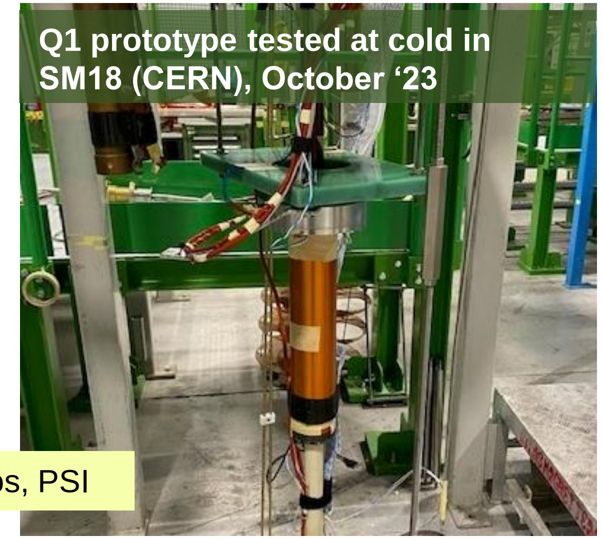
Machine detector interface

Key topics:

- SC IR magnet system & Cryostat design
- 3D integration
- IR mock-up at INFN Frascati !

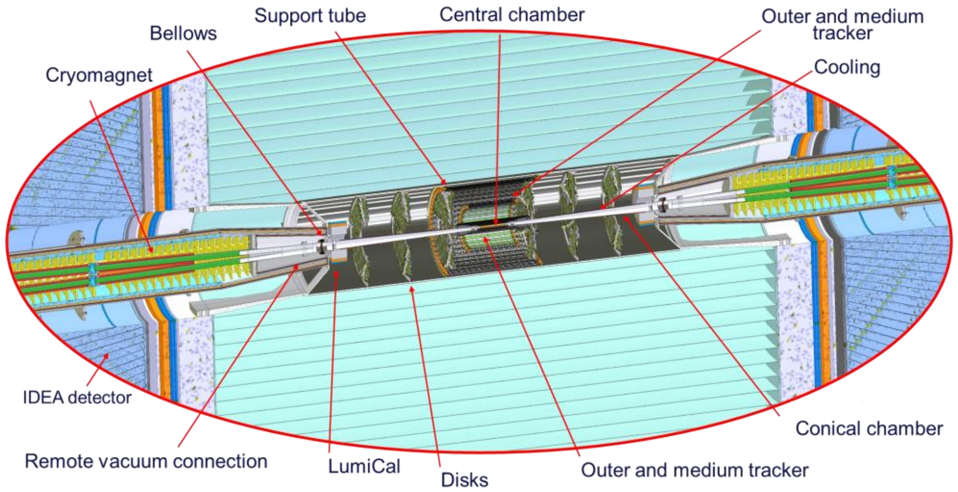


M. Koratzinos, PSI



P. Tavares , CERN
J. Seeman, SLAC

Machine		FCCee	CEPC	ILC	SuperKEKB
Crossing-angle	mrad	30	33	14	83
L*	m	2.2	1.9	3.5	0.935
Vertical β_y* at IP	mm	0.7-1.6	0.9-2.7	0.4	0.3
Detector soln field	T	2/3	3	3.5/5	1.5
Detector stay clear	mrad	100	118/141	90	350/436
Two beam ΔX at L*	mm	66	62.7	49	77.6
He temperature	K	1.9	4.2	4.5	4.5

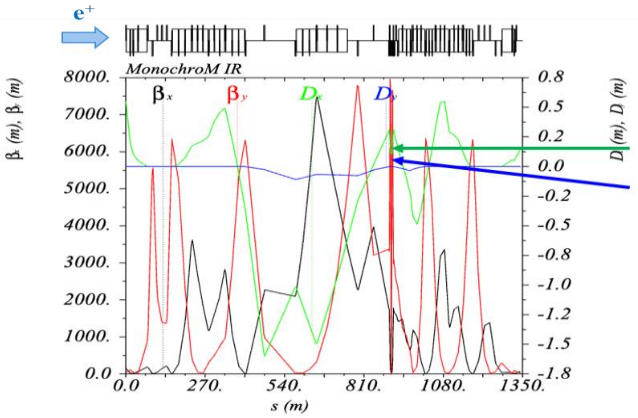


M. Boscolo, F. Palla, INFN

FCC-ee option:

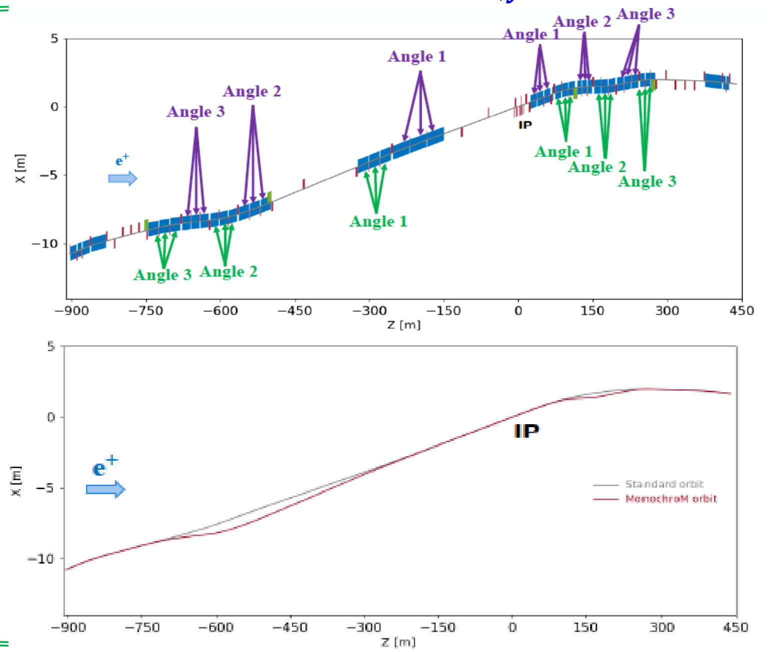
Monochromatization at 125 GeV

So far best performance is obtained with **ttbar lattice** based **“mix” mode**, which reaches $y_e < 2.9 * y_e(SM)$ in the Higgs-electron Yukawa coupling

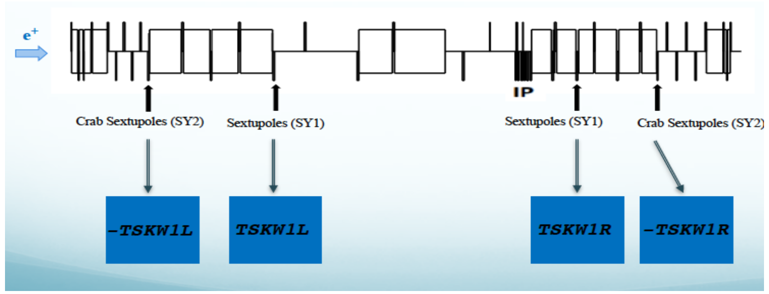


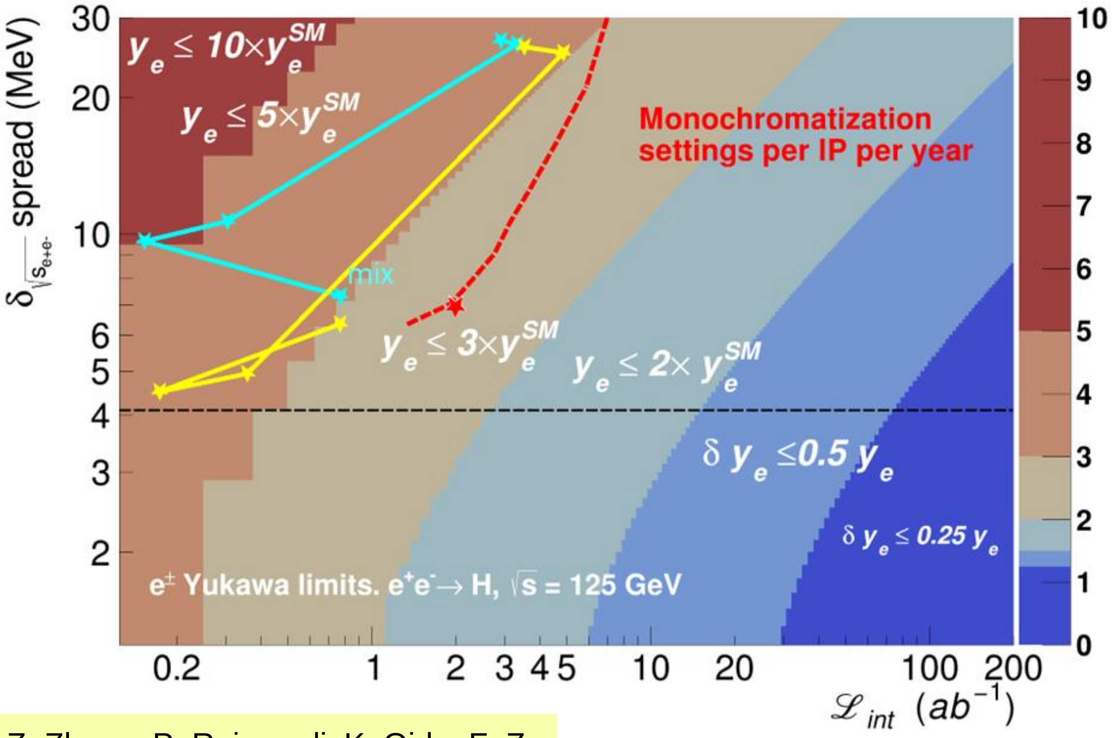
create opposite-sign $D^*_{x,y} \neq 0$

D^*_x



D^*_y





A. Faus-Golfe, Z. Zhang, P. Raimondi, K. Oide, F. Z.

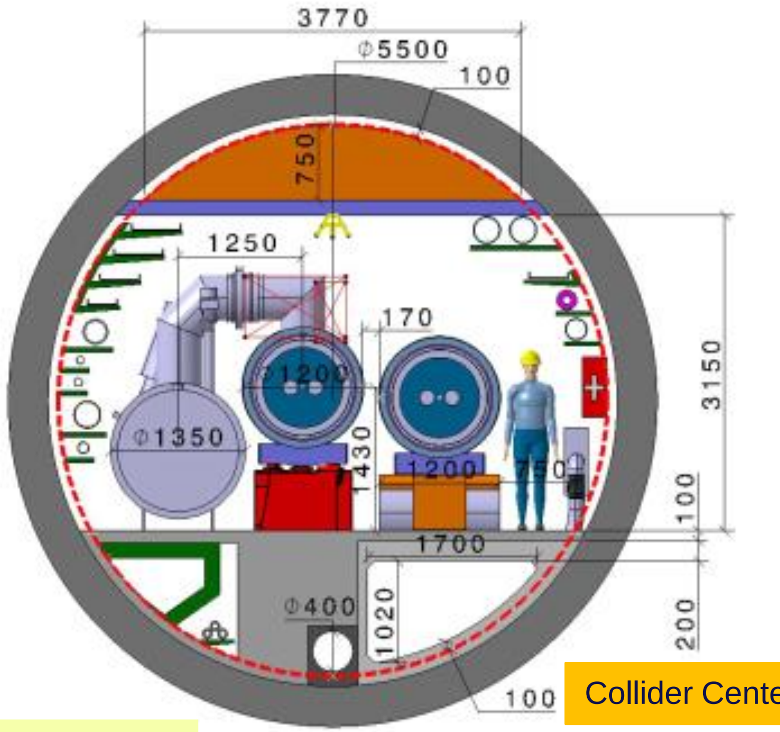
Key activities on FCC-hh

M. Giovannozzi. G. Perez, T. Risselada

Magnet system, optic design

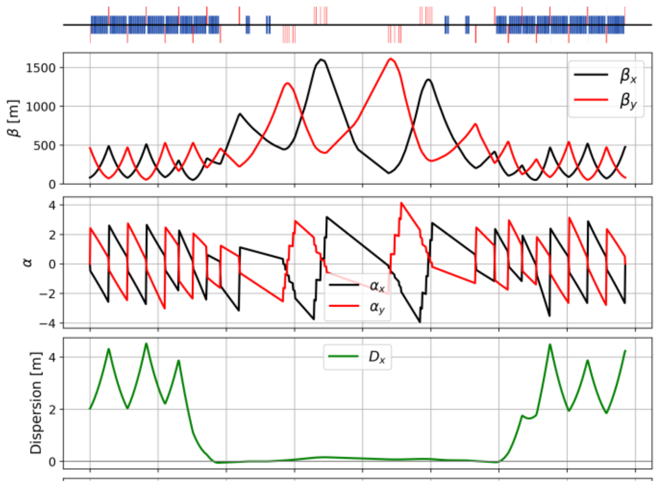
Optics design activities:

- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)

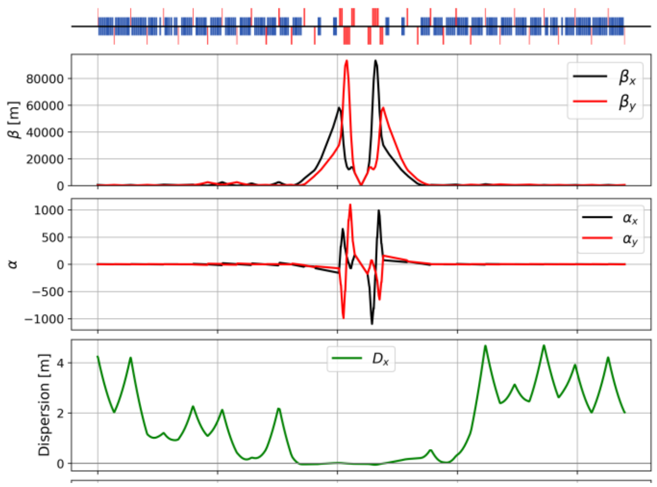


Collider Center

F. Valchkova



betatron collimation straight



experimental straight

High-field cryo-magnet system design

- Conceptual study of cryogenics concept and temperature layout for LTS and HTS based magnets, in view of electrical consumption.
- Update of integration study for the ongoing HFM designs and scaling to preliminary HTS design.
  → **Confirmation of tunnel diameter!**
- HFM R&D (LTS and HTS) on technology and magnet design, aiming also at bridging the TRL gap between HTS and Nb_3Sn.

Status of FCC global 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

141 Institutes

32 countries + CERN

FUTURE CIRCULAR COLLIDER
Feasibility Study

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

FCC Week 2024

Complete status of the FCC Study and all the latest advancements were presented at the Future Circular Collider Week 2024, in San Francisco, 10-14 June 2024

https://fccweek2024.web.cern.ch/

449 participants : 75 remote, 374 on site

Progress on international collaboration

Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science

The United States and CERN intend to:

- Enhance collaboration in future planning activities for large-scale, resource-intensive facilities with the goal of providing a sustainable and responsible pathway for the peaceful use of future accelerator technologies;
- Continue to collaborate in the feasibility study of the Future Circular Collider Higgs Factory (FCC-ee), the proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise and providing a clear pathway for future activities in open and trusted research environments; and
- Discuss potential collaboration on pilot projects on incorporating new analytics techniques and tools such as artificial intelligence (AI) into particle physics research at scale.

Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals.

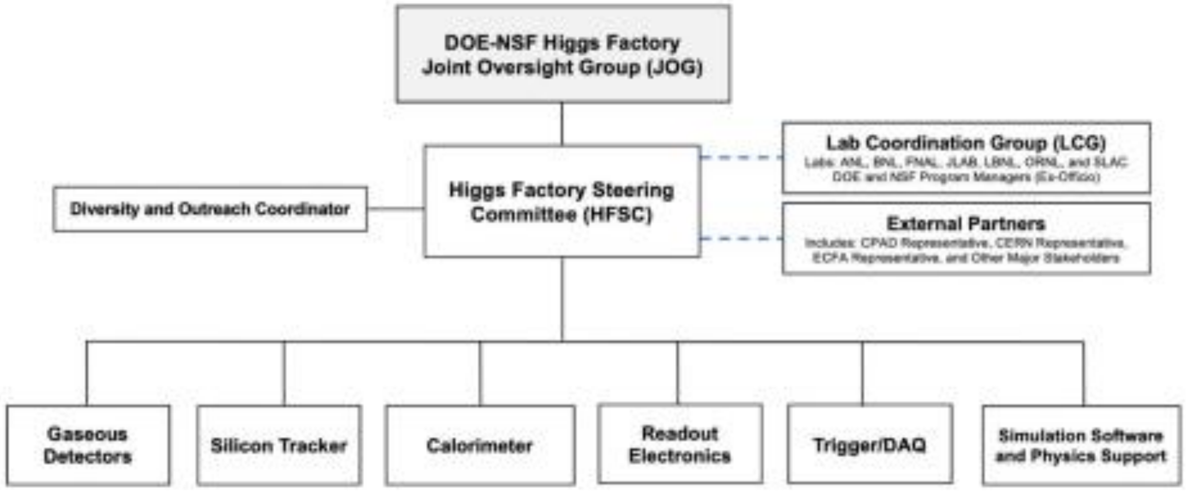
26 April 2024

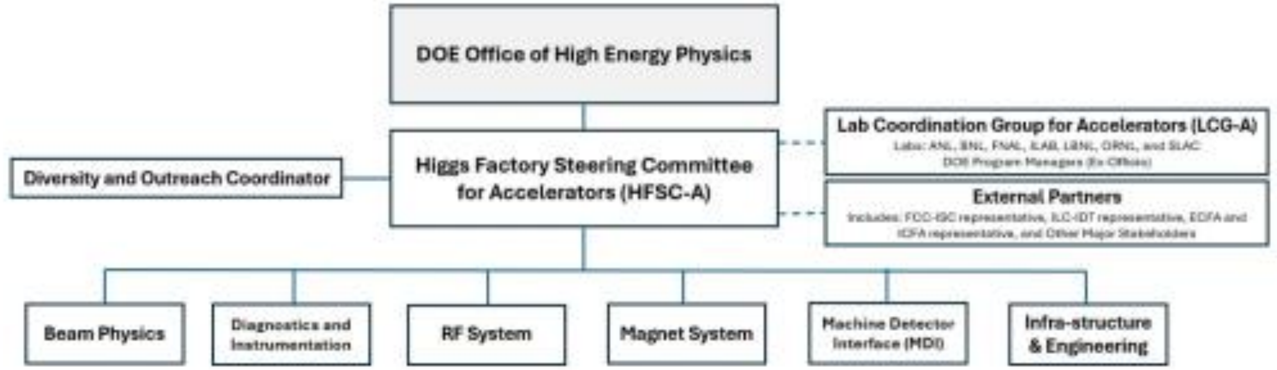
White House Office of Science and Technology Policy Principal Deputy U.S. Chief Technology Officer Deirdre Mulligan signed for the United States while Director-General Fabiola Gianotti signed for CERN.

US Organisation for Higgs Factory

DOE and NSF Higgs factory organisation

(organizations will evolve to follow the needs of the community)





Charge

1. Physics and technical feasibility studies, including any associated design and R&D efforts, to advance various experiment detector concepts at a future Higgs factory;
2. Prioritization and stewardship of the national R&D efforts should funds be identified by DOE and/or NSF;
3. Development of the pre-project detector R&D scope that will be required prior to DOE and/or NSF initiating any detector project at a future e+e- collider;
4. Conceptualization of the software and computing framework that will be needed to advance physics studies and R&D efforts; and to collect, store, and analyze the large volumes of physics data at future collider experiments;
5. In consultation with DOE and NSF program managers, develop various funding models that will be required to support the R&D efforts described in items (3) and (4) above; and
6. Ensure collaborations by the U.S. with our partners are cost-effectively carried out to advance the future Higgs factory initiatives. (CPAD, ECFA, DRD, others).

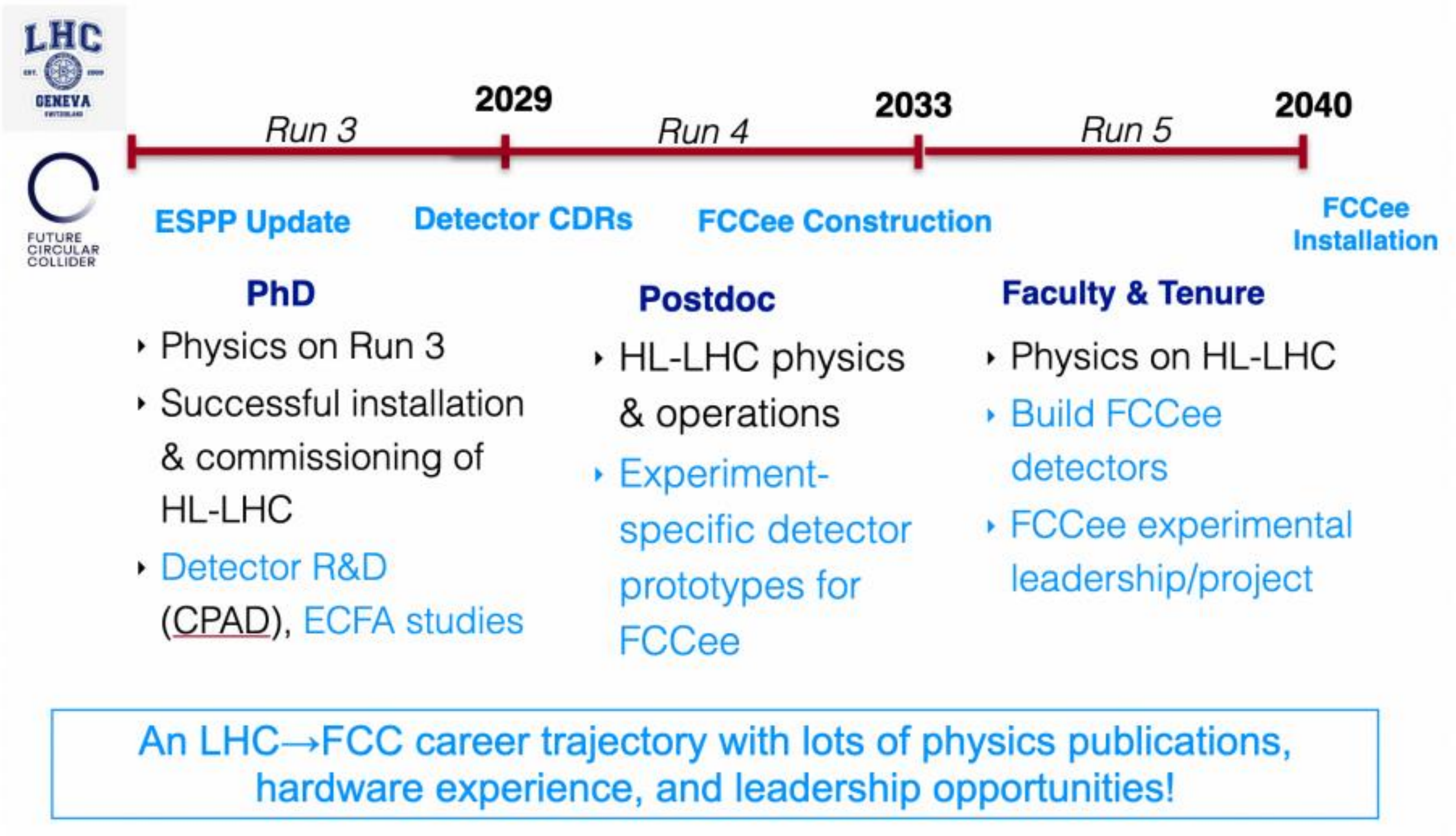
- Prepare the groundwork to respond to the P5 Recommendation 6: "[Convene a targeted panel to review] the level and nature of US contribution in a specific Higgs factory including an evaluation of the associated schedule, budget, and risks once crucial information becomes available"

Sarah Eno

Early Career Researchers

Session at FCCW2024

A possible FCC career



Matthew Citron, Julia Gonski

FCC Main Goals for Coming Years

- **Next milestone: by March 2025 completion of the FCC Feasibility Study**

- **By 2027-2028, possible FCC project approval, start of CE design contract:**
  - specifications to enable CE tender design by 2028
  - refined input for environmental evaluation and project authorisation process
  - requires overall integration study and designs based on technical pre-design of accelerators, technical infrastructure and detectors

- **By 2031-32, possible start of CE construction:**
  - CE groundbreaking
  - TDR to enable prototyping, industrialization towards component production

→ Strong collaboration with US and further international partners is essential for success !

Save the date: 19 – 23 May 2025

thank you for your attention

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FCC
SUISSE
FRANCE
Genève
Annecy
LHC

FUTURE CIRCULAR COLLIDER

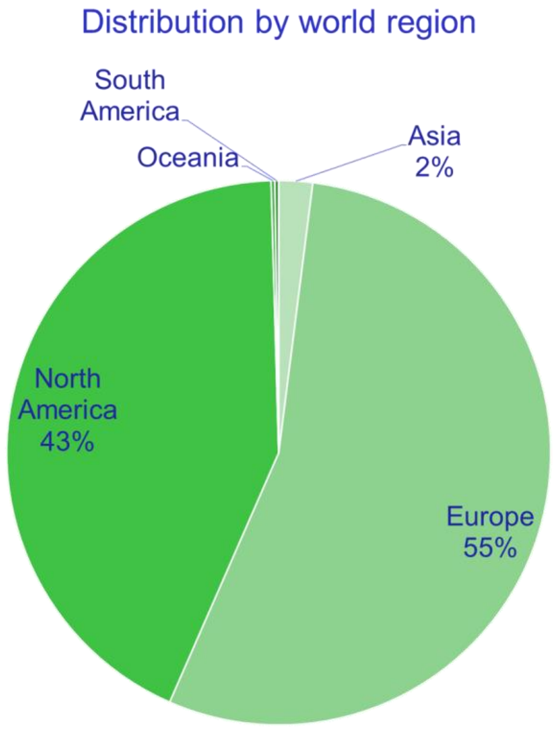
Version: 2.0 Date: 04.06.2024

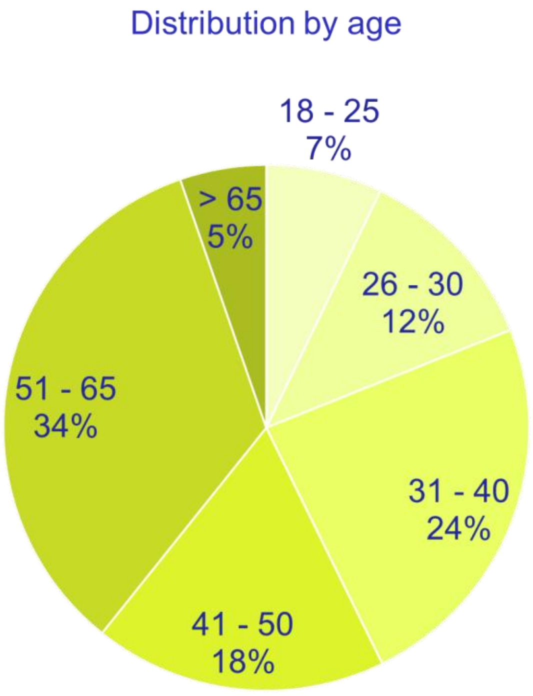
Day	Sunday	Monday		Tuesday					Wednesday					Thursday						Friday	Day
Time SFO	Front desk	Plenary	Board Room	Parallel 1	Parallel 2	Parallel 3	Parallel 4	Board Room	Plenary	Parallel 1	Parallel 2	Parallel 3	Board Room	Plenary	Parallel 1	Parallel 2	Parallel 3	Parallel 4	Board Room	Plenary	Time SFO
Room	Georgian	Colonial	Yorkshire	Elizabethan A	Elizabethan B	Elizabethan C	Elizabethan D	Yorkshire	Colonial	Elizabethan A	Elizabethan B	Elizabethan C	Yorkshire	Colonial	Elizabethan A	Elizabethan B	Elizabethan C	Elizabethan D	Yorkshire	Colonial	Room
08:00-08:30		Welcome coffee (Italian)		Welcome coffee (California East & West)					Welcome coffee (California East & West)					Welcome coffee (California East & West)						Welcome coffee	
08:30-09:00		1) Welcome remarks 2) CERN plans 3) A view from CERN Council 4+5) NSF and DOE Opening Remarks		Physics Case & Th. Calculations (i)	FCC-ee baseline design & optics, top-up	Safety				Detector Requirements (i)	Collective Effects	Sustainability and impact generation			Detector Requirements (ii)	FCC-ee code development and other themes		RF and Cryo	Governance meeting	Plenary session: summaries	08:30-09:00
09:00-09:30																					09:00-09:30
09:30-10:00																					09:30-10:00
10:00-10:30		Coffee break (Italian)		Coffee Break (California East & West)					Coffee Break (California East & West)					Coffee Break (California East & West)							10:00-10:30
10:30-11:00		1) Key Note 2) FCC FS status 3) FCC Collaboration status		Physics Case & Th. Calculations (ii)	Optics alternatives & lessons	Transport, logistic and Survey	Synergies and innovation			Software	FCC-ee optics correction & tuning	Sustainability and impact generation			Machine Detector Interface (ii)	FCC-hh design	Injection & instrumentation	Utilities		Coffee break	10:30-11:00
11:00-11:30																				Plenary session: summaries	11:00-11:30
11:30-12:00																					11:30-12:00
12:00-12:30				Lunch break (California East & West)				Governance meeting	Lunch break (California East & West)					Lunch break (California East & West)							12:00-12:30
12:30-13:00		Lunch break (California East & West)																			12:30-13:00
13:00-13:30																			Governance meeting		13:00-13:30
13:30-14:00				Detector Concepts (i)	FCC-ee injector incl. booster (i)	Civil Engineering	Directions for R&D			Machine Detector Interface (i)	SRF Technology (ii)	Magnets			EPOL (i)	high-field magnets for FCC-hh 1	Vacuum	AIML mini workshop			13:30-14:00
14:00-14:30		1) Implementation scenario 2) Civil Engineering 3) Accelerator status 4) Technologies & TI						Governance meeting													14:00-14:30
14:30-15:00																					14:30-15:00
15:00-15:30	Registration + as from 07:30am on Monday			Coffee Break (California East & West)					Coffee Break (California East & West)					Coffee Break (California East & West)							15:00-15:30
15:30-16:00		Coffee break (Italian room)		Detector Concepts (ii)	FCC-ee injector incl. booster (ii)	Layout optimisation and services	SRF Technology (i)		Plenary: US Session						EPOL (ii)	high-field magnets for FCC-hh 2	Beam Intercepting devices	AIML mini workshop			15:30-16:00
16:00-16:30		1) Super KEKB status and plans 2) The Physics at FCC 3) Detectors requirements an… 4) Plan… 5+6) U…	Governance meeting																		16:00-16:30
16:30-17:00																					16:30-17:00
17:00-17:30																					17:00-17:30
17:30-18:00																					17:30-18:00
18:00-18:30				(iii)	booster (iii)	Gov…															18:00-18:30
18:30-19:00																					18:30-19:00
19:00-19:30														Poster session + cocktail (Colonial & Italian)							19:00-19:30
19:30-20:00		(W…																			19:30-20:00
20:00-20:30																					20:00-20:30
20:30-21:00																					…1:00
21:00-21:30																					…1:30

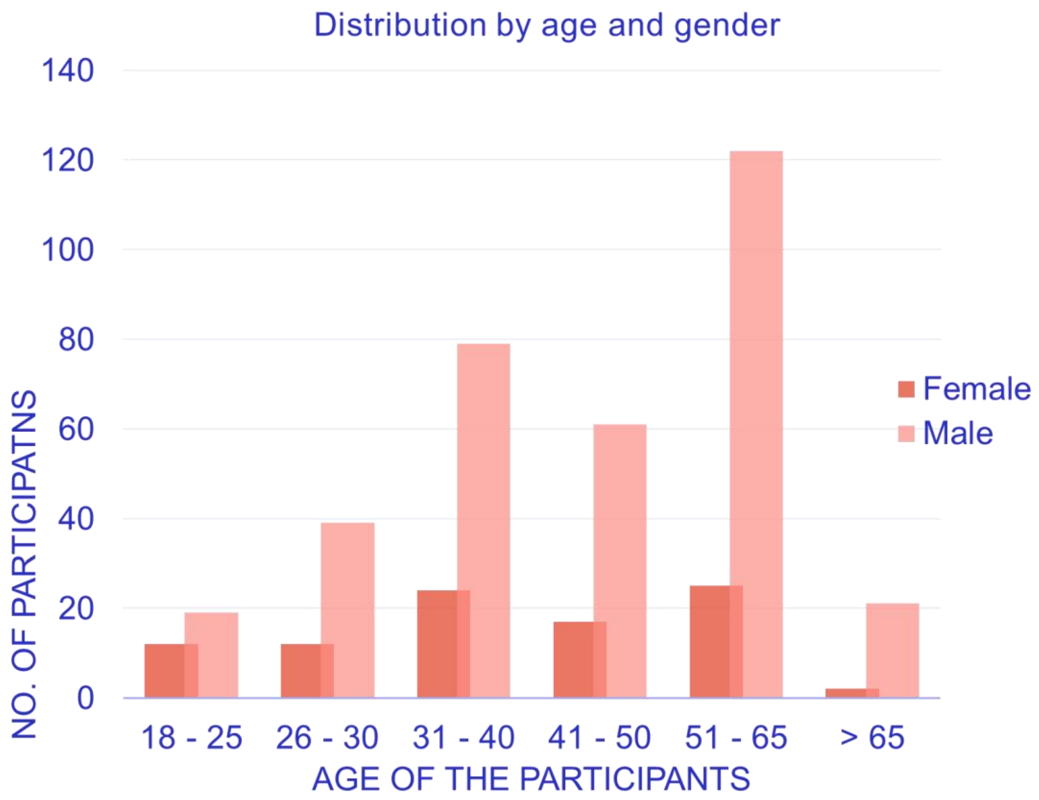
FCC Week 2024: 50 public sessions, 216 oral presentations, 32 posters

great spirit, much progress, US efforts getting organized on the best way to completing the Feasibility Study by March 2025

Participants' distribution by region, age and gender







According to the registration form, excluding 'would rather not say' answers