FCC Feasibility Study Status

Manuela Boscolo
INFN-LNF

on behalf of FCC collaboration
with warm thanks to
Michael Benedikt

LNF General Seminar
17 January 2024

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **FCCIS**, grant agreement 951754*

http://cern.ch/fcc

photo: J. Wenninger

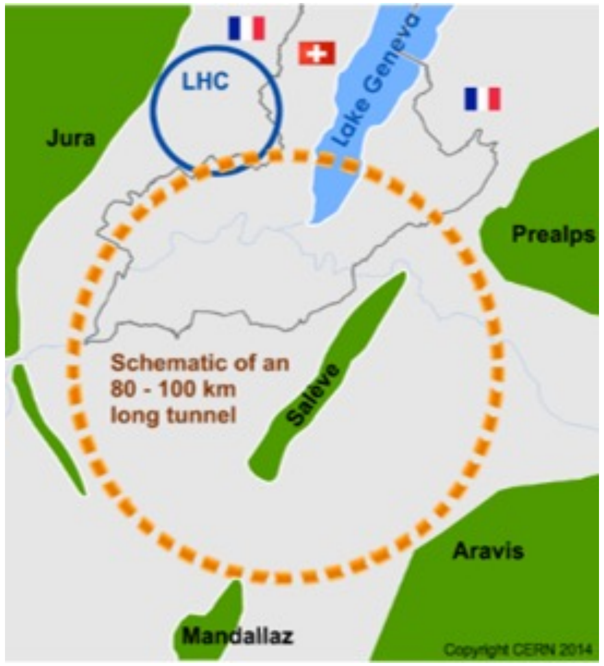
Outline

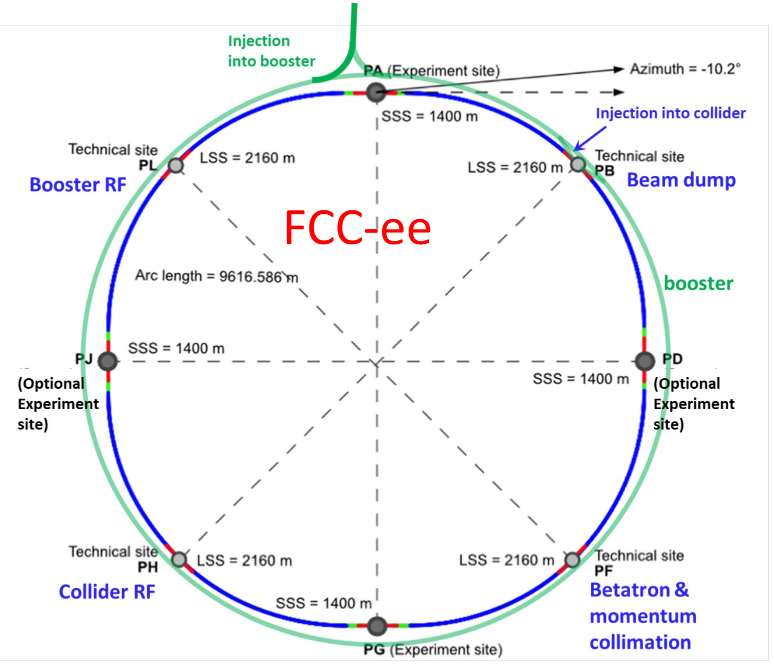
- Introduction
- Feasibility Study
  - Mid-term review
  - FCC Schedule
- Accelerator Design
- FCC Italia activities and involvement
- Outlook

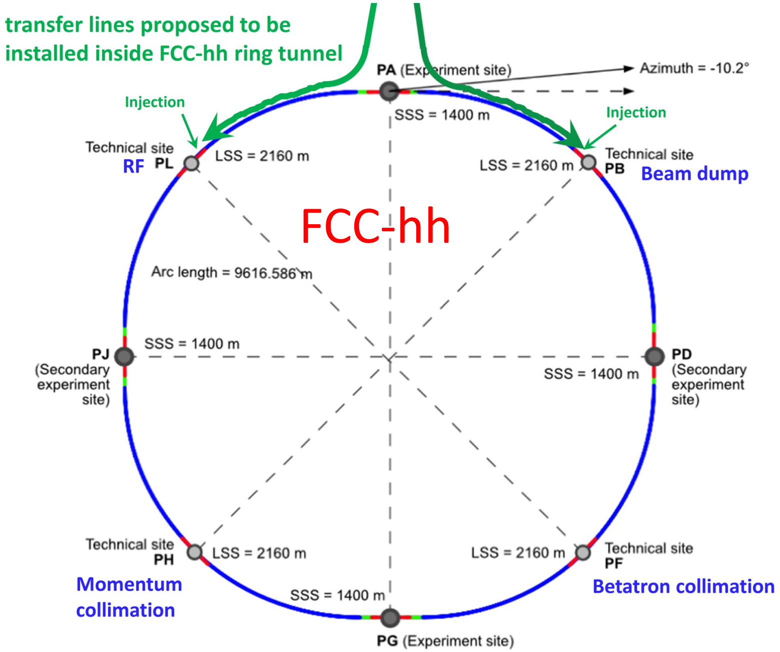
FCC integrated program

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, pp & AA collisions; e-h option
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







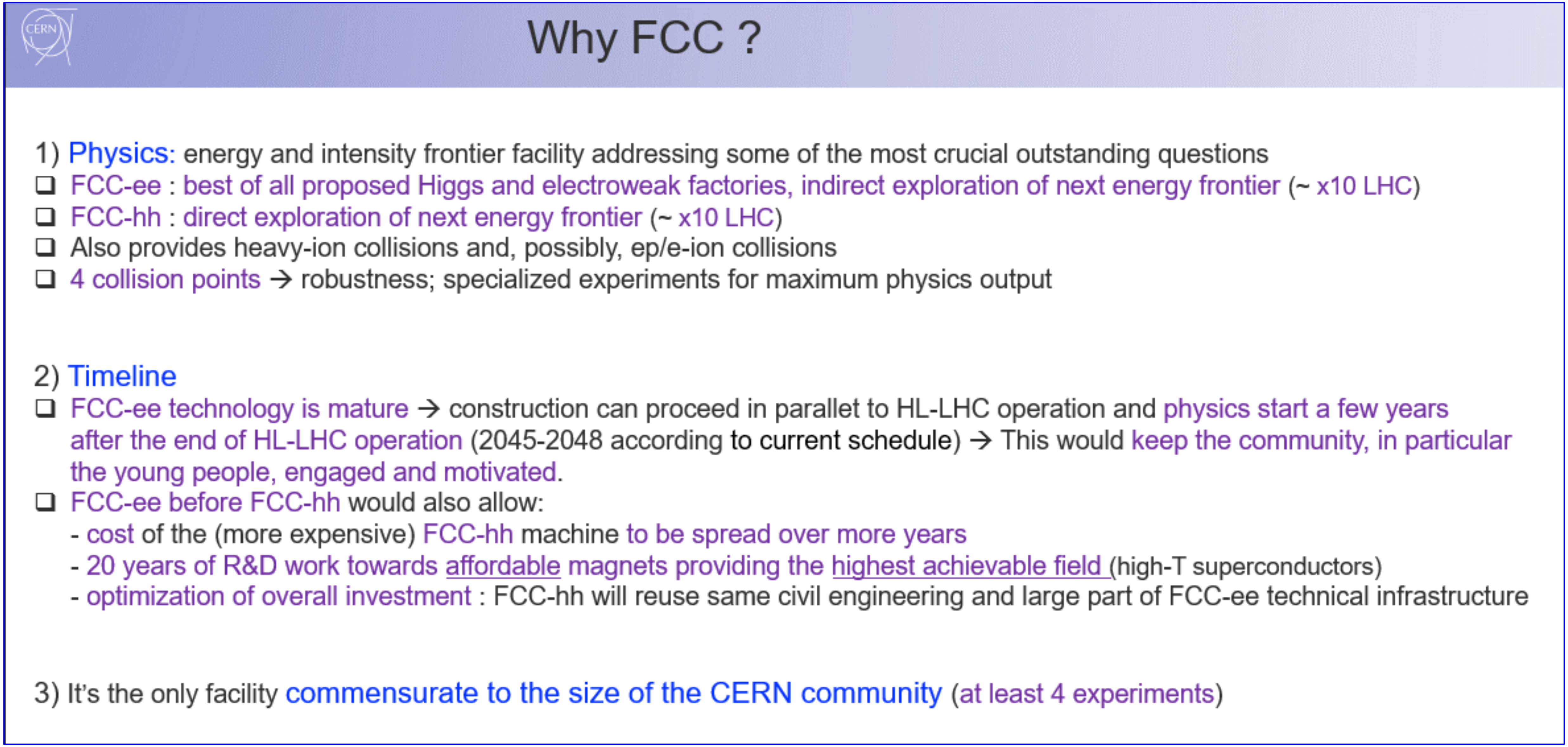
2020 - 2040

2045 - 2063

2070 - 2095

Fabiola Gianotti

FCC WEEK 2023 London



Why FCC ?

1) Physics: energy and intensity frontier facility addressing some of the most crucial outstanding questions

- ☐ FCC-ee : best of all proposed Higgs and electroweak factories, indirect exploration of next energy frontier (~ x10 LHC)
- ☐ FCC-hh : direct exploration of next energy frontier (~ x10 LHC)
- ☐ Also provides heavy-ion collisions and, possibly, ep/e-ion collisions
- ☐ 4 collision points → robustness; specialized experiments for maximum physics output

2) Timeline

- ☐ FCC-ee technology is mature → construction can proceed in parallel to HL-LHC operation and physics start a few years after the end of HL-LHC operation (2045-2048 according to current schedule) → This would keep the community, in particular the young people, engaged and motivated.
- ☐ FCC-ee before FCC-hh would also allow:
  - cost of the (more expensive) FCC-hh machine to be spread over more years
  - 20 years of R&D work towards affordable magnets providing the highest achievable field (high-T superconductors)
  - optimization of overall investment : FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) It's the only facility commensurate to the size of the CERN community (at least 4 experiments)

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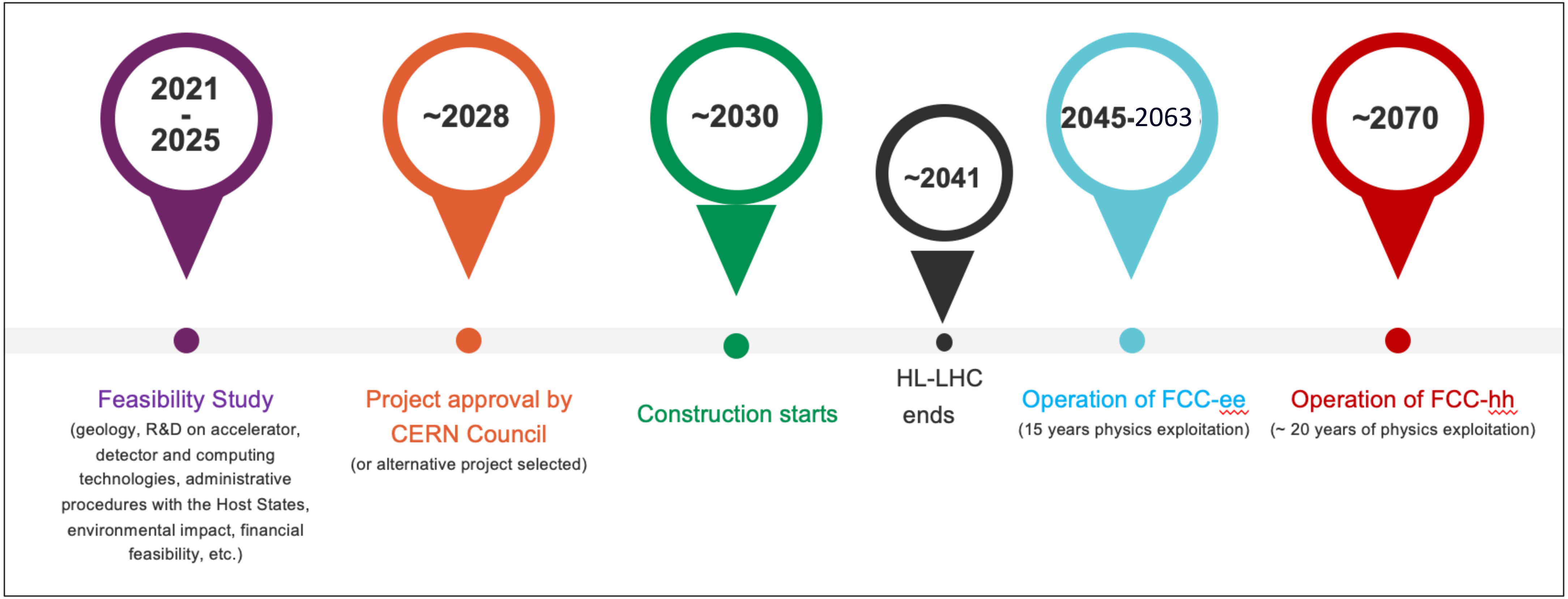
FCC WEEK 2023 London

FCC integrated program - timeline



2021 - 2025

Feasibility Study

(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

~2028

Project approval by CERN Council

(or alternative project selected)

~2030

Construction starts

~2041

HL-LHC ends

2045-2063

Operation of FCC-ee

(15 years physics exploitation)

~2070

Operation of FCC-hh

(~ 20 years of physics exploitation)

Realistic schedule takes into account:

- ❑ CERN Council approval timeline
- ❑ past experience in building colliders at CERN
- ❑ that HL-LHC will run until ~ 2041

→ ANY future collider at CERN cannot start physics operation before 2045-2048
(but construction will proceed in parallel to HL-LHC operation)

Fabiola Gianotti

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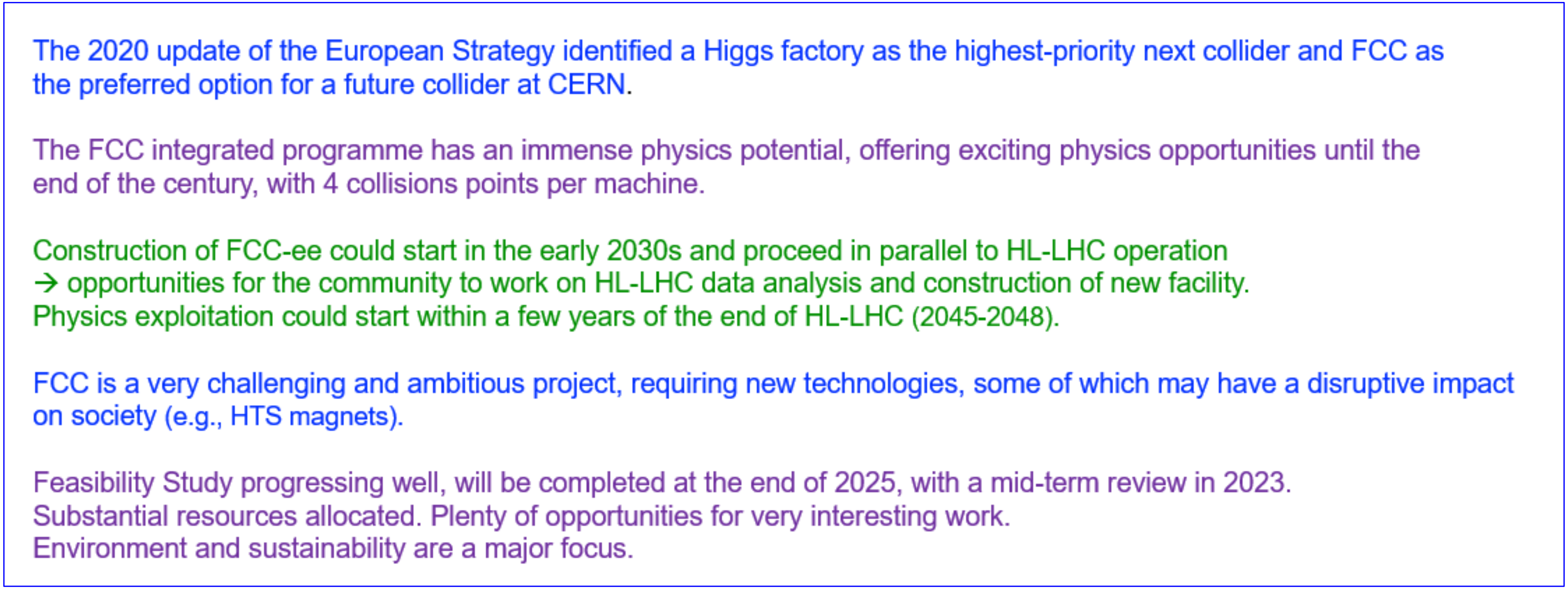
Fabiola’s conclusions



The 2020 update of the European Strategy identified a Higgs factory as the highest-priority next collider and FCC as the preferred option for a future collider at CERN.

The FCC integrated programme has an immense physics potential, offering exciting physics opportunities until the end of the century, with 4 collisions points per machine.

Construction of FCC-ee could start in the early 2030s and proceed in parallel to HL-LHC operation
→ opportunities for the community to work on HL-LHC data analysis and construction of new facility.
Physics exploitation could start within a few years of the end of HL-LHC (2045-2048).

FCC is a very challenging and ambitious project, requiring new technologies, some of which may have a disruptive impact on society (e.g., HTS magnets).

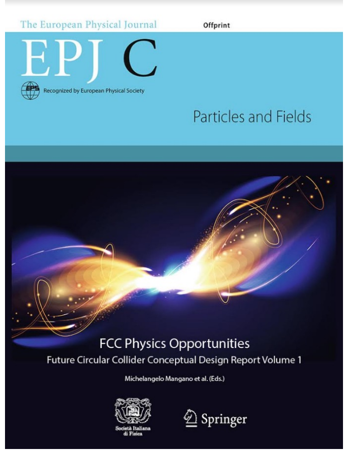
Feasibility Study progressing well, will be completed at the end of 2025, with a mid-term review in 2023.
Substantial resources allocated. Plenty of opportunities for very interesting work.
Environment and sustainability are a major focus.

European Strategy for Particle Physics

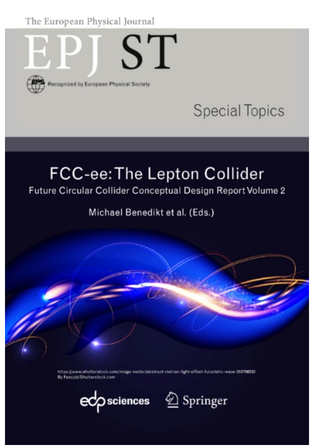
2013 Update of European Strategy for Particle Physics:

“CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.”

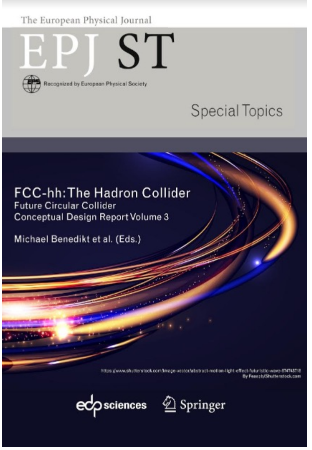
→ FCC Conceptual Design Reports (2018/19)



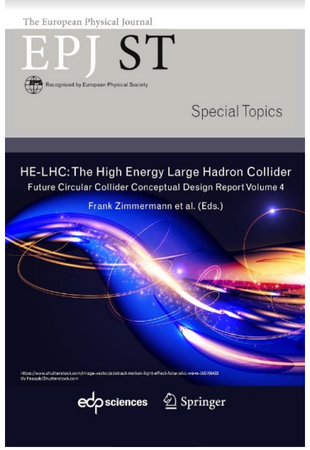
The European Physical Journal
Offprint
EPJ C
Recognized by European Physical Society
Particles and Fields
FCC Physics Opportunities
Future Circular Collider Conceptual Design Report Volume 1
Michelangelo Mangano et al. (Eds.)
Società Italiana di Fisica
Springer



The European Physical Journal
EPJ ST
Recognized by European Physical Society
Special Topics
FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
Michael Benedikt et al. (Eds.)
edp sciences
Springer



The European Physical Journal
EPJ ST
Recognized by European Physical Society
Special Topics
FCC-hh: The Hadron Collider
Future Circular Collider
Conceptual Design Report Volume 3
Michael Benedikt et al. (Eds.)
edp sciences
Springer



The European Physical Journal
EPJ ST
Recognized by European Physical Society
Special Topics
HE-LHC: The High Energy Large Hadron Collider
Future Circular Collider Conceptual Design Report Volume 4
Frank Zimmermann et al. (Eds.)
edp sciences
Springer

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

2020 Update of European Strategy for Particle Physics:

“Europe, together with its international partners, should investigate 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.”

FCC Feasibility Study (2021-2025): high-level objectives

- ❑ demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- ❑ pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- ❑ optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- ❑ elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- ❑ development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- ❑ identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- ❑ consolidation of the physics case and detector concepts for both colliders.

F. Gianotti

Results will be summarised in a Feasibility Study Report to be released at end 2025

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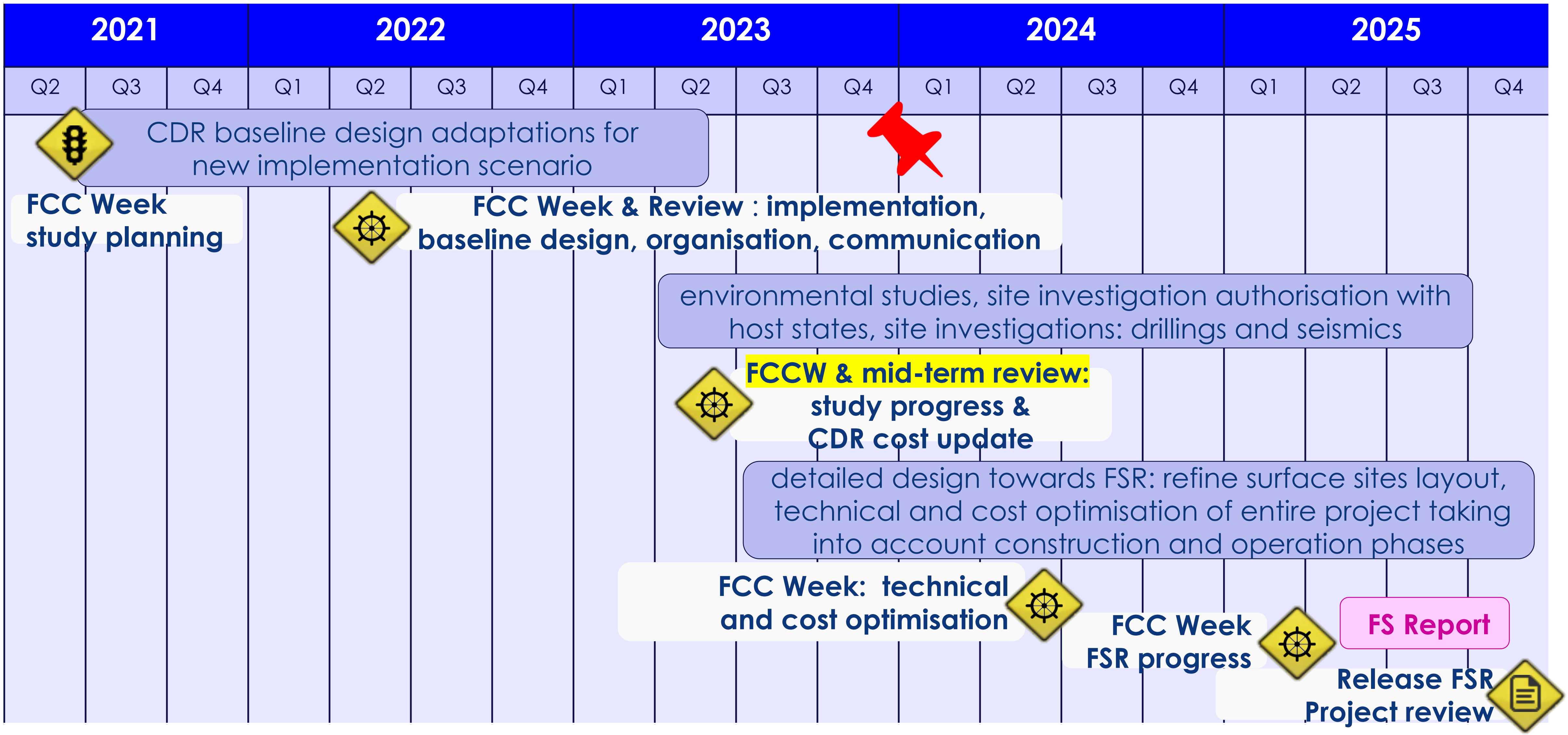
Feasibility Study funded from CERN budget: 100 MCHF total over 5 years; in addition: ~20 MCHF/year for high-field magnet R&D
Additional funding from the European Commission and collaborating insitutes (e.g. CHART collaboration with Switzerland)

Feasibility Study timeline and main activities/milestones



CDR baseline design adaptations for new implementation scenario

FCC Week study planning

FCC Week & Review : implementation, baseline design, organisation, communication

environmental studies, site investigation authorisation with host states, site investigations: drillings and seismics

FCCW & mid-term review: study progress & CDR cost update

detailed design towards FSR: refine surface sites layout, technical and cost optimisation of entire project taking into account construction and operation phases

FCC Week: technical and cost optimisation

FCC Week FSR progress

FS Report

Release FSR Project review

Mike Lamont

ATS New Year 2024, 11/1/24

2023 Process – FCC mid-term review

Intense preparation

- FCC Feasibility Study mid-term review report (~800 pages) plus a lot of presentations

FCC Mid-Term Review

- 16 Oct 2023 → 18 Oct 2023
- Scientific Advisory Committee (SAC) and Cost Review Panel (CRP) did their stuff

Joint SPC and FC Normal Sessions

- 20 Nov 2023 → 22 Nov 2023
- Summaries and recommendations presented

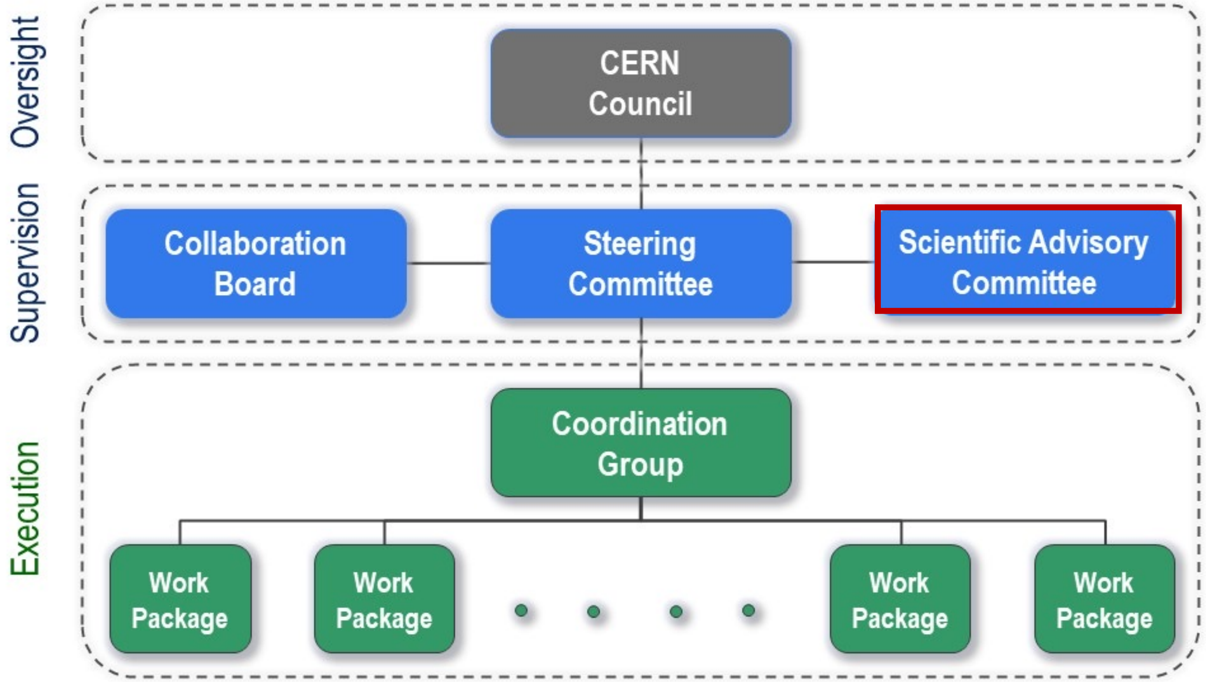
SPC and FC reported into December's Restricted Council

Final deliberations at Restricted Council - Friday 2 Feb 2024

Mid-Term review well received by SAC and CRP
Encouraging high level support, understandable reservations

Scientific Advisory Committee (SAC)

SAC follows and reviews the implementation of the Feasibility Study, giving scientific and technical advice to FCC Steering Committee and Coordination Group, and providing them with guidance to facilitate major technical decisions.



Composition: up to 16 international experts not directly involved in the Feasibility Study with renowned expertise in one or more scientific and technical domains relevant to the Study (accelerators, technical infrastructure, key technologies, physics, detectors, etc.). Members and Chair are appointed by the Steering Committee.

Riccardo Bartolini (DESY), Alain Chabert (Société Française du Tunnel Routier du Fréjus), Brigitte Fargevieille (Électricité de France), Belen Gavela Legazpi (UAM), Katri Huitu (Helsinki), Srinivas Krishnagopal (BARC), Peter Krizan (Ljubljana), Philippe Lebrun (CERN, retired), Peter McIntosh (STFC), Michiko Minty (BNL), **Andrew Parker** (**Chair**, Cambridge), Kyo Shibata (KEK), **Roberto Tenchini (Pisa)**

Cost Review Panel (CRP)

Ad-hoc committee established to review the updated cost assessment of the FCC project, which is one of the mid-term review deliverables.

CRP's mandate:

- Review the methodology and assumptions used in producing the cost estimates
- Identify inaccurate or missing cost information
- Check the consistency of the cost estimates with respect to applicable reference work, e.g., recent large-scale infrastructure and accelerator projects
- Review the uncertainty estimates
- Identify potential areas of savings and cost mitigation for future work
- Advise the FCC Feasibility Study team on matters of cost estimation with a view to the preparation of the final Feasibility Study Report by end 2025.

Composition: around 10 international experts, not directly involved in the Feasibility Study, with renowned expertise in costing and project management aspects related to the scientific and technical domains relevant to the Study (accelerators, technical infrastructure, civil engineering, detectors, etc.). Members and Chair are appointed by the Steering Committee.

Carlos Alejaldre (Fusion for Energy), Austin Ball (CERN, retired), Umberto Dosselli (INFN), Vincent Gorgues (CEA), **Norbert Holtkamp** (**Chair**, Stanford), Christa Laurila (National Audit Office, Finland), Ursula Weyrich (German Cancer Research Centre), Jim Yeck (BNL), Thomas Zurbuchen (ETH Zürich)

Summary of P5 Report for USFCC

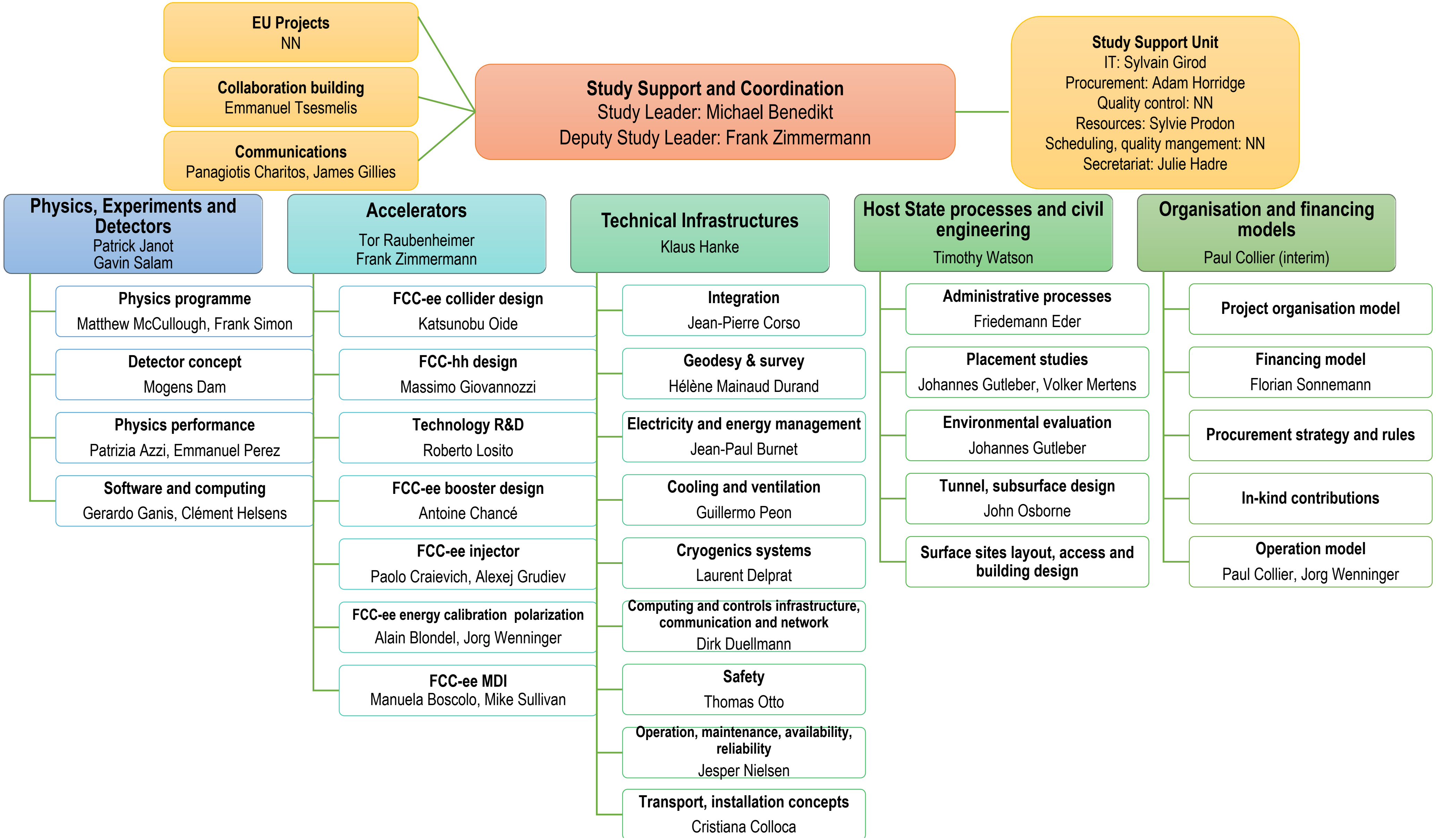
December 2023

Funding for an offshore Higgs factory such as FCC-ee is recommended is all studied budget scenarios.
It is recommended to allocate investment in detector R&D to accelerate US leadership in this area.

Now more than ever, particle physics is an international, global endeavor.
Resources and cooperation are required at a global scale and experiments take more than a decade to design and build.

Strong participation from the US on the milestones set by P5, both helping CERN prepare the feasibility study, and showing the depth of support in the US for this project, is essential.

FCC Feasibility Study – coordination team and contact persons



- **Study Support and Coordination**
  - Study Leader: Michael Benedikt
  - Deputy Study Leader: Frank Zimmermann
- **EU Projects**
  - NN
- **Collaboration building**
  - Emmanuel Tsesmelis
- **Communications**
  - Panagiotis Charitos, James Gillies
- **Study Support Unit**
  - IT: Sylvain Girod
  - Procurement: Adam Horridge
  - Quality control: NN
  - Resources: Sylvie Prodon
  - Scheduling, quality mangement: NN
  - Secretariat: Julie Hadre

- **Physics, Experiments and Detectors**: Patrick Janot, Gavin Salam
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  - **Detector concept**: Mogens Dam
  - **Physics performance**: Patrizia Azzi, Emmanuel Perez
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  - **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
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  - **Cryogenics systems**: Laurent Delprat
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  - **Operation, maintenance, availability, reliability**: Jesper Nielsen
  - **Transport, installation concepts**: Cristiana Colloca
- **Host State processes and civil engineering**: Timothy Watson
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  - **Placement studies**: Johannes Gutleber, Volker Mertens
  - **Environmental evaluation**: Johannes Gutleber
  - **Tunnel, subsurface design**: John Osborne
  - **Surface sites layout, access and building design**
- **Organisation and financing models**: Paul Collier (interim)
  - **Project organisation model**
  - **Financing model**: Florian Sonnemann
  - **Procurement strategy and rules**
  - **In-kind contributions**
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FCC

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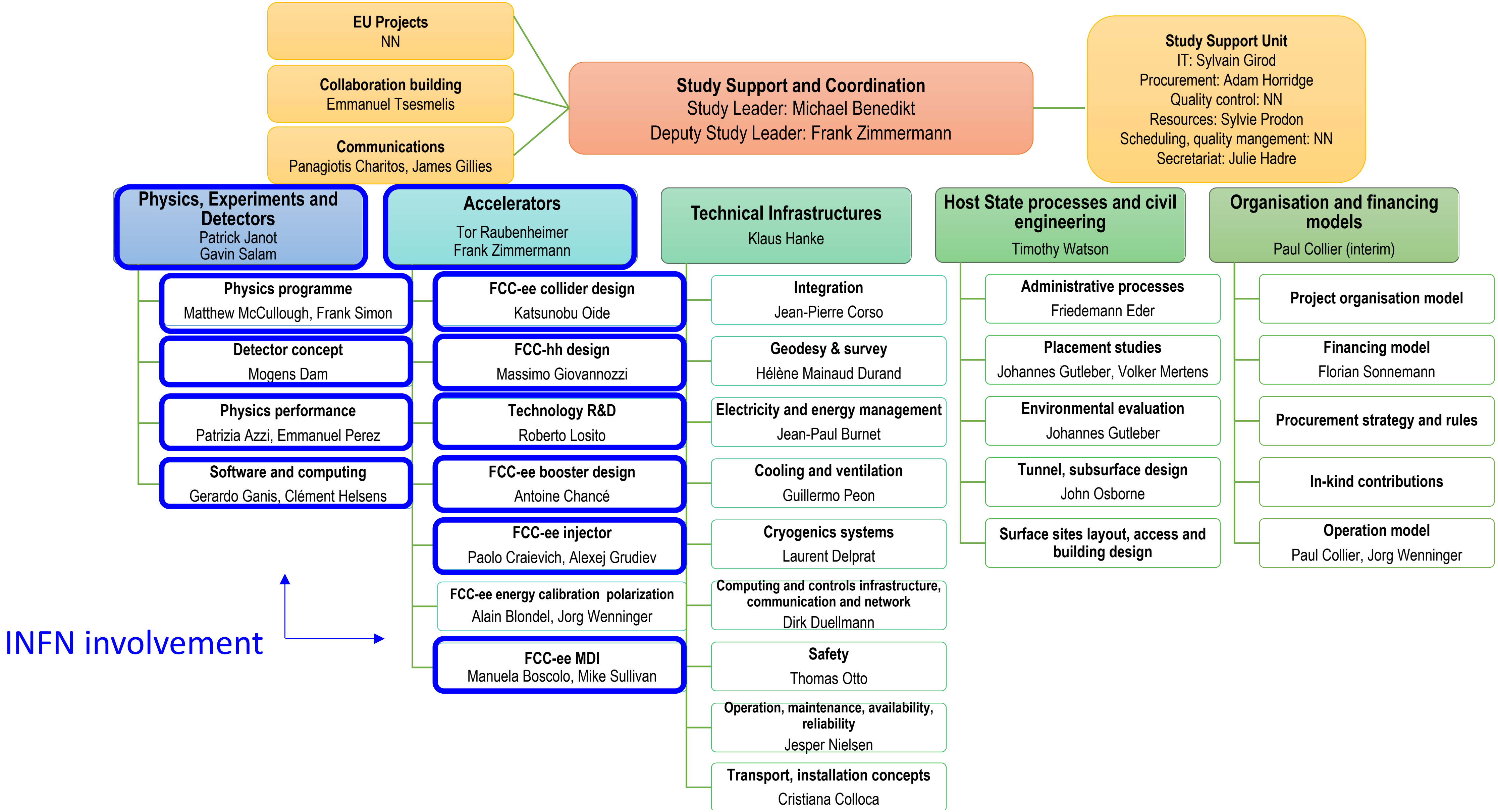

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INFN involvement

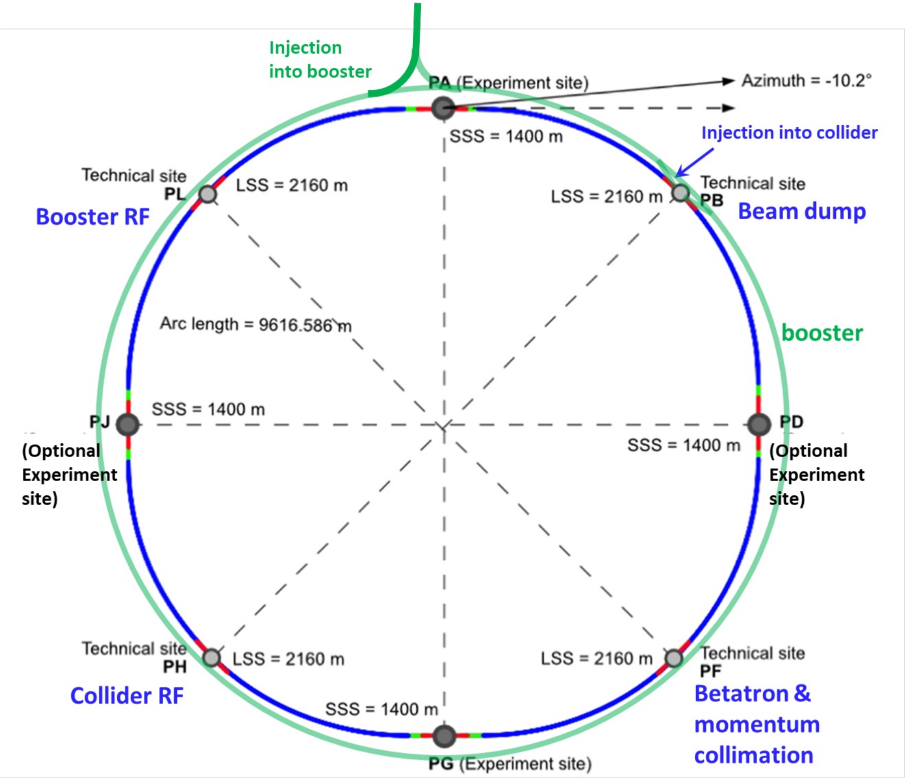
Accelerator Design

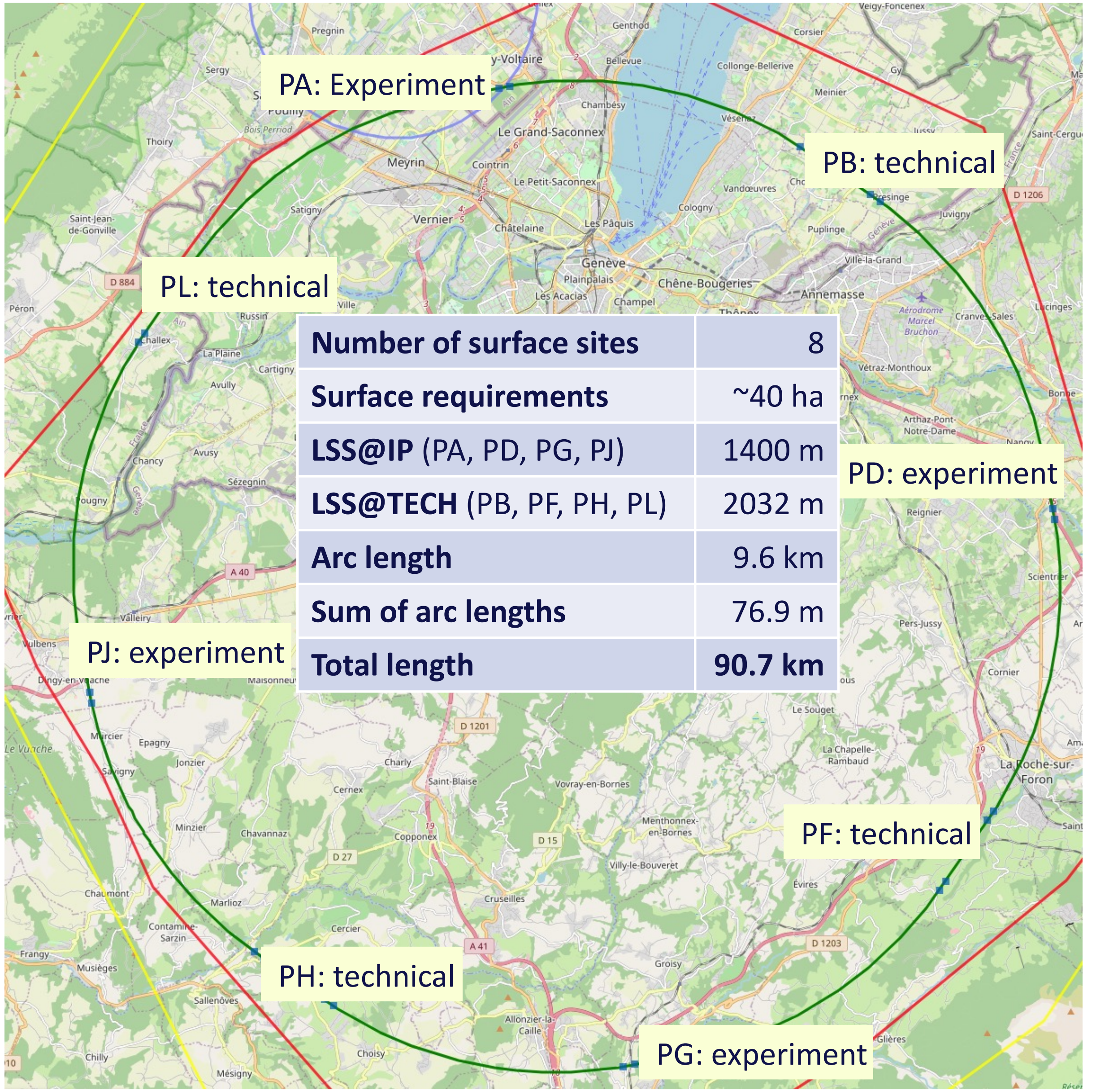
Optimized placement and layout for feasibility study

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





Number of surface sites	8
Surface requirements	~40 ha
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**

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

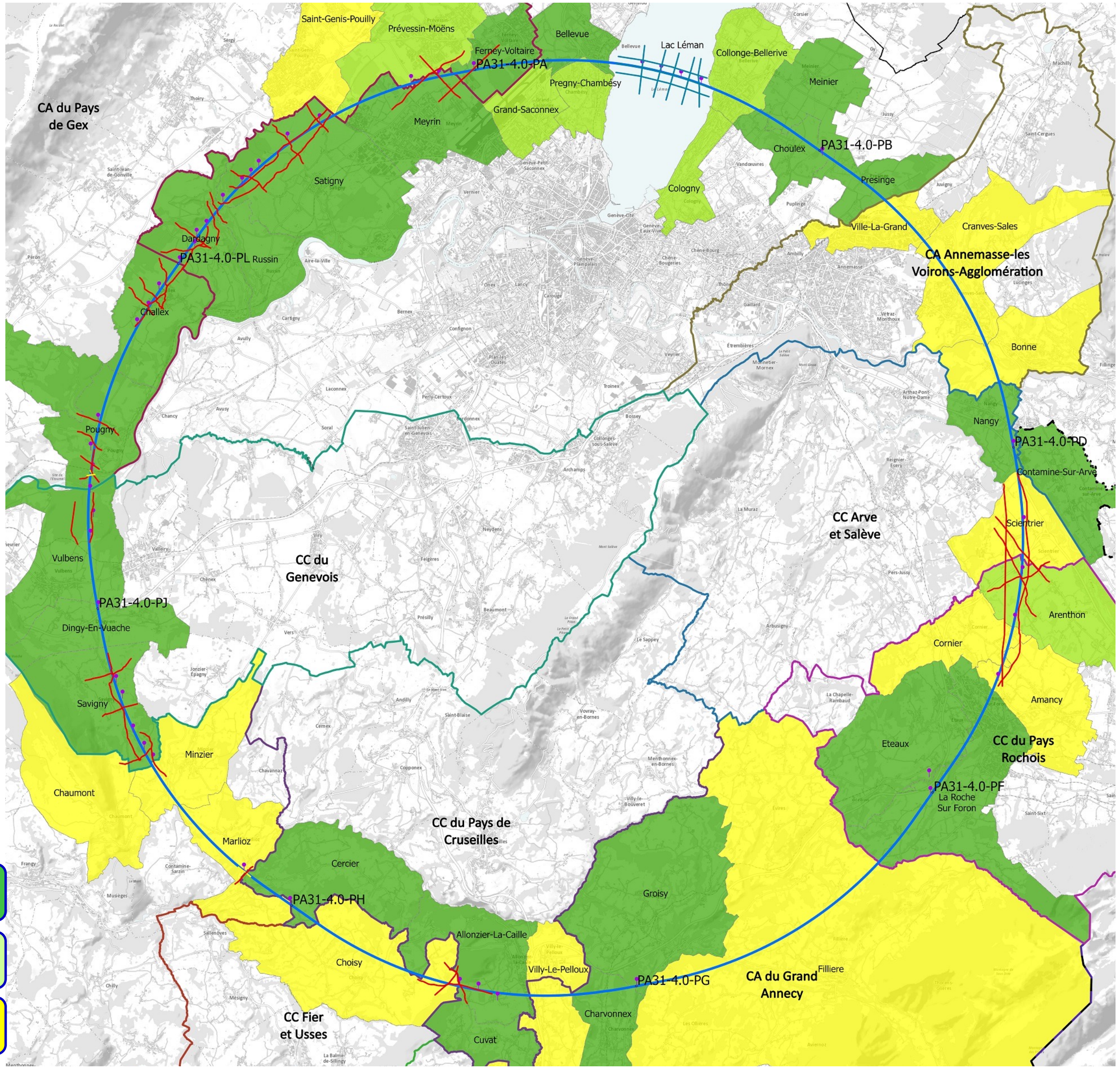
PJ – Vulbens/Dingy en Vuache (FR) site experimental

PL – Challex (FR) – site technique

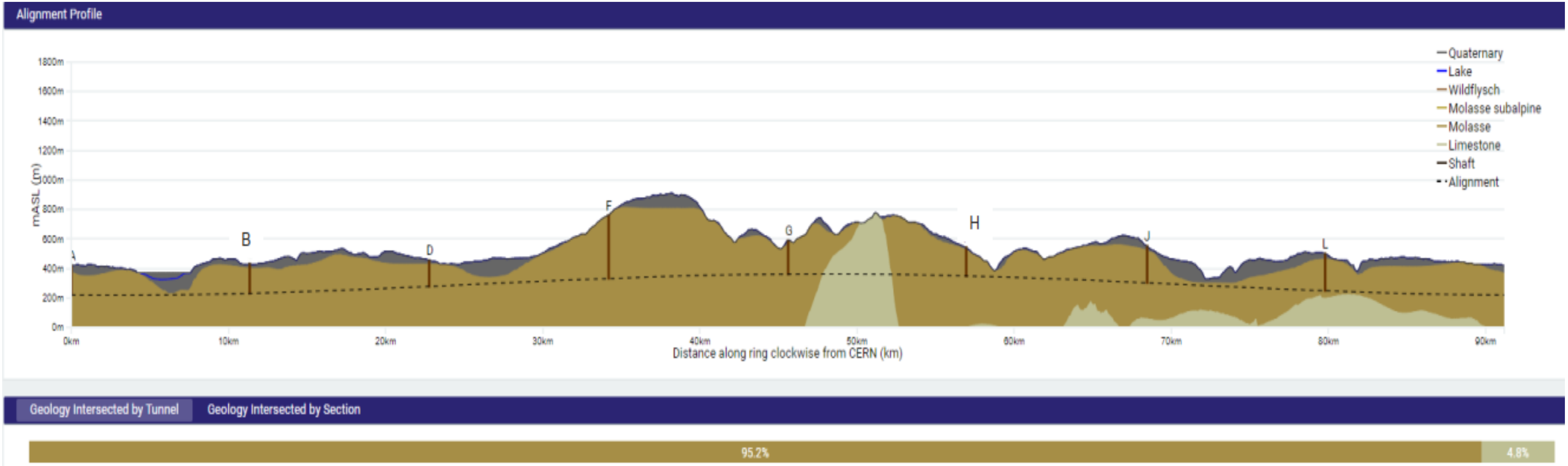
🟩 Individual meeting

🟩 Individual meeting planned

🟨 Collective meeting



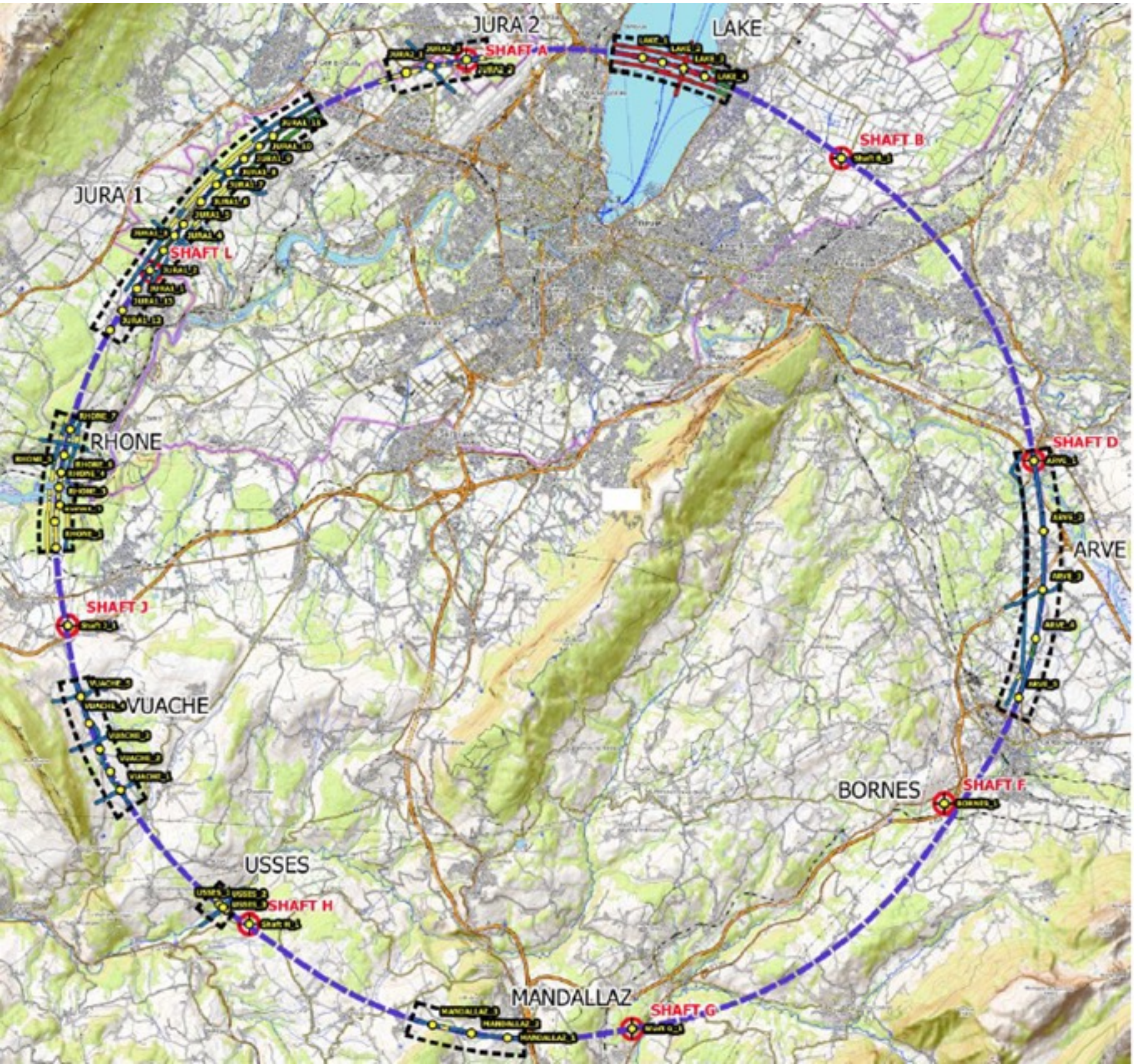
FCC tunnel implementation



Tunnel implementation summary

- 91 km circumference
- 95% in molasse geology for minimising tunnel construction risks
- 8 surface sites with ~5 ha area each.

Status of site investigations



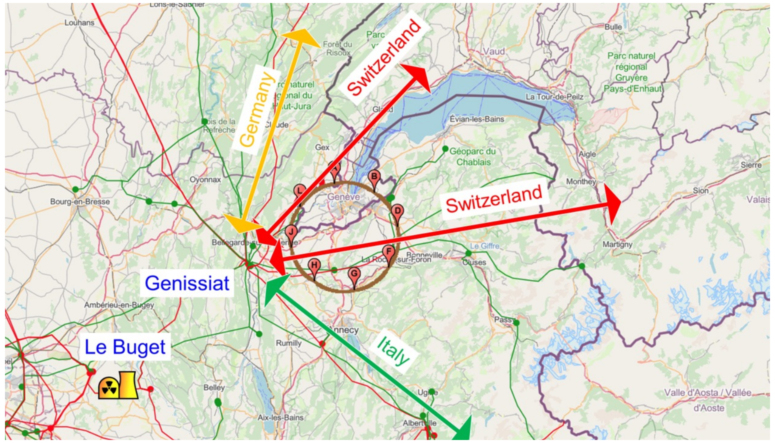
Site investigations in areas with less well known geological conditions:

- Optimisation of localisation of drilling locations ongoing with site visits since end 2022.
- Alignment with FR and CH on the process for obtaining autorisation procedures. Start of drillings planned for 03/2024.


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

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**

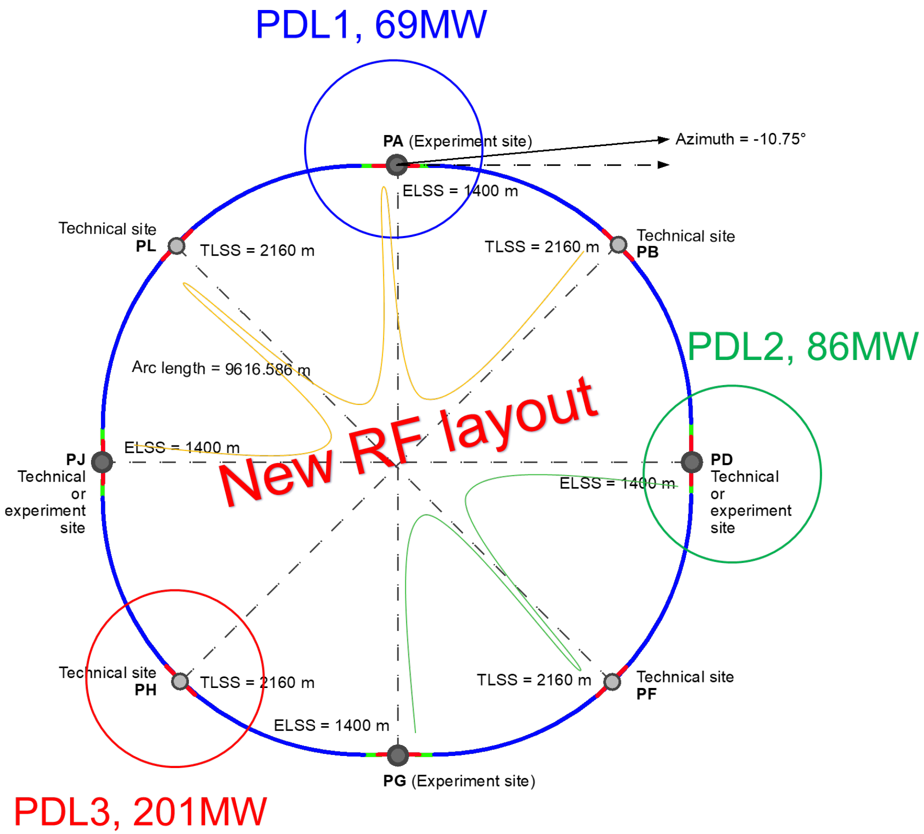


Powering concept and max power load by sub-stations:

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

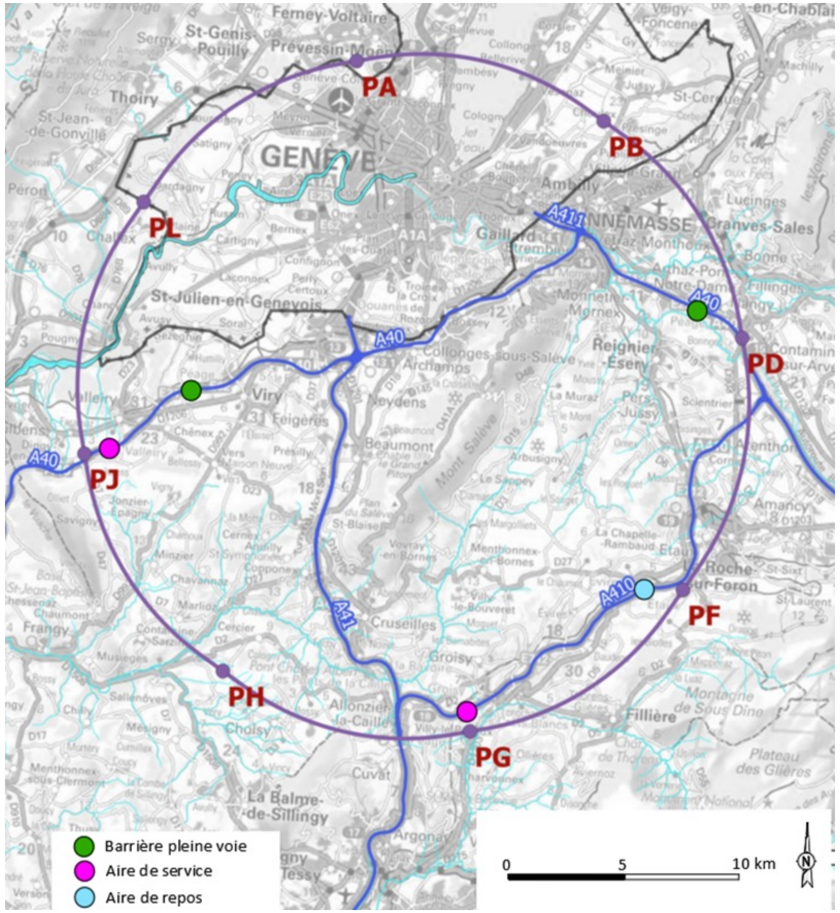
- Point D with a new sub-station covering PB – PD – PF – PG
- Point H with a new dedicated sub-station for collider RF
- Point A with existing CERN station covering PB – PL – PJ

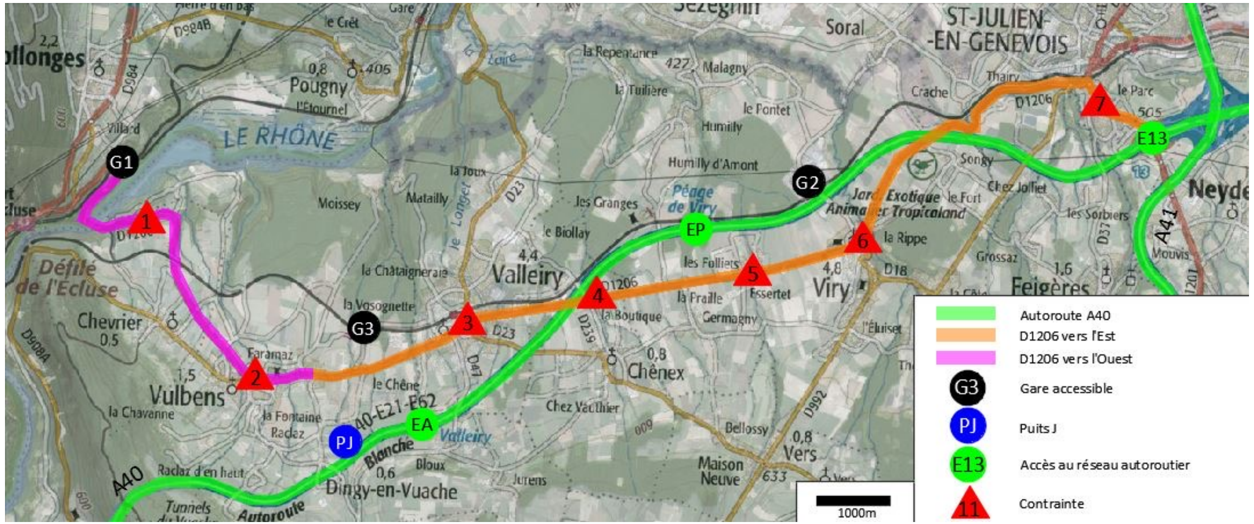
- Connection concept was studied and confirmed by RTE (French electrical grid operator)
- Requested loads have no significant impact on grid
- Powering concept and power rating of the three sub-stations compatible with FCC-hh

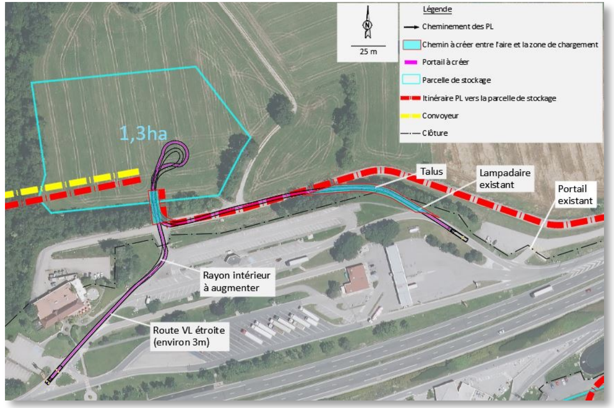


Connections to transport infrastructure

- 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)







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

Stage 1: FCC-ee – highest-luminosity lepton collider

double ring e^+e^- collider, with full-energy booster

2 or 4 interaction points

efficient $\mathcal{L}$ from Z to $t\bar{t}$

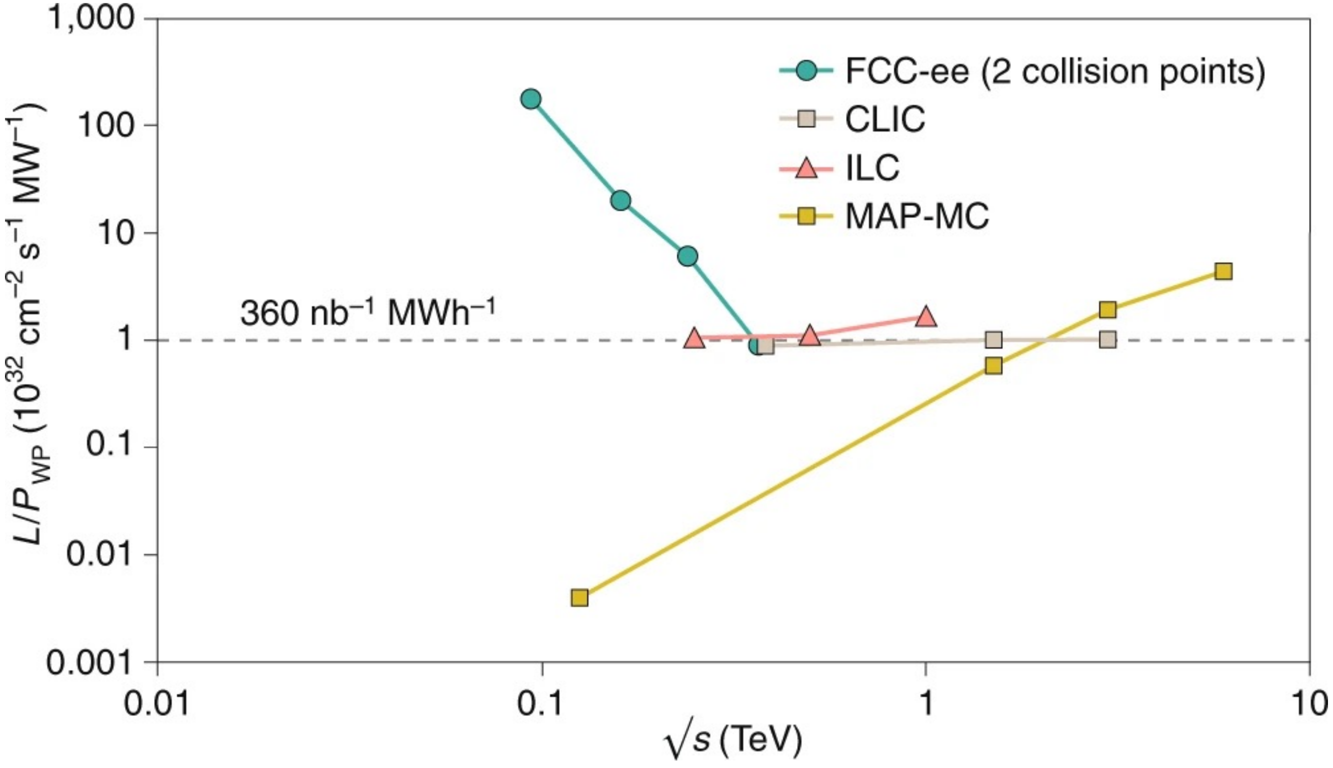
thanks to twin-aperture magnets, high-Q SRF, efficient RF power sources, top-up injection, etc.

>2.5 ab^{-1} / IP with ~0.5x10^{6} H / IP (3y)

>75 ab^{-1} / IP with ~2x10^{12} Z / IP (4y)

collects LEP data statistics in few minutes

luminosity vs. electricity consumption



highest lumi/power of all H fact. proposals

Nature Physics 16, 402–407 (2020)

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
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_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

technical feasibility of changing operation sequences was assessed (e.g. starting at ZH energy)

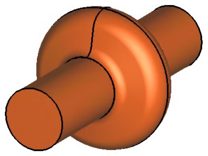
- ❑ x 10-50 improvements on all EW observables
- ❑ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ❑ x10 Belle II statistics for b, c, τ
- ❑ indirect discovery potential up to ~ 70 TeV
- ❑ direct discovery potential for feebly-interacting particles over 5-100 GeV mass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

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

FCC-ee SRF system

Z

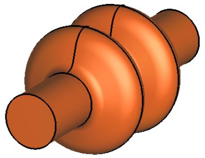
1-cell
400 MHz,
Nb/Cu



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

W, H

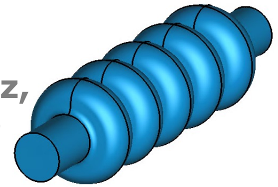
2-cell
400 MHz,
Nb/Cu



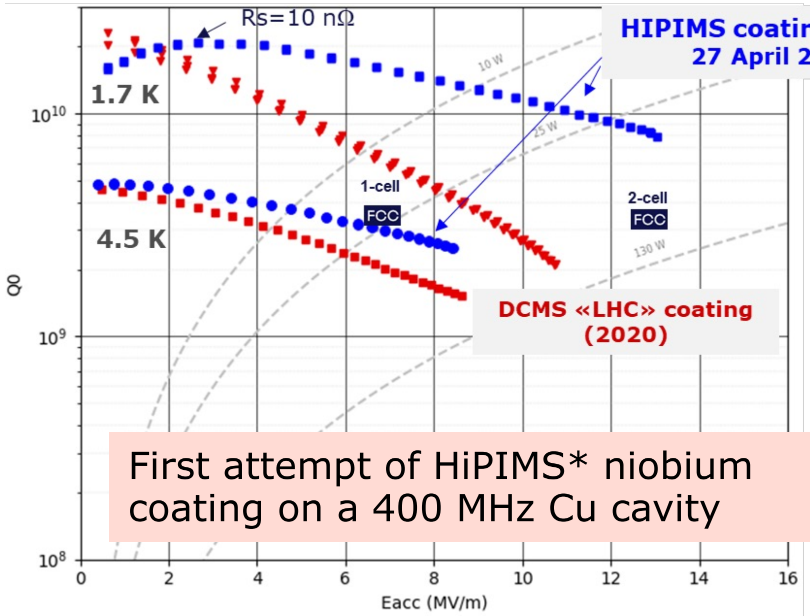
moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

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

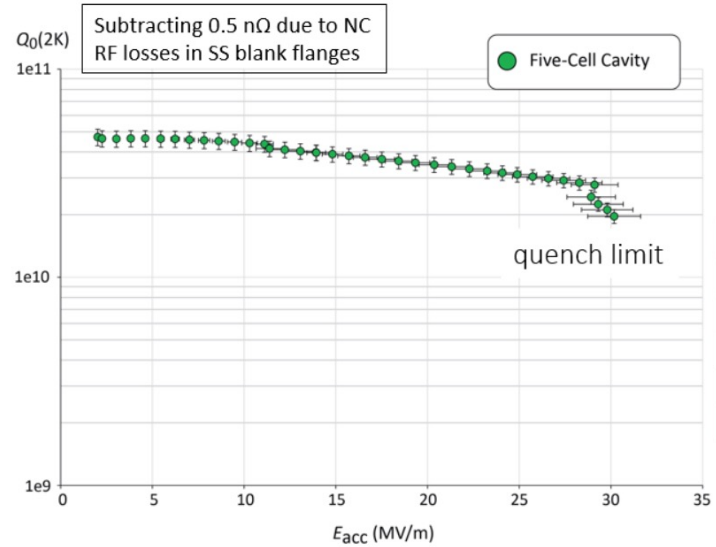


First attempt of HiPIMS* niobium coating on a 400 MHz Cu cavity

*High-power impulse magnetron sputtering

Promising R&D towards ultra-high Q_0. Collaboration with FNAL

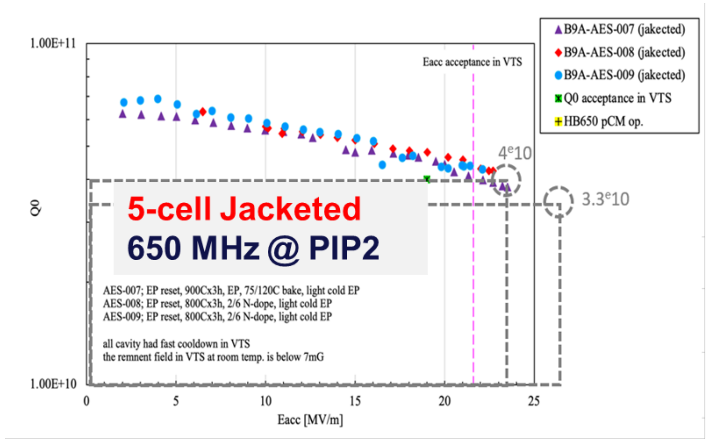
5-cell cavity development (2018), successful collaboration with JLAB



FCC Week 2018, 9-13 April 2018, Beurs van Berlage, Amsterdam, Netherlands

Main post-processing steps

	Unit	*CRN5*
Bulk BCP	µm	216
High-T heat treatment	°C, hrs.	800, 3
Final EP	µm	30
HPR cycles		4
Low-T bake-out	°C, hrs.	120, 12

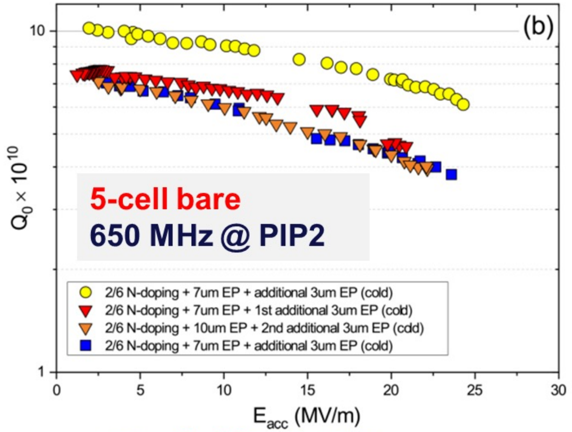


5-cell Jacketed
650 MHz @ PIP2

AES-007; EP reset, 900Cx3h, EP, 75/120C bake, light cold EP
AES-008; EP reset, 800Cx3h, 2/6 N-dope, light cold EP
AES-009; EP reset, 800Cx3h, 2/6 N-dope, light cold EP

all cavity had fast cooldown in VTS
the remnent field in VTS at room temp. is below 7mG

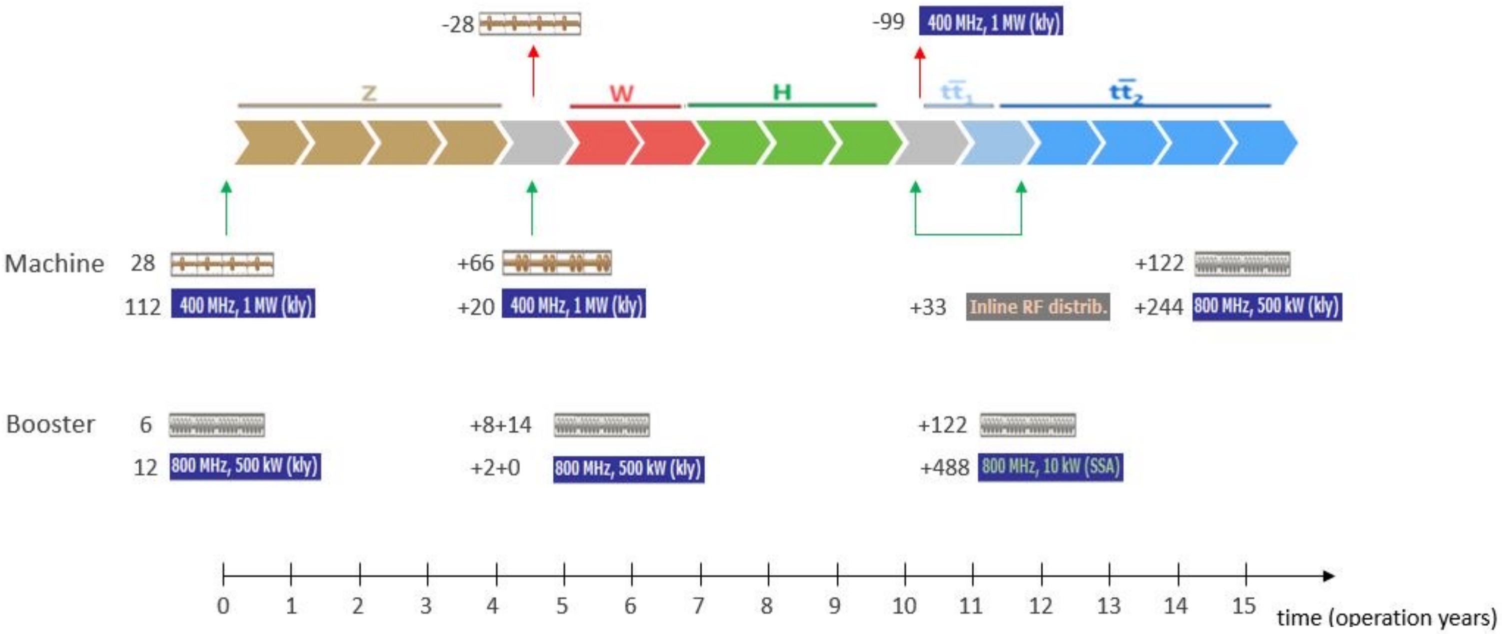
Q0 = 3.5e10 @ 25 MV/m with 2/6 N-doping or midT bake + EP

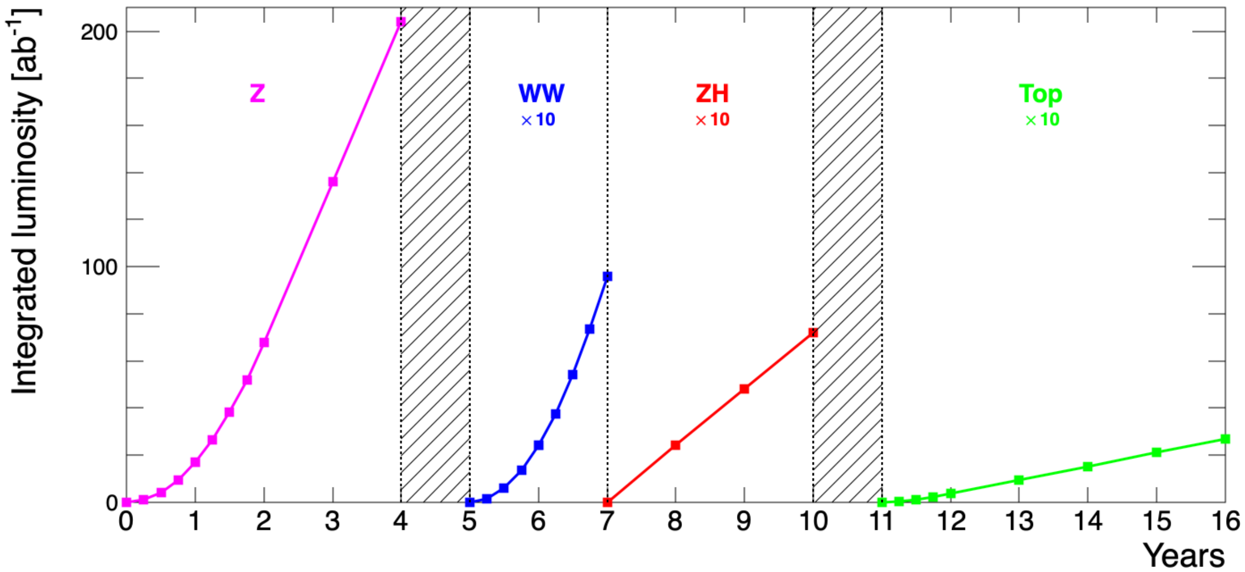


5-cell bare
650 MHz @ PIP2

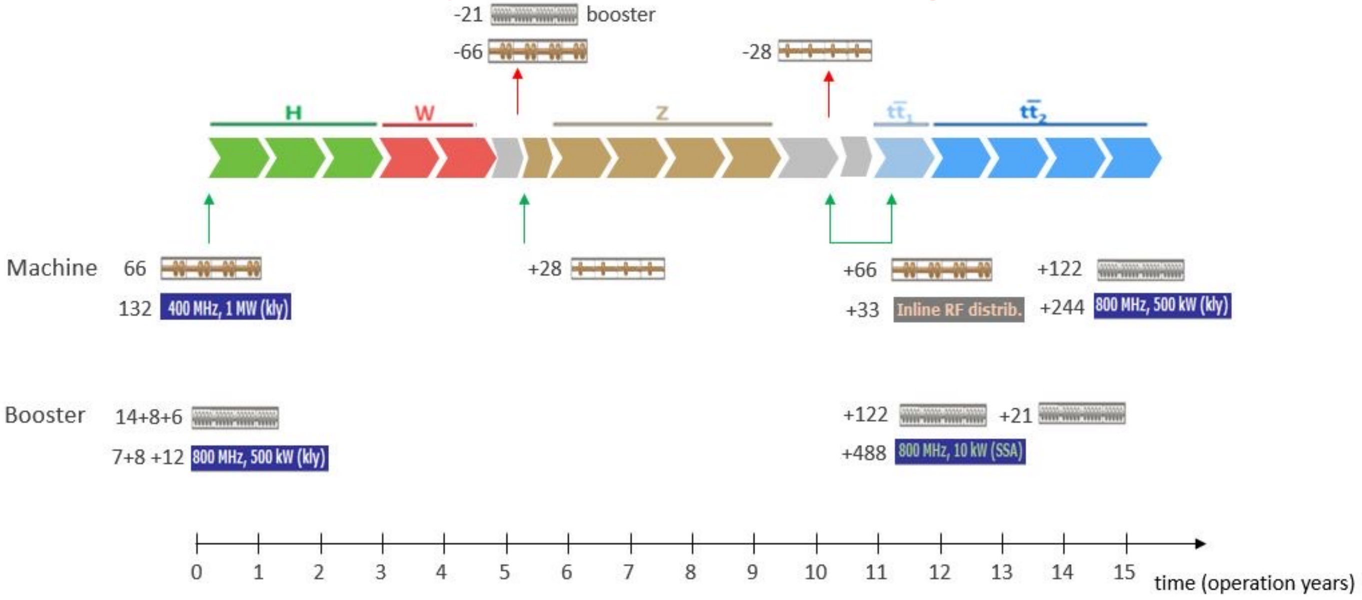
Q0 = 6e10 @ 25 MV/m with 2/6 N-doping + EP + cold EP

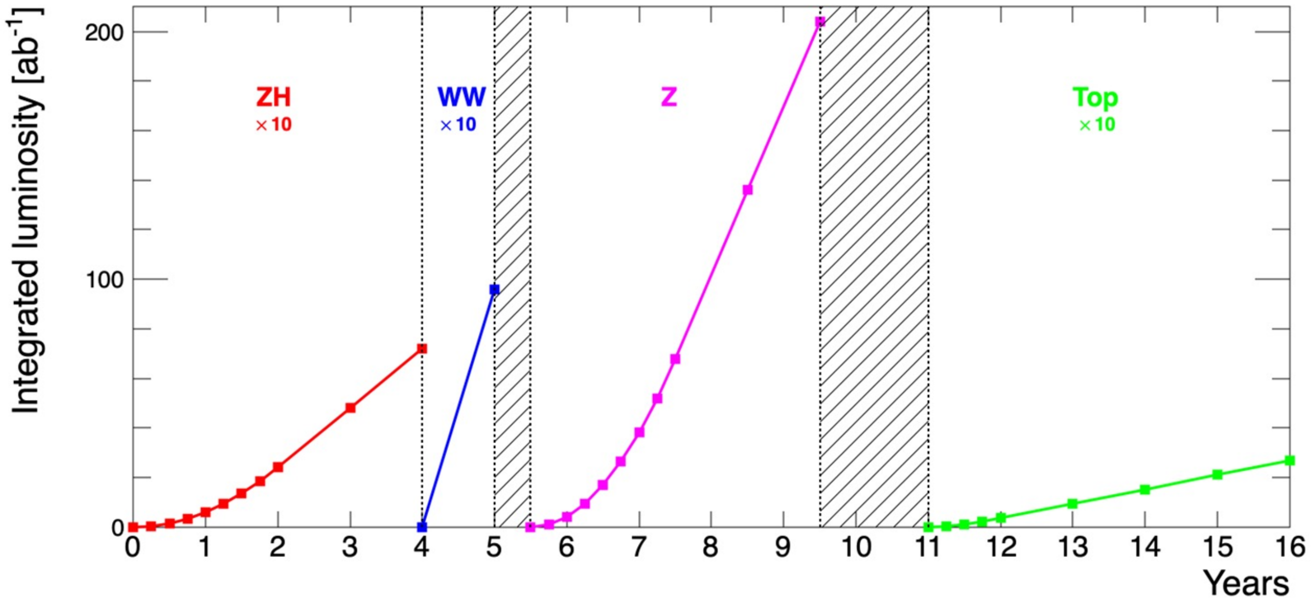
Baseline operational sequence starting from Z





Alternative operational sequence starting from ZH





“more demanding, more complex, riskier and less efficient”

Recently updated

FCC-ee RF parameter table

Number of 800 MHz cavities: 1088
Total number of cavities: 1456

20-Apr-23	Z		W		H		ttbar2		
	Collider per beam	booster	Collider per beam	booster	Collider 2 beams	booster	Collider 2 beams	Collider 2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.93	6.23	10.78	20.76	10.78	20.76	10.78	20.12	20.10
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.22	5.83	8.08	19.44	8.08	19.44	8.08	18.85	18.83
#cells	54	120	260	270	520	540	520	2440	3000
# cavities	54	24	130	54	260	108	260	488	600
# CM	13.5	6	32.5	13.5	65	27	65	122	150
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	23	0.3	158	4	158	4	158	23	3
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.9E+04	3.2E+05	1.1E+06	8.0E+06	1.1E+06	1.6E+07	5.4E+06	4.2E+06	8.3E+07
Detuning [kHz]	8.620	4.393	0.479	0.136	0.096	0.014	0.007	0.056	0.003
Pcav [kW]	912	205	379	91	379	46	79	163	8
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9936
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9876.13
cos phi	0.32	0.27	0.35	0.35	0.88	0.88	0.98	0.86	0.87
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

* heat loads from power coupler and HOM couplers not included

one RF system per beam

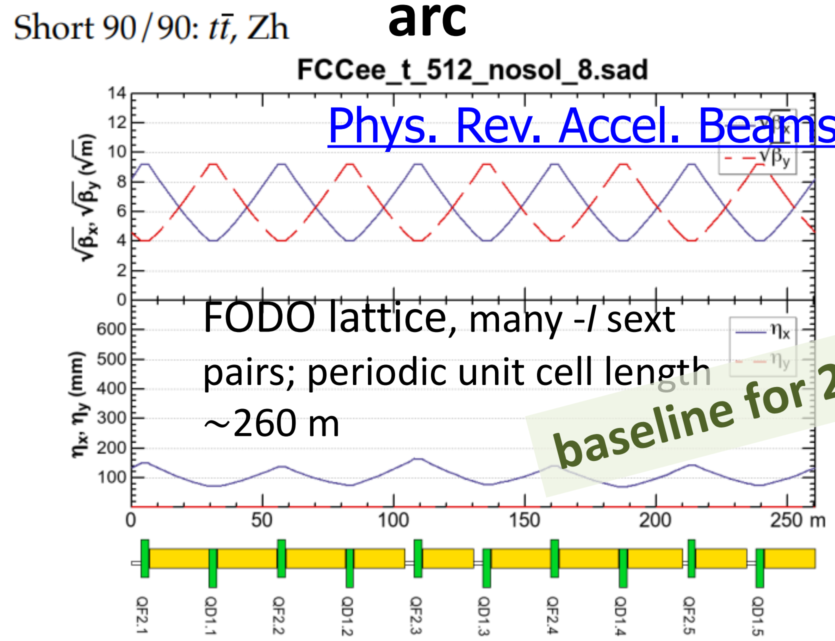
common RF system for both beams

Limiting parameters for RF

- Cavity performances: 20 % margin added on Eacc and Q0 between vertical test and operation
- In total: 364 cryomodules, 1456 cavities, 25% with Nb/Cu technology, 75% with bulk niobium technology

FCC-ee collider optics development: 2 options

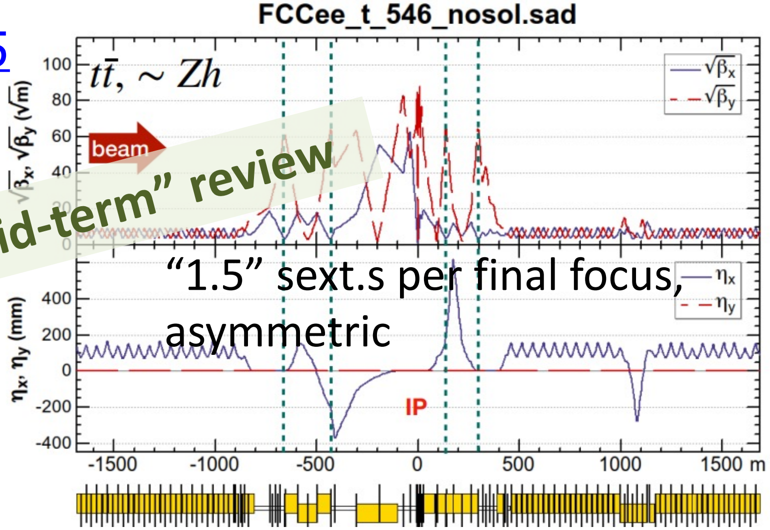
arc



Phys. Rev. Accel. Beams **19**, 111005

FODO lattice, many -*I* sext pairs; periodic unit cell length ~260 m

interaction region



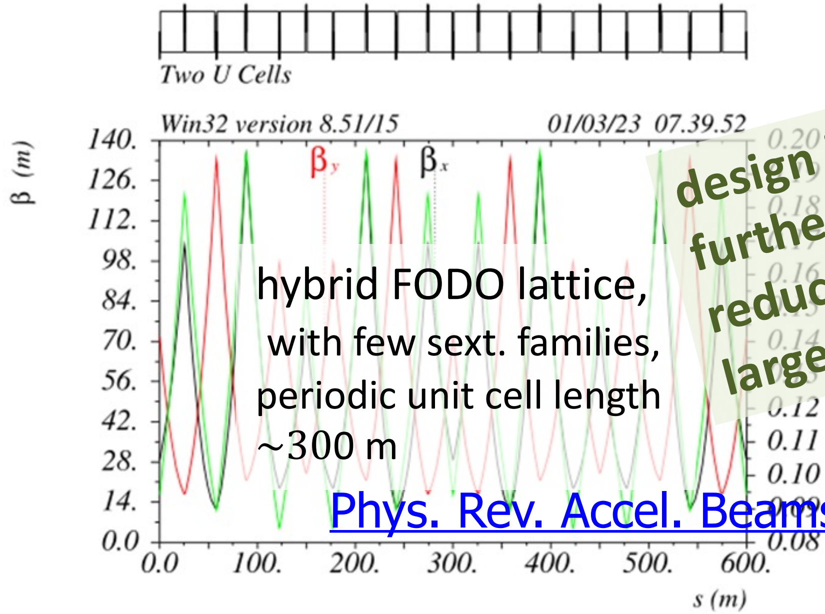
"1.5" sext.s per final focus, asymmetric

baseline for 2023 FCC "mid-term" review

The beam optics are asymmetric between upstream/downstream due to crossing angle & suppression of the SR upstream to the IP

K. Oide, 2023 EPS
Rolf Wideroe award winner

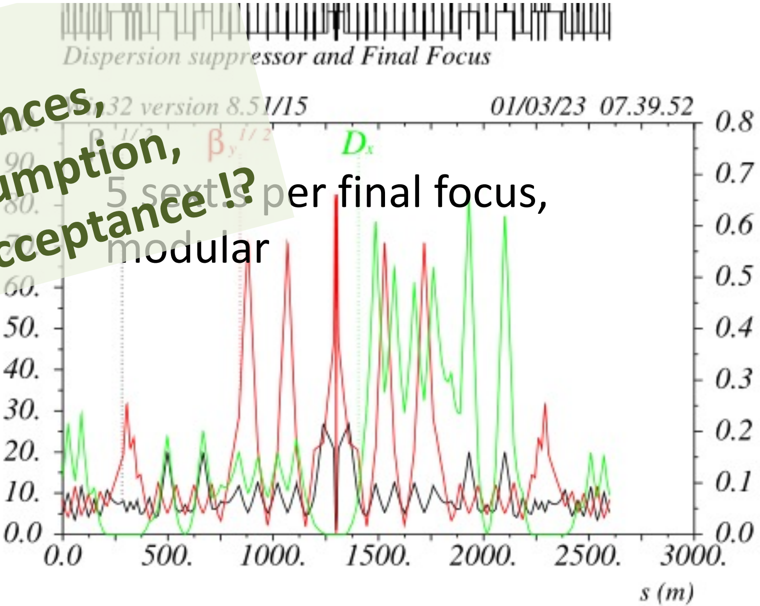
P. Raimondi, 2017 EPS
Gersh Budker award winner



hybrid FODO lattice, with few sext. families, periodic unit cell length ~300 m

Phys. Rev. Accel. Beams **26**, 021601

design in progress - further relaxed tolerances, reduced power consumption, larger momentum acceptance !?



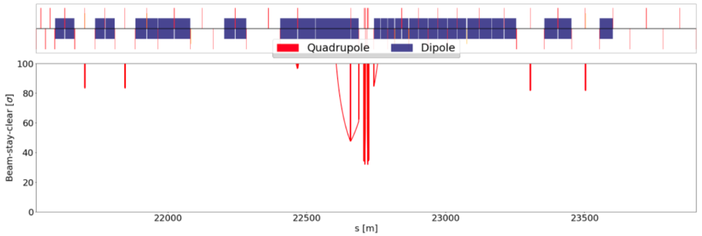
5 sext.s per final focus, modular

LCCO Final Focus - Impact to IR design

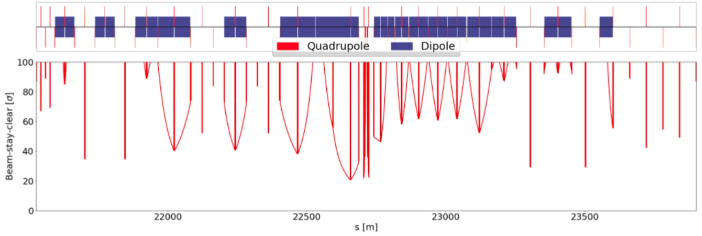
- The Final Focus is optimized to have the **largest possible beam stay clear (BSC) and minimum losses** in the final focus system and all the way through the IR
- The goal of the FF design is to have the **dynamic aperture larger than the physical aperture**

Beam Stay Clear

Z-pole



ttbar



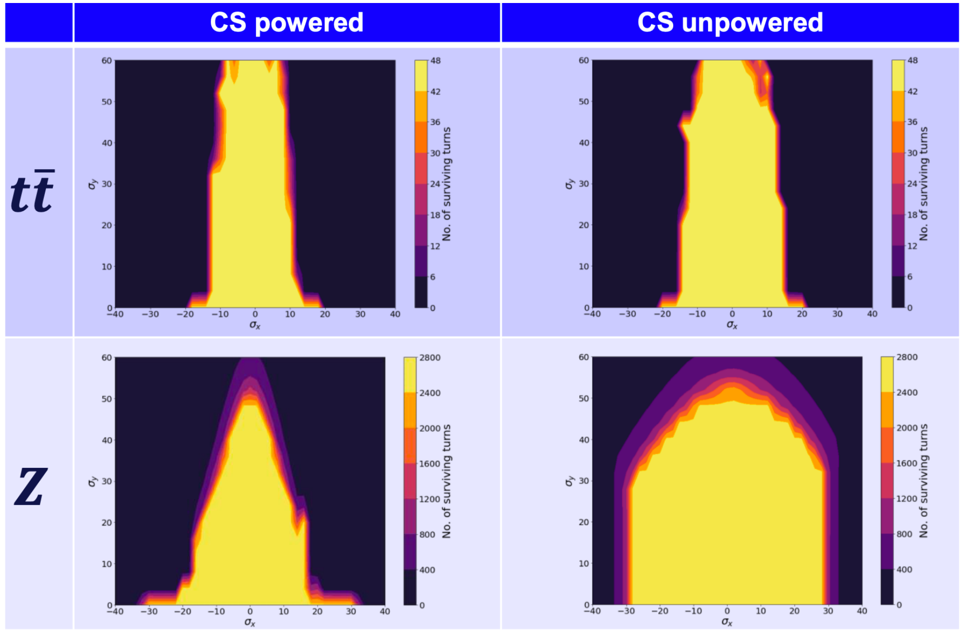
Preliminary aperture model same as baseline, r=35 mm everywhere, but: r=15 mm at QC1; r=20 mm at QC2

Bottlenecks:

- **baseline Z: 14.5 σ_x / tt$_{bar}$: 14.4 σ_x**
- **LCCO Z: 31 σ_x / tt$_{bar}$: 20 σ_x**

Dyn. Apert. with SR and Crab sextupoles (CS)

- DA tracking performed using Xsuite and Xdyna
- Crabsextupoles (CS) powered to 80% (Z)/ 40% (tt) of their geometric strength
- Tracking performed for ~ one damping time 2500 turns (Z)/ 45 turns (tt)
- CS have small impact on DA at Z,



Standard solenoid compensation

P. Raimondi, MDI meeting #50, 11/12/23
https://indico.cern.ch/event/1346902/

Coupling compensation

After a few iterations the best compromise between performances and feasibility, under finalization by A Ciarma seems to be:

- no compensating solenoid
- zero the Bs (solenoid) field with starting from 2mt from the IP until the end of the detector solenoid
- zero the Sum(Bs*l) with antisolenoids (2 per beam) outside the IR quads.
- corrects residual coupling with weak skew quads wrapped around the IR quads.
- correct orbit with weak correctors in several locations around the IR
- correct dispersion with standard tuning knobs

Correctors and skew are no matter what needed for orbit and coupling correction (tuning knobs)

This solution is “optics independent”, could be applied to the baseline or the LCCO optic

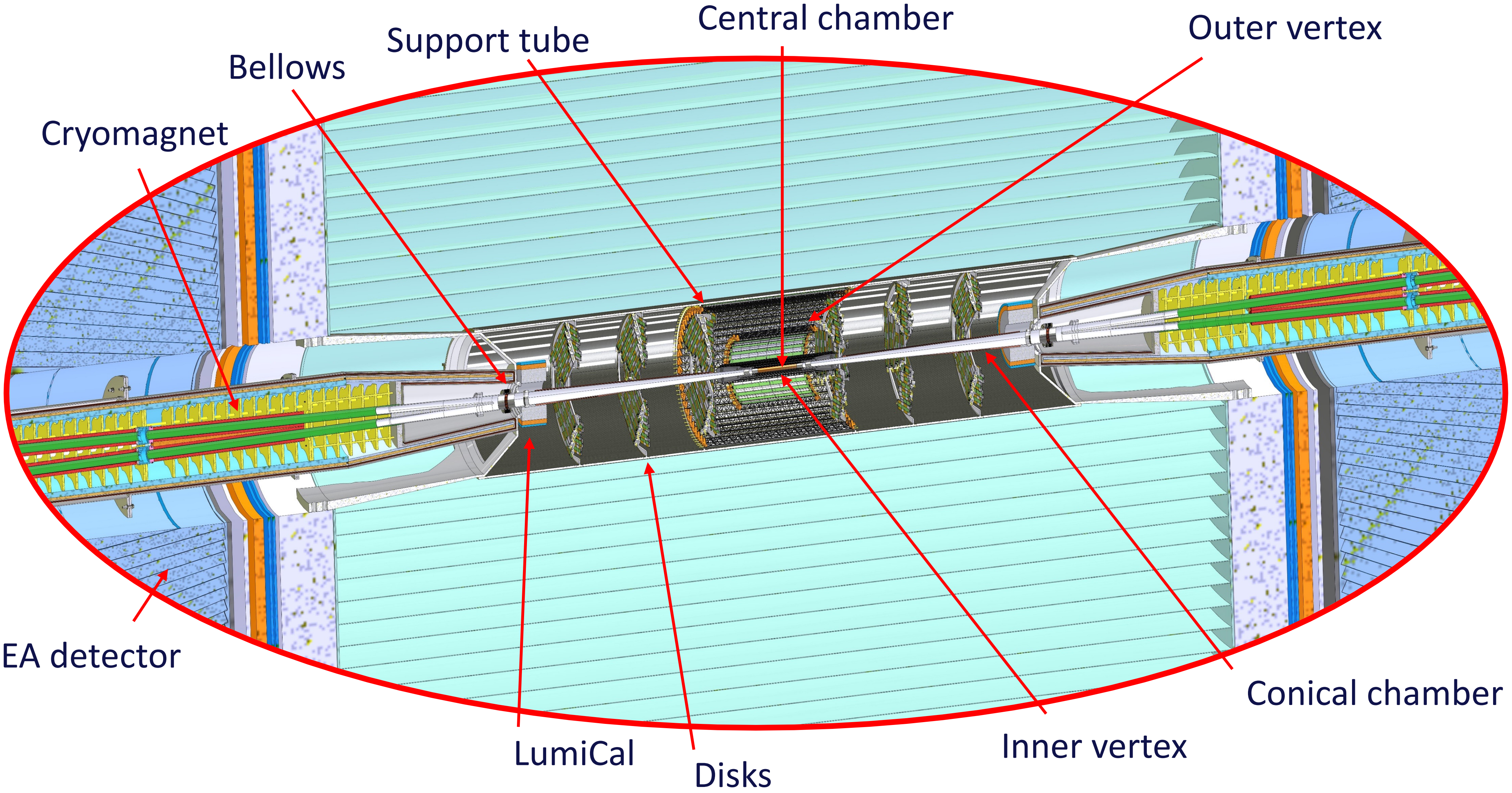
Synchrotron radiation in the tunnel

	LEP-II (1999-2000)	FCC-ee Z	FCC-ee W	FCC-ee ZH	FCC-ee ttbar
Beam energy	98-104.5 GeV	45.6 GeV	80 GeV	120 GeV	182.5 GeV
Bending radius	3.1 km	10 km			
Beam current	6.2 mA (@98 GeV)	2 x 1270 mA	2 x 137 mA	2 x 26.7 mA	2 x 4.86 mA
Energy loss/turn (arcs)	2.6 GeV (@98 GeV) 3.4 GeV (@104.5 GeV)	0.04 GeV	0.37 GeV	1.9 GeV	10.3 GeV
Power loss (arcs)	16 MW (@98 GeV)*	100 MW			
Total arc length	23 km	77 km			
Power loss/unit length (arcs)	0.7 kW/m (@98 GeV)*	1.3 kW/m			
Critical energy	0.7 MeV – 0.8 MeV	0.02 MeV	0.1 MeV	0.4 MeV	1.3 MeV

**Indicative value (beam current decreased from 98 GeV to 104.5 GeV)*

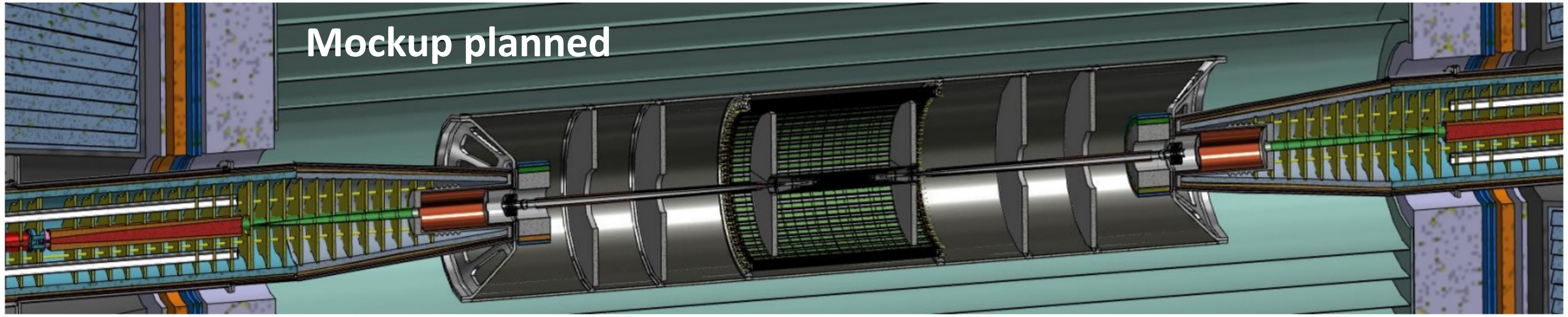
- **Source term comparable to LEP operation, higher critical energy for ttbar run.**
- **Baseline with distributed (water cooled) photon stops every ~6 m.**
- **Different shielding strategies for (Z, W, ZH) vs ttbar?**

Interaction Region



FCC-ee MDI

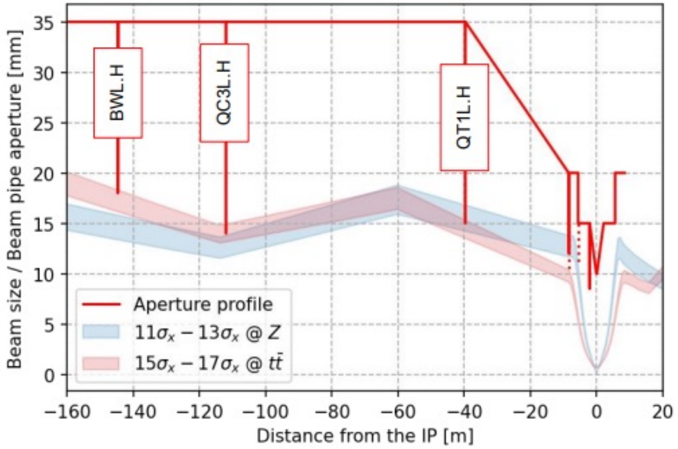
Novel outer support tube for central beam pipe and vertex detector



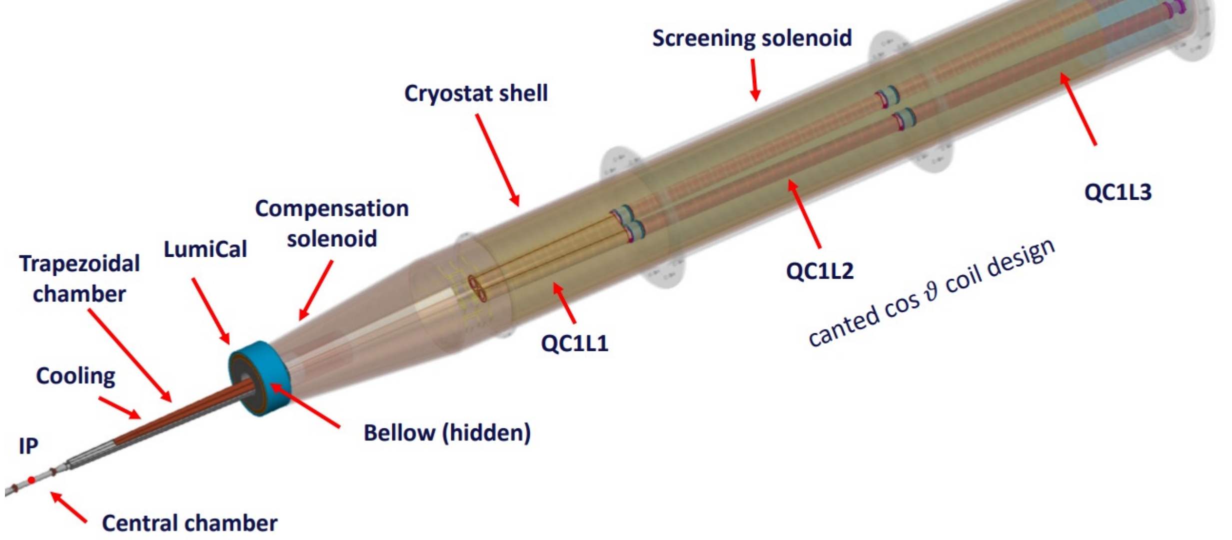
Mockup planned

- Inside the same volume of the support tube that holds also the LumiCal
  - Vertex detector supported by the beam pipe
  - Outer Tracker (1 barrel and 6 disks) fixed to the support tube

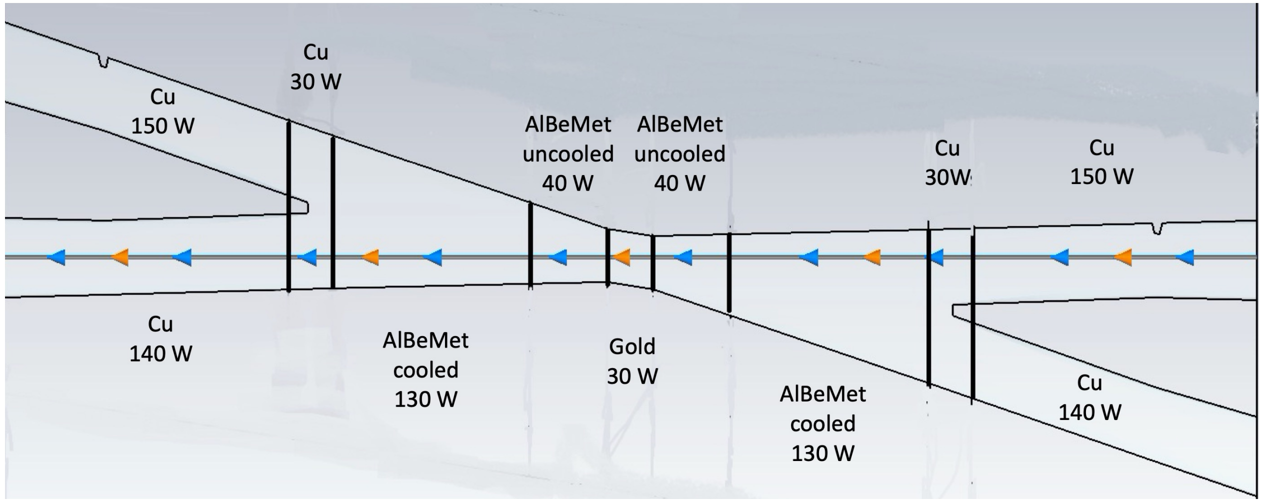
IR SR masks



3D view of IR



IR heat load distribution

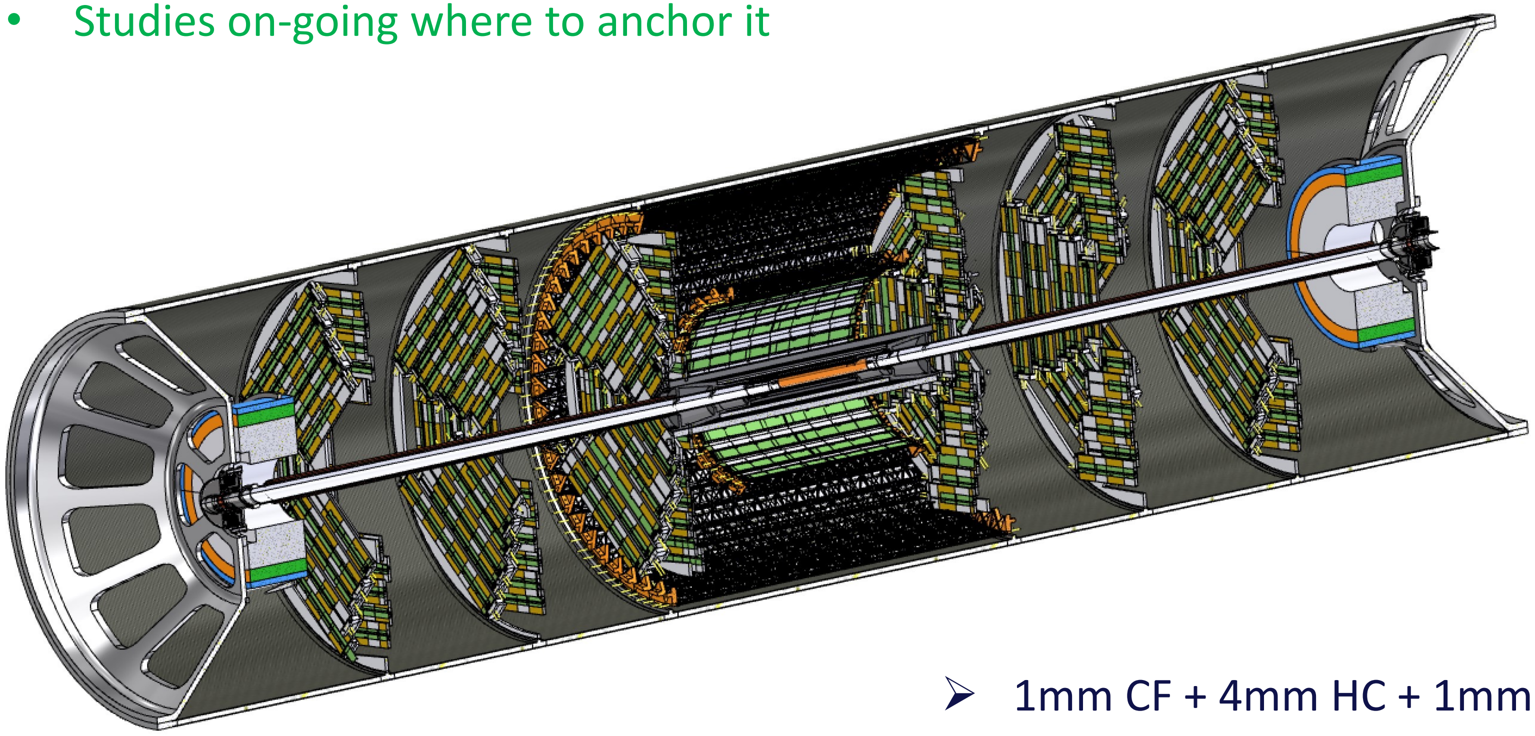


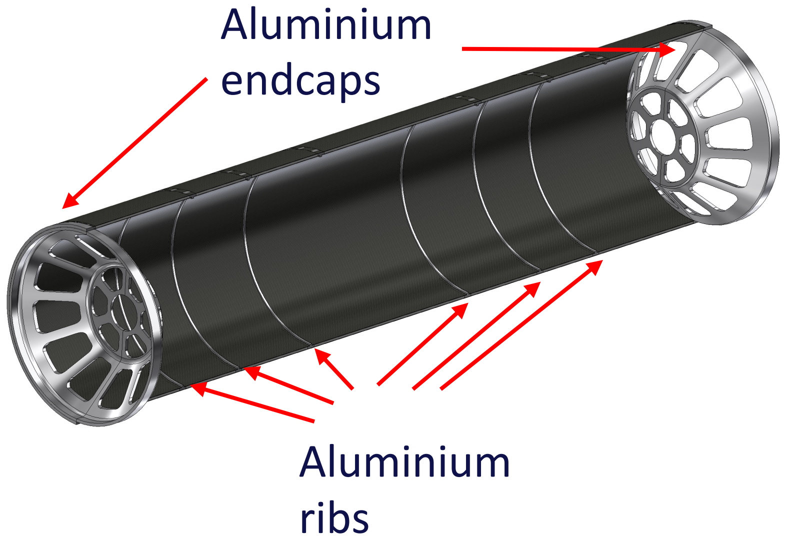
Support cylinder

All elements in the interaction region (Vertex and LumiCal) are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment

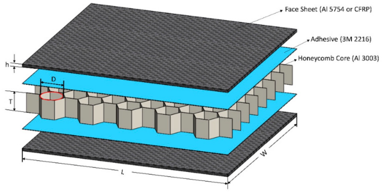
- Provides a cantilevered support for the pipe
- Avoids loads on thin-walled central chamber during assembly or due to its own weight

- Once the structure is assembled it is slided inside the rest of the detector
- Studies on-going where to anchor it



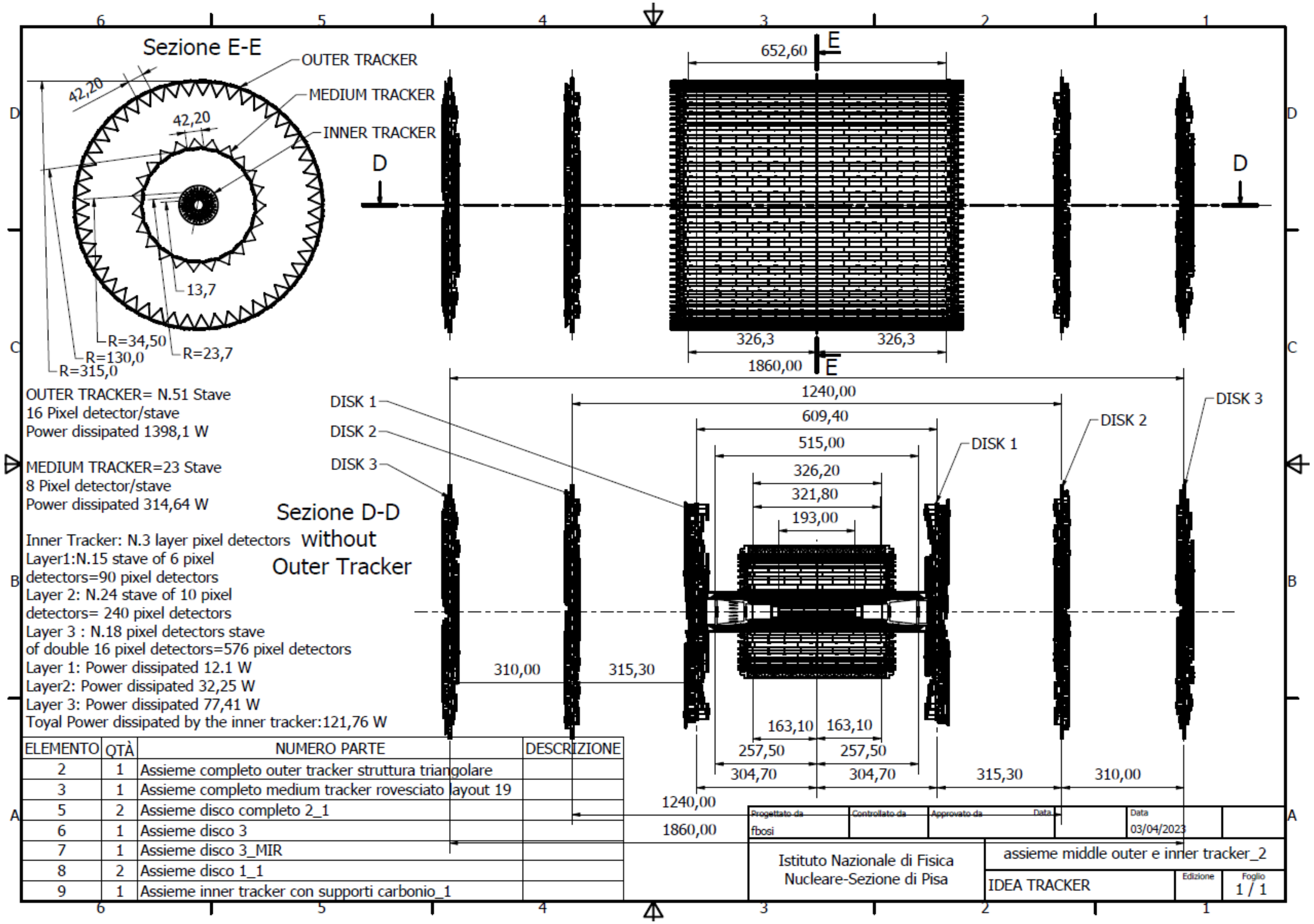


➢ 1mm CF + 4mm HC + 1mm CF



Overall Vertex detector layout and dimensions

Vertex detector engineered



OUTER TRACKER= N.51 Stave
16 Pixel detector/stave
Power dissipated 1398,1 W

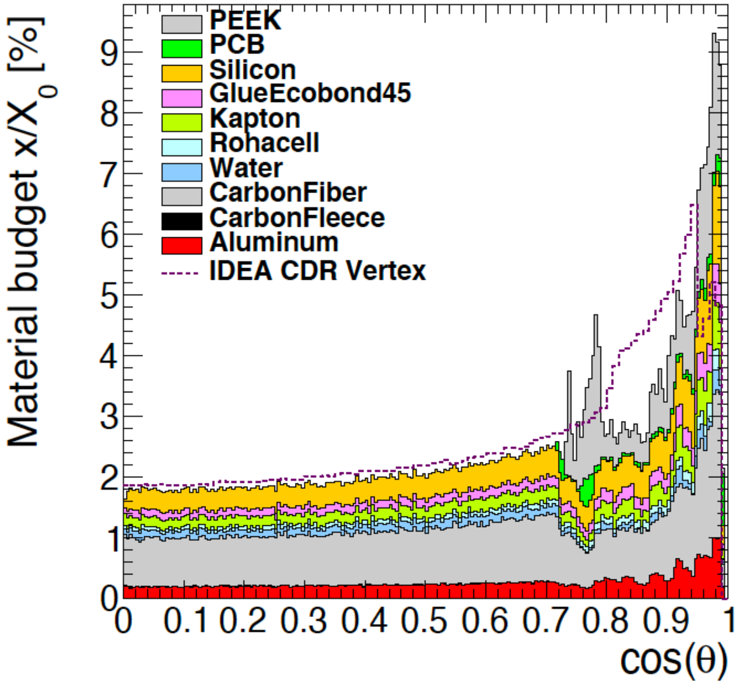
MEDIUM TRACKER=23 Stave
8 Pixel detector/stave
Power dissipated 314,64 W

Inner Tracker: N.3 layer pixel detectors
Layer1:N.15 stave of 6 pixel detectors=90 pixel detectors
Layer 2: N.24 stave of 10 pixel detectors= 240 pixel detectors
Layer 3 : N.18 pixel detectors stave of double 16 pixel detectors=576 pixel detectors
Layer 1: Power dissipated 12.1 W
Layer2: Power dissipated 32,25 W
Layer 3: Power dissipated 77,41 W
Toyal Power dissipated by the inner tracker:121,76 W

ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
2	1	Assieme completo outer tracker struttura triangolare	
3	1	Assieme completo medium tracker rovesciato layout 19	
5	2	Assieme disco completo 2_1	
6	1	Assieme disco 3	
7	1	Assieme disco 3_MIR	
8	2	Assieme disco 1_1	
9	1	Assieme inner tracker con supporti carbonio_1	

Progettato da: fbosi
Controllato da
Approvato da
Data
Data: 03/04/2023
Istituto Nazionale di Fisica Nucleare-Sezione di Pisa
assieme middle outer e inner tracker_2
IDEA TRACKER
Edizione
Foglio: 1 / 1

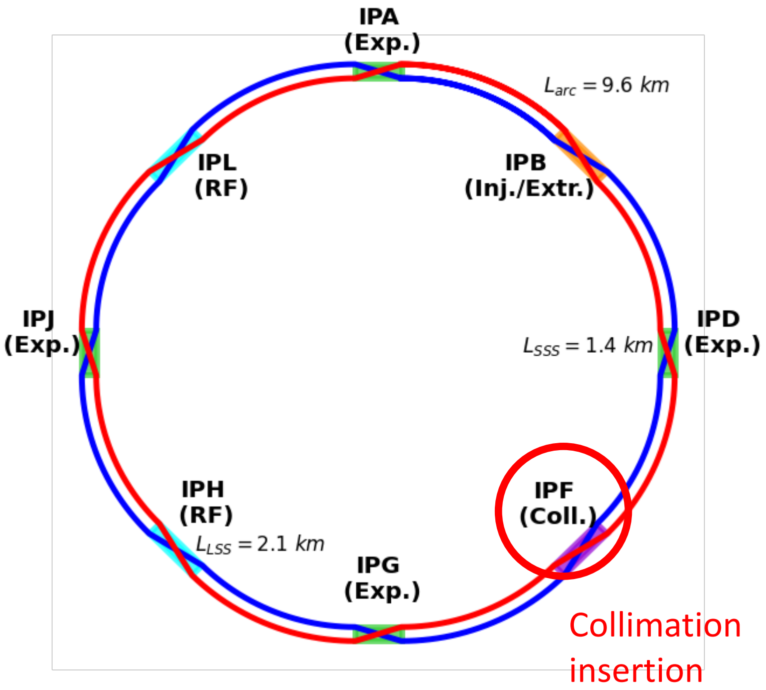
Simulated material budget



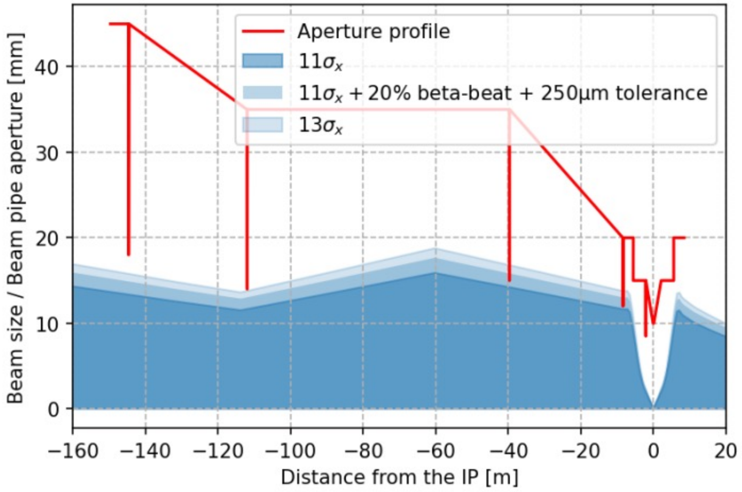
- In agreement with CAD estimates
- Smaller X/X_0 wrt IDEA CDR estimates even including power and readout cables in the sensitive region
- Silicon only ~15% of the total

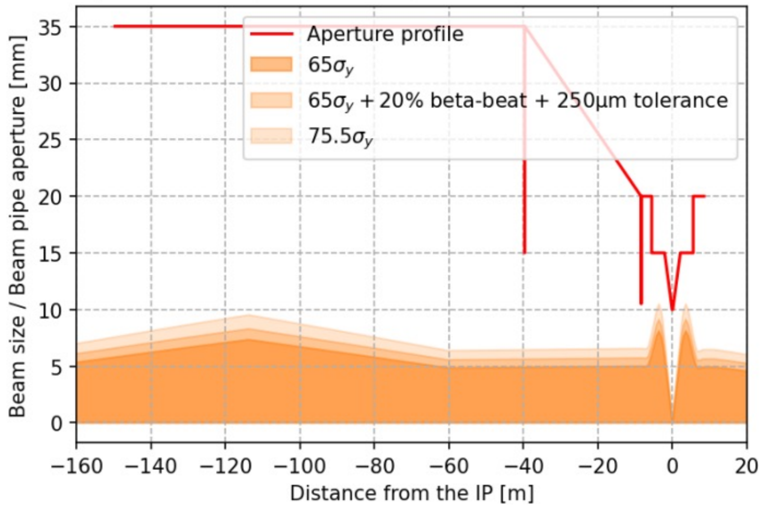
Main Ring Collimation

- **Dedicated halo collimation system in point PF**
  - Two-stage betatron and off-momentum collimation in PF
  - Defines the global aperture bottleneck
  - First collimator design
- **Synchrotron radiation collimators around the IPs**
  - 6 collimators and 2 masks upstream of the IPs
  - Designed to reduce detector backgrounds and power loads in the inner beam pipe due to photon losses



Collimation insertion





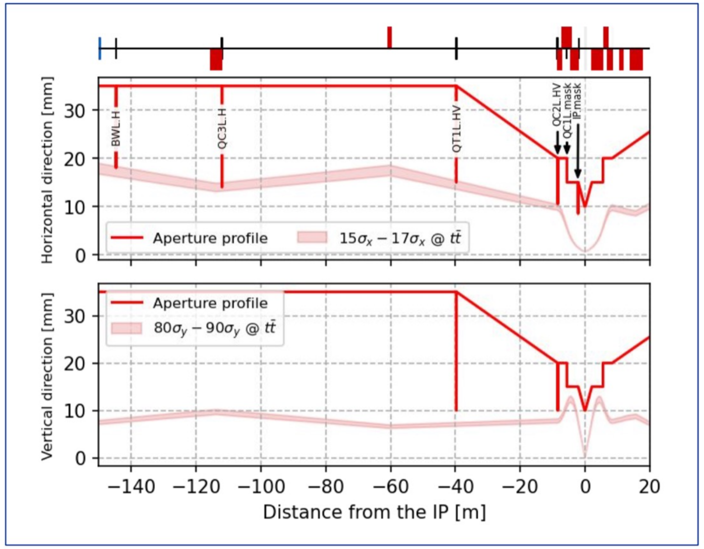
Synchrotron Radiation backgrounds

Simulations with **BDSIM** (GEANT4 toolkit), featuring SR from Gaussian beam core and transverse halo.

Characterisation of the SR produced for **all beam energies**.

Name	s [m]	half-gap [m]	plane
BWL.H	-144.69	0.018	H
QC3L.H	-112.05	0.014	H
QT1L.H	-39.75	0.015	H
PQC2LE.H	-8.64	0.011	H
MSK.QC2L	-5.56	R = 0.015	H&V
MSK.QC1L	-2.12	0.007	H

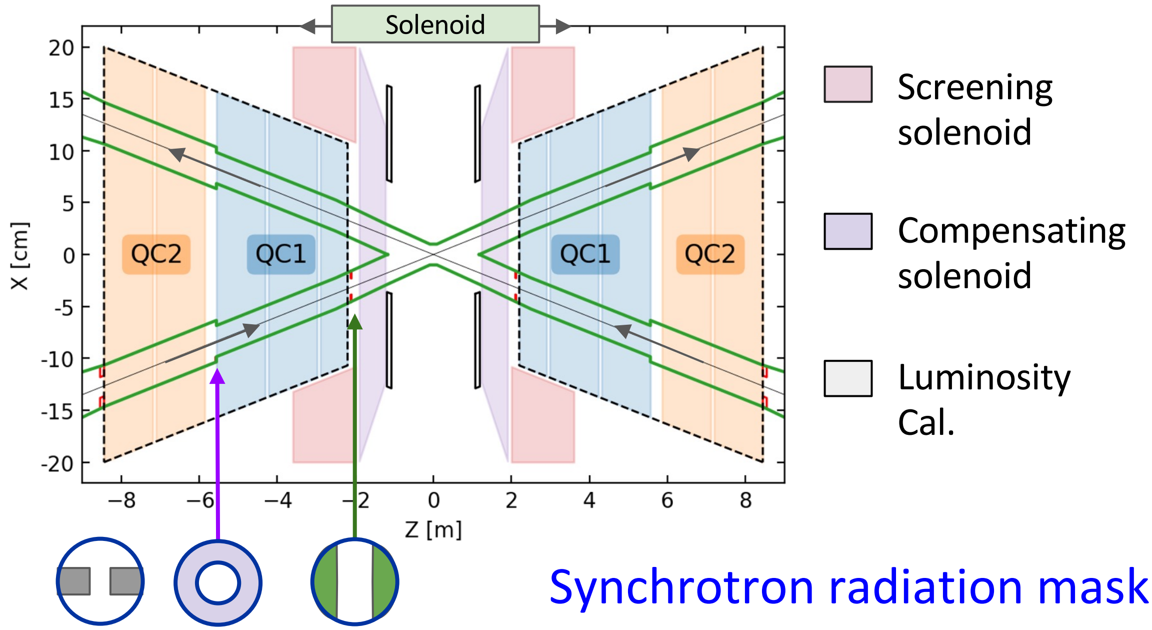
15 σ_x corresponds to the aperture of the **primary** collimators, **17 σ_x** corresponds to the aperture of the **secondary** collimators.



Synchrotron radiation collimators

SR produced upstream the IP:

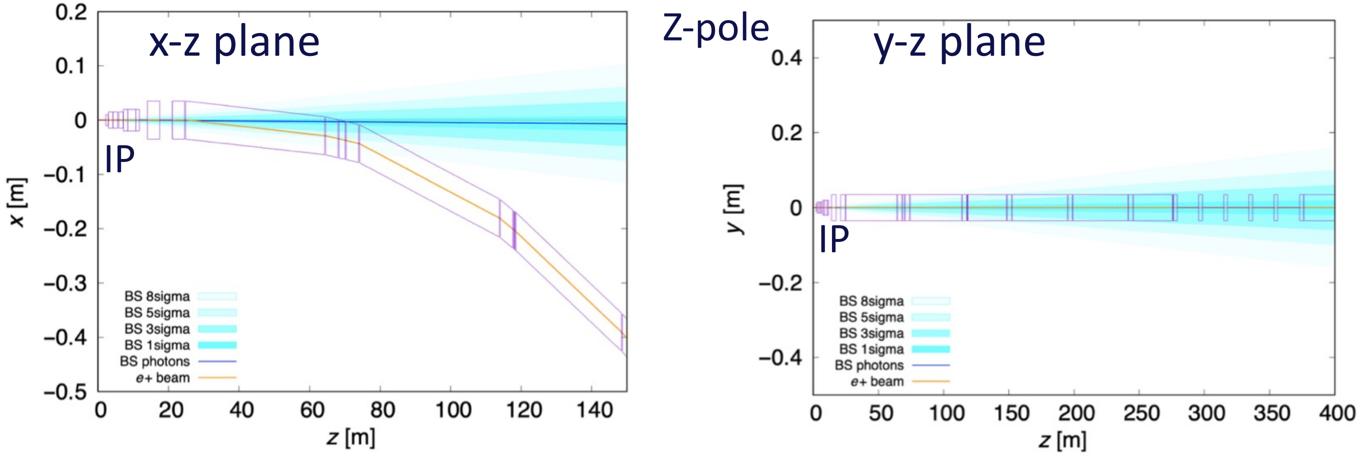
- by the **last dipoles and quadrupoles upstream the IR** can be a background source, to be collimated and masked
- by the **IR quads and solenoids** collinear with the beam and will hit the beam pipe at the first dipole after the IP.



Synchrotron radiation masks

Beamstrahlung Radiation

Radiation from the colliding beams is very intense 400 kW at Z
Study performed with GuineaPig.



MB and A. Ciarma, PRAB 26, 111002 (2023), link

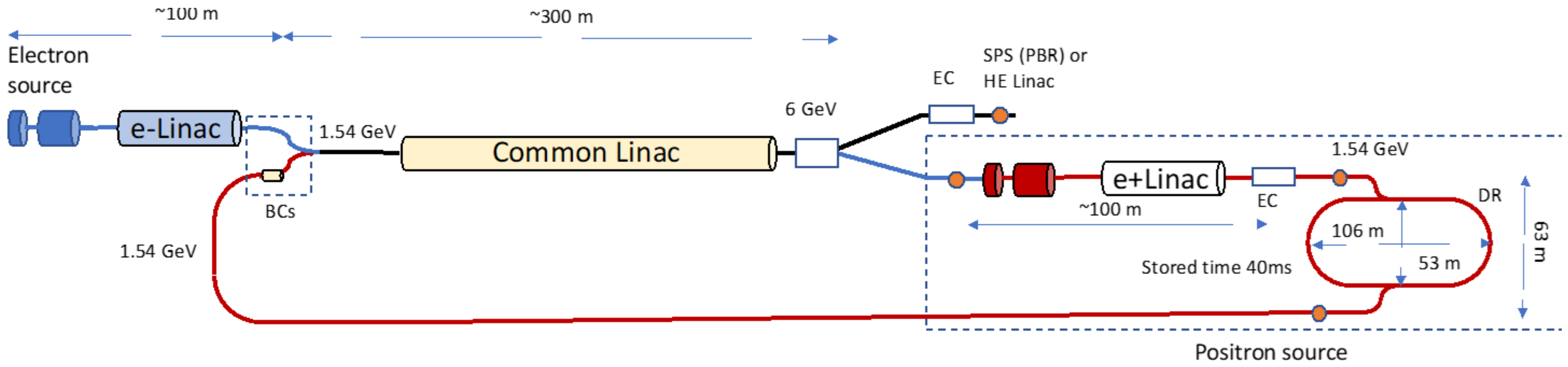
This BS radiation exits the vacuum chamber around the first bending magnet BC1 downstream the IP

	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

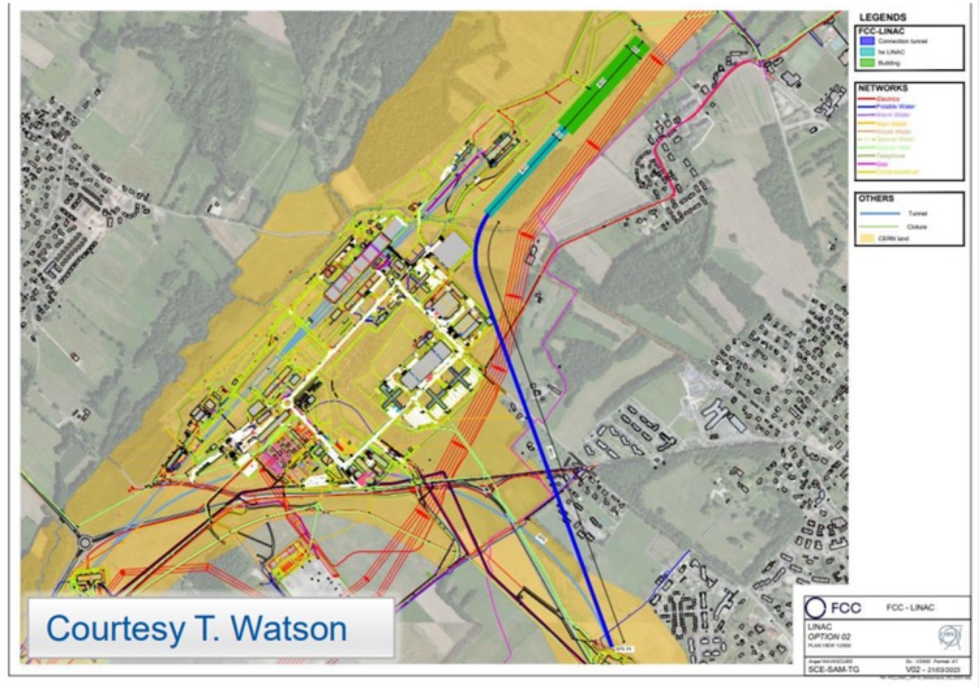
High-power beam dump needed to dispose of these BS photons **+ all the radiation from IR**: FLUKA simulation ongoing

- Different targets as dump absorber material are under investigation
- Shielding needed for equipment and personnel protection for radiation environment

New FCC-ee injector layout & implementation

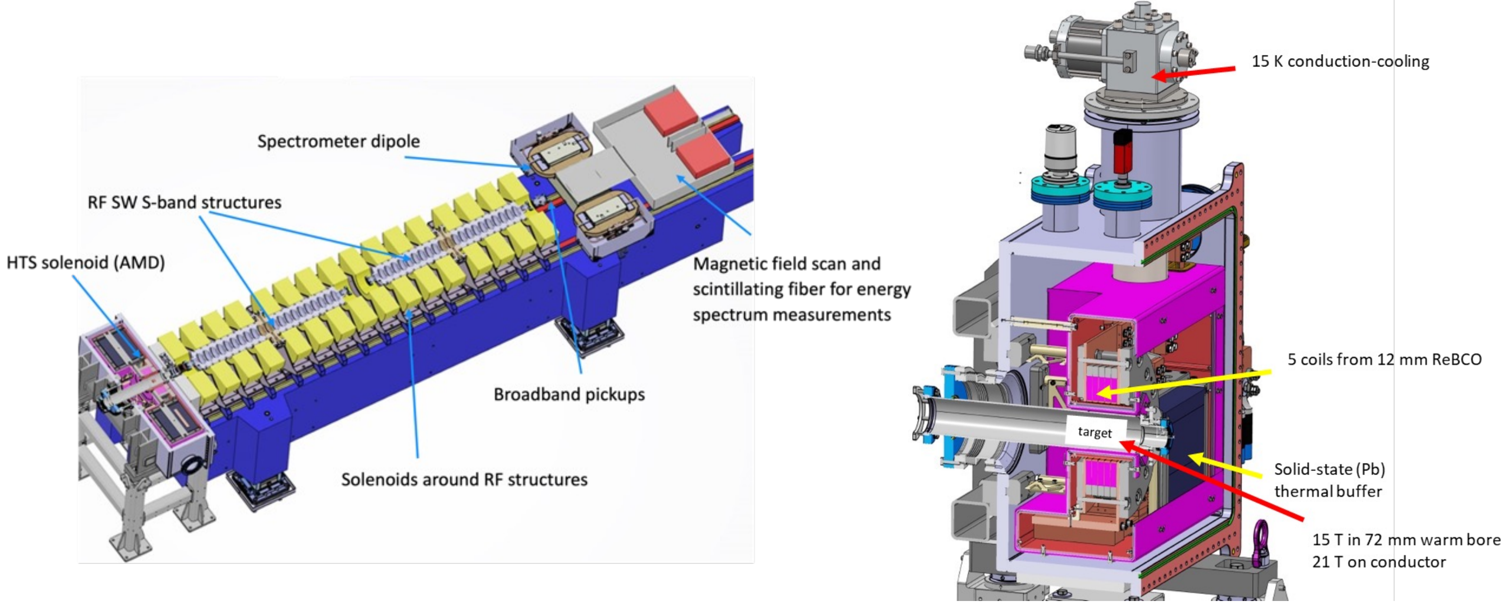


implementation study on Prevessin site



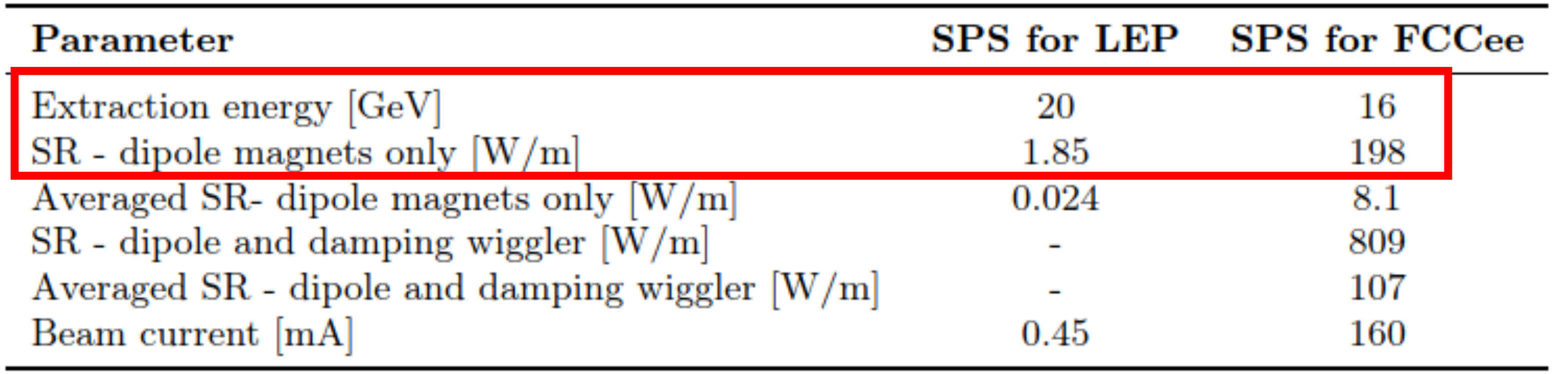
Courtesy T. Watson

“Positron production experiment” at PSI’s SwissFEL, beam tests from 2025/26



SPS as alternative to high-energy linac as pre-booster

- Synchrotron radiation masks would need to be reinstalled at every SPS dipole magnet, or else a fully new vacuum chamber be constructed and installed
- LEP-era SR masks in the SPS used the same flange for installation as the impedance shields now installed for the SPS LHC hadron beam operation
- Masks were/are welded in place; difficult access ! SPS magnets are closed and not C-shaped
- Removal of impedance shields is incompatible with HL-LHC operation
- There were about 20 different variants of LEP masks; it is uncertain if these masks would cope with 100-400x higher radiation power levels for FCC-ee beams at 16 GeV (see table below)
- Time required for SPS modifications: several years of SPS shutdown for the installation, plus a lot of human resources
- Impact on p-physics operation: during Z-run period SPS blocked for ~85% for top-up operation.



Parameter	**SPS for LEP**	**SPS for FCCee**
Extraction energy [GeV]	20	16
SR - dipole magnets only [W/m]	1.85	198
Averaged SR- dipole magnets only [W/m]	0.024	8.1
SR - dipole and damping wiggler [W/m]	-	809
Averaged SR - dipole and damping wiggler [W/m]	-	107
Beam current [mA]	0.45	160

FCC-hh layout, optics work, geom. integration

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

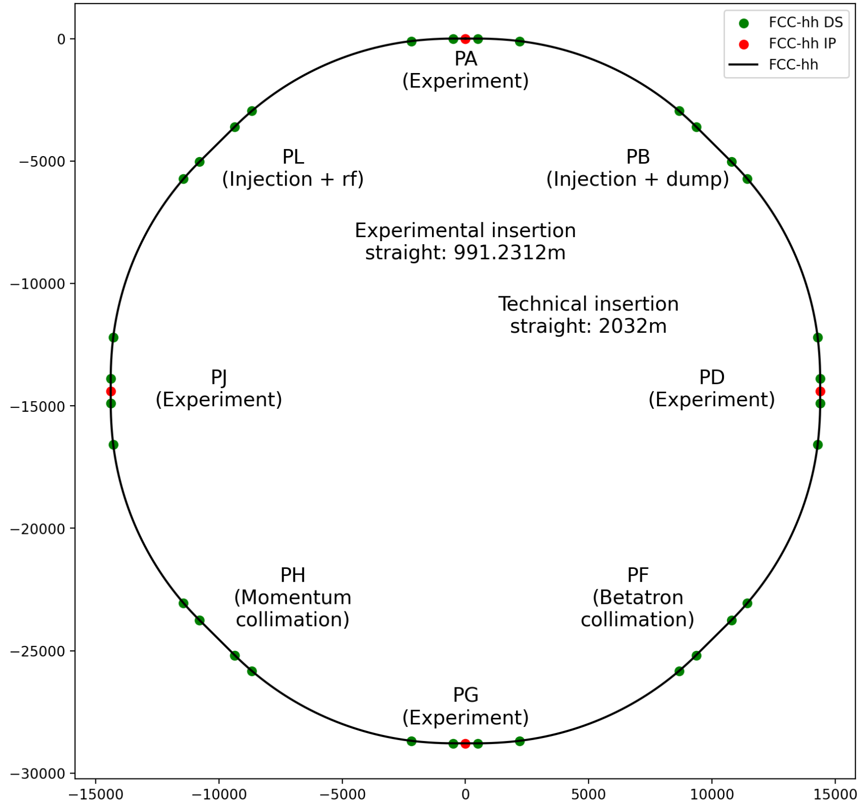
Formidable challenges:

- ☐ 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:

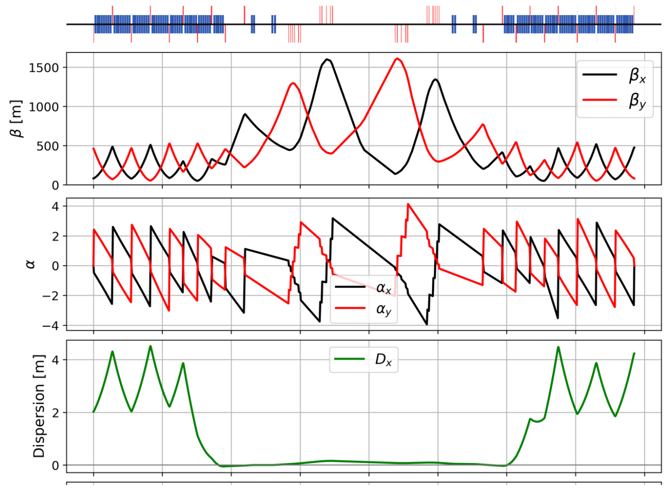
- ☐ Direct discovery potential up to ~ 40 TeV
- ☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ☐ Final word about WIMP dark matter

FCC-hh layout, optics work, geom. integration

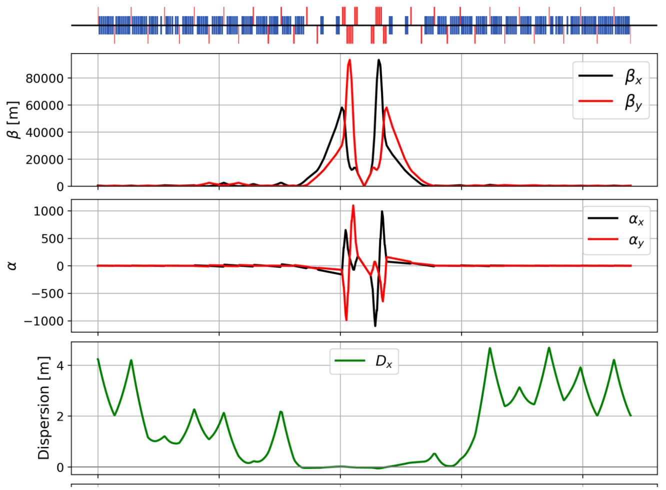


- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)
- move hh IPs on top of ee IP to optimise tunnel and cavern widths.

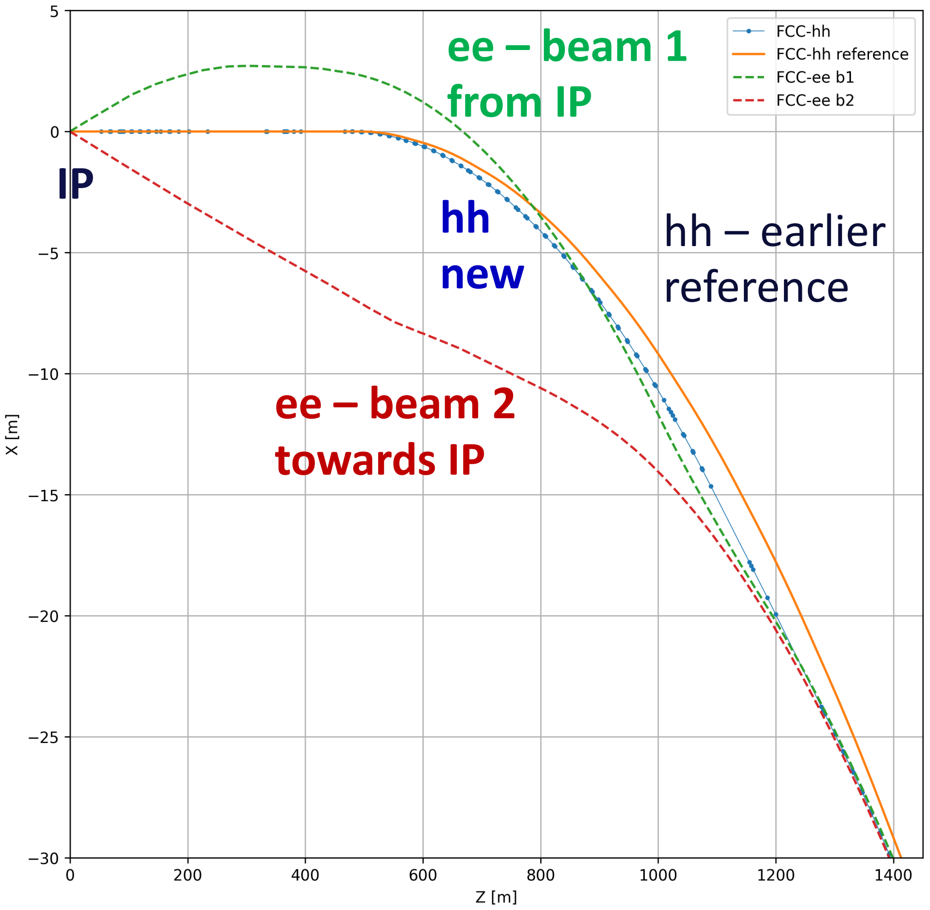
betatron collimation straight



experimental straight

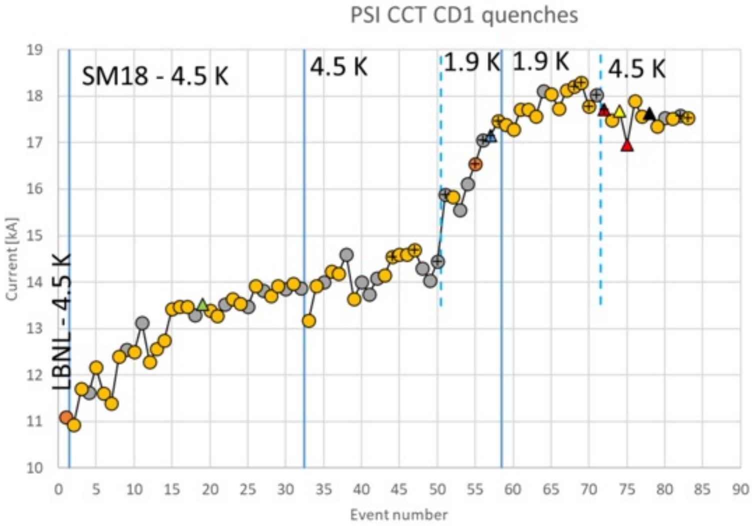


3 - beam footprint at interaction point



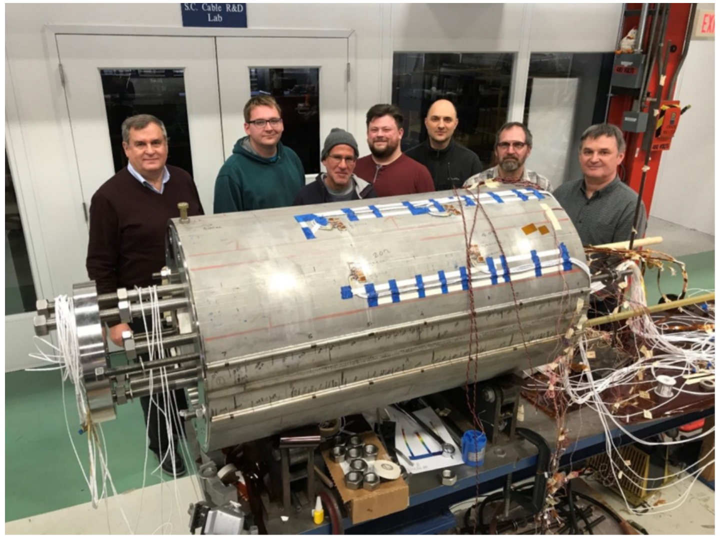
High-field magnets for FCC-hh: Nb_3Sn & HTS R&D

PSI Nb3Sn CCT «CD1» main test carried out in 2022/23

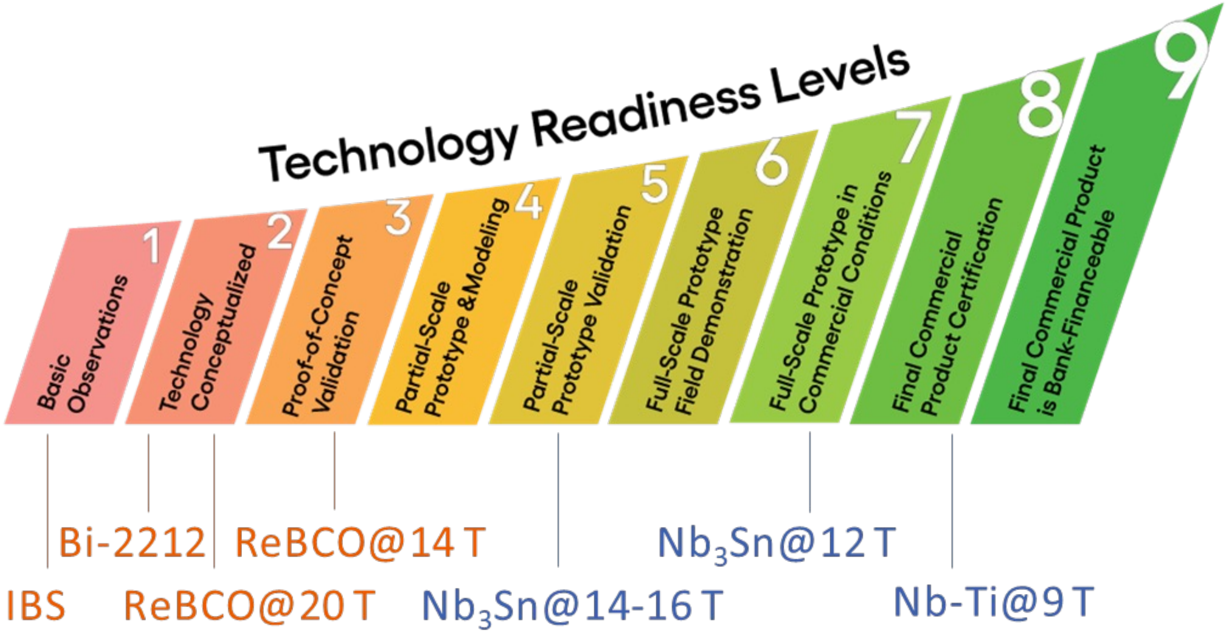


It trained A LOT. It reached 100% of maximum field at 4.5 K. No conductor degradation occurred from handling, assembly, powering, or thermal cycling.

Stress-management works, CD1 is a robust magnet.



FNAL dipole
demonstrator
4-layer cosϑ
14.5 T Nb_3Sn
in 2019

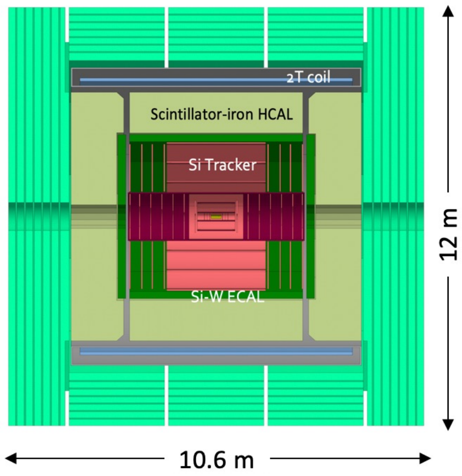


Rough estimates

Bottom line: HTS technology must catch up over the coming 10 years in TRL to LTS

FCC-ee Detector Concepts

CLD

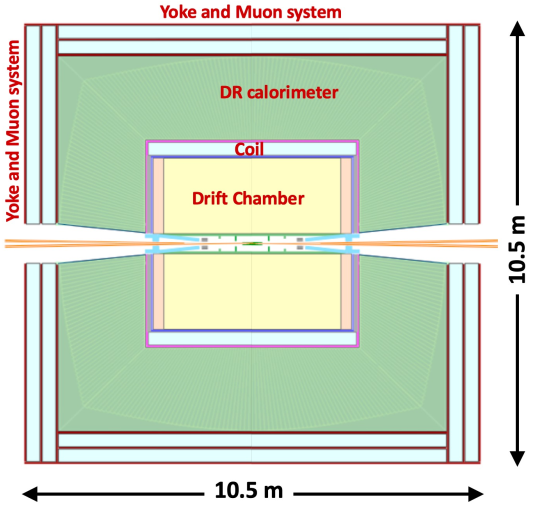


- Full Silicon vertex detector + tracker;
- Very high granularity, CALICE-like calorimetry;
- Muon system
- Large coil outside calorimeter system;

- Possible optimization for
  - Improved momentum and energy resolutions
  - PID capabilities

CDR

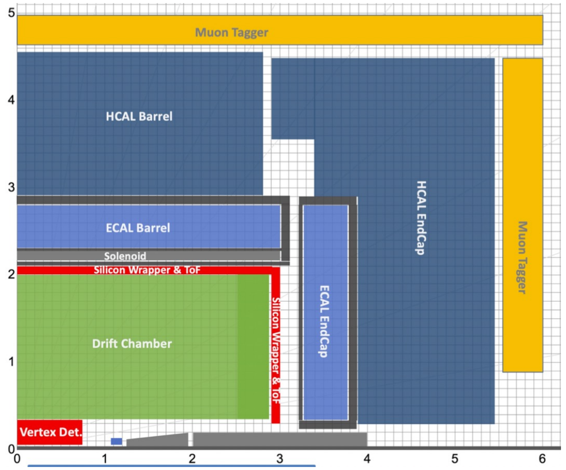
IDEA



- Si vertex detector;
- Ultra light drift chamber w. powerfull PID;
- Monolitic dual readout calorimeter;
- Muon system;
- Compact, light coil inside calorimeter;

- Possibly augmented by crystal ECAL in front of coil;

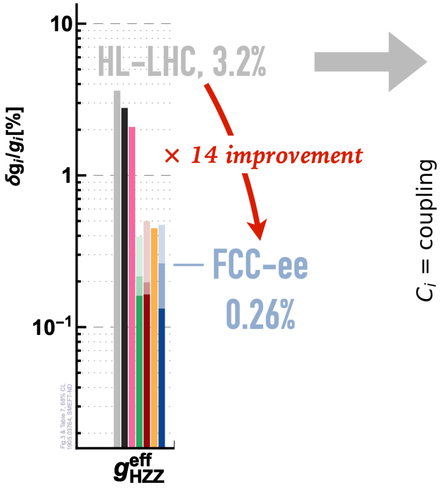
ALLEGRO



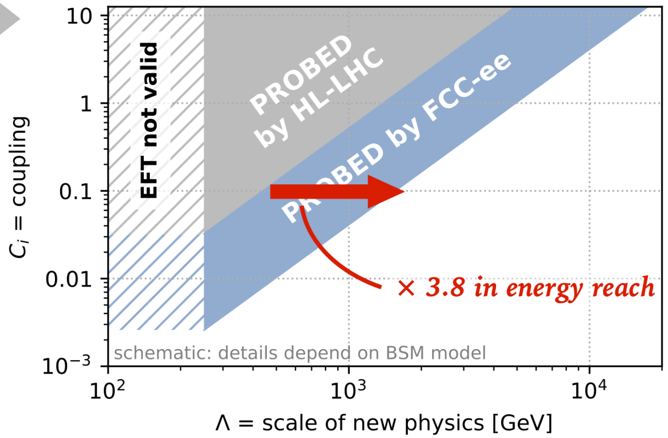
- Noble Liquid ECAL based
- High granularity Noble Liquid ECAL as core;
  - PB+LAr (or denser W+LCr)
- Drift chamber (or Si) tracking;
- CALICE-like HCAL;
- Muon system;
- Coil inside same cryostat as LAr, possibly outside ECAL.

Physics Potential

Interpret higher precision as increase in indirect reach

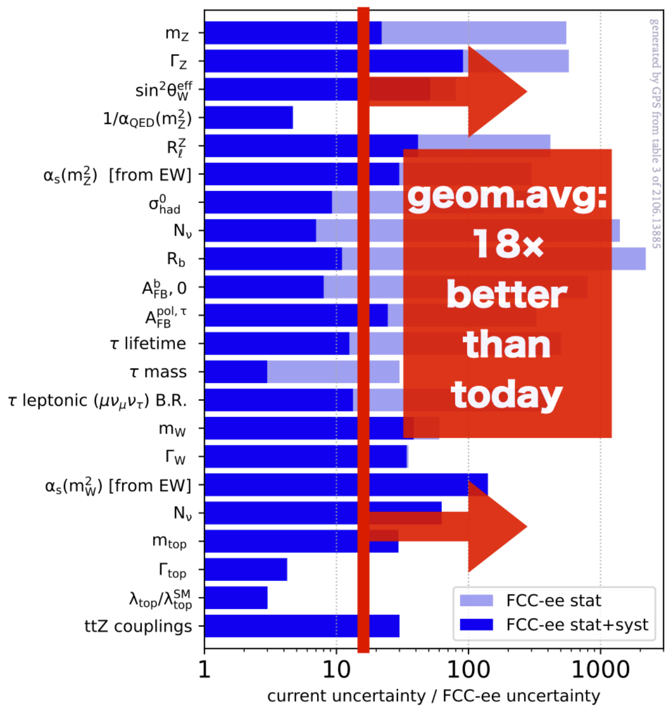


interpret as mass-coupling sensitivity

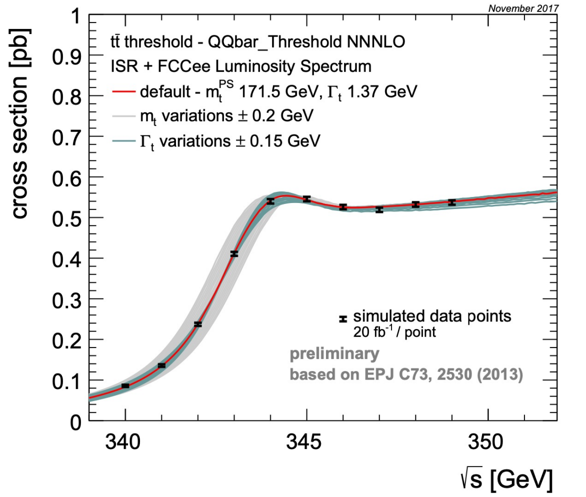


Gavin Salam FCC week, London, June 2023

FCC-ee precision gain

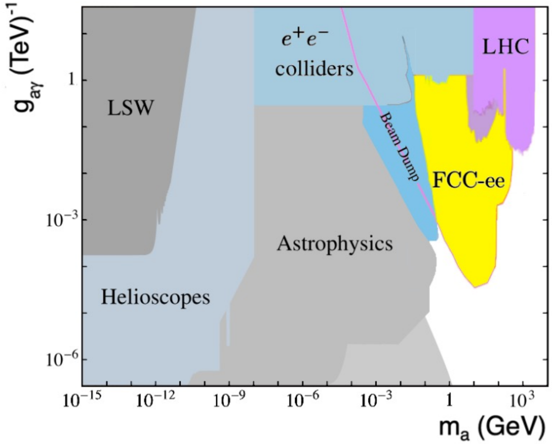


threshold scan for top mass



Gavin Salam FCC week, Lond

Axions



Flavour physics: 15× more b-pairs at FCC-ee than at Belle II

2106.01259

Attribute	$\Upsilon(4S)$	pp	FCC-ee Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

FCC Italia

Activity funded by CSN1 within **RD_FCC**
National Responsible Paolo Giacomelli (Bologna), that substitutes Franco Bedeschi
Activity organized in WP:

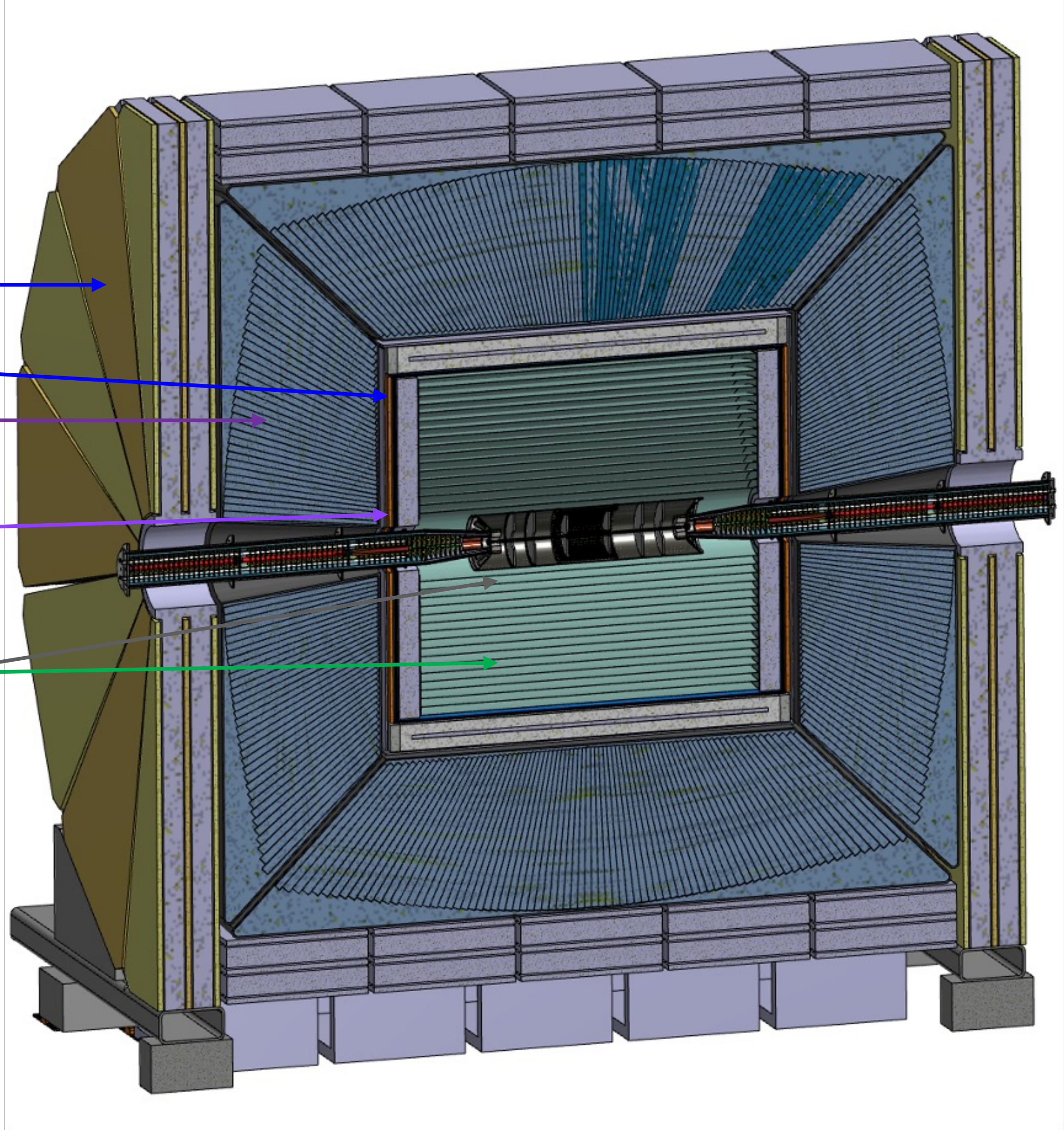
WP1 Physics & software	P. Azzi PD, N. De Filippis BA
WP2 Acceleratore	M. Boscolo **LNF**
WP3 Silicon/Vertex detectors	M. Caccia MI, A. Andreazza MI
WP4 Drift chamber	F. Grancagnolo LE
WP5 MPGD for muon/preshower	M. Poli Lener **LNF**
WP6 Dual readout calorimetry	R. Ferrari PV

Increase in manpower

2023: 19 units
  - Researchers /Tecnologists: 151
  - FTE: 30.70

2024: 19 units
  - Researchers /Tecnologists: 170
  - FTE: 38.20

IDEA Detector



- µRWell muon chambers
    - Pre-shower
- Dual Readout calorimeter

  Also with crystals
- Silicon wrapper

  ATLASpix3 or LGADs
- Drift Chamber
- Vertex detector

  MAPS (ARCADIA)

Activities at LNF

8 FTE of which:

WP2 Acceleratore

Interaction region Design
- Mechanical model of the IR
- Beam backgrounds and mitigation
- Beamstrahlung radiation and handling

IR Mockup R&D

Collective Effects

Positron Damping Ring

7 FTE

WP5 MPGD

- R&D 2024: construction of 2 detectors 50x50 cm^2 2D readout

0.9 FTE

WP1 Fisica

- B Physics

0.1 FTE

INFN special funds to FCC for the ESPPU

Special funds have been allocated by INFN executive board to projects on future colliders, in preparation of the Next European Strategy for Particle Physics Update (ESPPU).

Two (out of five) funded projects are for FCC

- IR and MDI full-scale mockup **LNF**
- SRF cavities **LNL**

Addendum CERN-INFN under final approval now.

All of these funded projects are revised by the INFN MAC and approved by the INFN GE.
Activity is part of the CSN1.

Italian FCC Accelerator Team (WP2 RD_FCC)

**External funds,
European projects, and
synergic programs**

Main activities

- Interaction region and Machine-Detector Interface **LNF, Pisa, Perugia** (FCCIS, AidaInnova)
- Collimation studies **CERN doctoral student & Sapienza /LNF**
- Superconducting RF cavities **LNL** (iFAST)
- Collective effects **INFN-Roma1, LNF** (FCCIS)
- Hybrid crystal Positron source **INFN-Ferrara** (PRIN)
- Beam dynamics e+ beamline from source to damping ring **INFN-Milano**
- Bunch-by-bunch current control via Compton scattering **INFN-Milano**
- Positron Damping Ring e+ and TL **LNF** (CHART)
- High-field magnets for FCC-hh [separate project and funding] **INFN-Genova, INFN-Mi**

New activities and interests, group is expanding

Slide from FCC WEEK 2018, Amsterdam
M. Boscolo, “FCC-ee machine design overview”

Converting DAΦNE to Test Facility ?

DAΦNE will **shut down** as a **collider** at the **end** of **2019**

proposal:

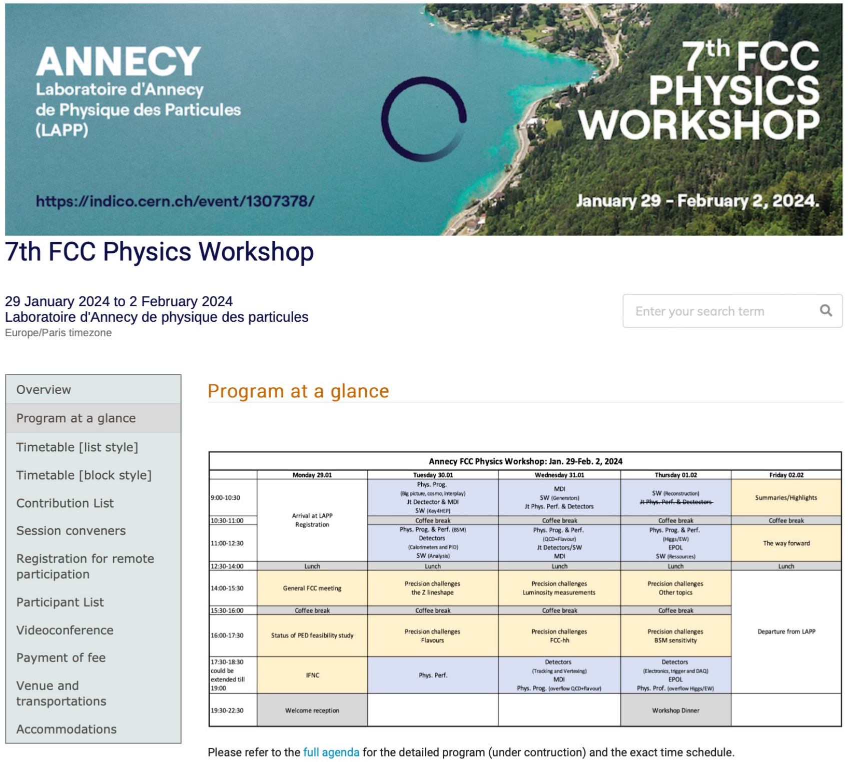
exploiting DAΦNE as an

European/International high-current beam facility

some ideas:

- impedance, HOM effects for accelerator components
- SR effects on vacuum, SEY measurements
- positron source studies
- multi-cell SC cavities for high current CW operation, provided compatibility rf frequency

Next Events



ANNECY
Laboratoire d'Annecy
de Physique des Particules
(LAPP)

7th FCC PHYSICS WORKSHOP

https://indico.cern.ch/event/1307378/

January 29 – February 2, 2024.

7th FCC Physics Workshop

29 January 2024 to 2 February 2024
Laboratoire d'Annecy de physique des particules
Europe/Paris timezone

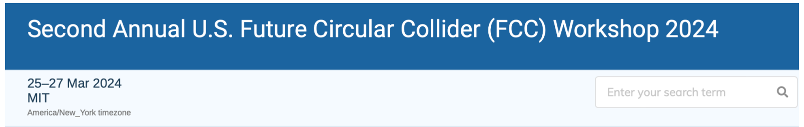
Program at a glance

Annecy FCC Physics Workshop: Jan. 29-Feb. 2, 2024

	Monday 29.01	Tuesday 30.01	Wednesday 31.01	Thursday 01.02	Friday 02.02
9:00-10:30	Arrival at LAPP Registration	Phys. Prog. (Big picture, cosmo, interplay) Jt Dectector & MDI SW (Key4HEP)	MDI SW (Generators) Jt Phys. Perf. & Detectors	SW (Reconstruction) ~~Jt Phys. Perf. & Dectectors~~	Summaries/Highlights
10:30-11:00		Coffee break	Coffee break	Coffee break	Coffee break
11:00-12:30		Phys. Prog. & Perf. (BSM) Detectors (Calorimeters and PID) SW (Analysis)	Phys. Prog. & Perf. (QCD+Flavour) Jt Detectors/SW MDI	Phys. Prog. & Perf. (Higgs/EW) EPOL SW (Ressources)	The way forward
12:30-14:00	Lunch	Lunch	Lunch	Lunch	Lunch
14:00-15:30	General FCC meeting	Precision challenges the Z lineshape	Precision challenges Luminosity measurements	Precision challenges Other topics	Departure from LAPP
15:30-16:00	Coffee break	Coffee break	Coffee break	Coffee break	
16:00-17:30	Status of PED feasibility study	Precision challenges Flavours	Precision challenges FCC-hh	Precision challenges BSM sensitivity	
17:30-18:30 could be extended till 19:00	IFNC	Phys. Perf.	Detectors (Tracking and Vertexing) MDI Phys. Prog. (overflow QCD+flavour)	Detectors (Electronics, trigger and DAQ) EPOL Phys. Prof. (overflow Higgs/EW)	
19:30-22:30	Welcome reception			Workshop Dinner	

Please refer to the full agenda for the detailed program (under contruction) and the exact time schedule.

https://indico.cern.ch/event/1307378/



Second Annual U.S. Future Circular Collider (FCC) Workshop 2024

25–27 Mar 2024
MIT
America/New_York timezone

25-27 March, MIT
https://indico.mit.edu/event/876/

FCC Week 2024
June 2024

2nd "FCC Italy & France Workshop"

4–6 Nov 2024
Venice
Europe/Rome timezone

The second joint FCC-France&Italy workshop on Higgs, Top, EW, HF and SM physics will take place at Palazzo Franchetti, in Venice from 4-6th of November 2024.

In 2020 CERN started a feasibility study for the construction of a Future Circular Collider (FCC) in the Geneva region with a circumference of about 100 km. An e+e- collider (FCC-ee), covering the energy range from the Z pole up to the top pair production threshold is the first step to collect incredible statistics of the heaviest particles of the SM. The FCC integrated project, that includes the hadron collider FCC-hh, offers an incredible discovery potential with a careful mixture of precision measurements sensitive to very weak couplings or to very heavy objects, and very high energies where the new heavy particle could be directly produced.
During this 5 year process, toward the preparation of a document for the next European Strategy for Particle Physics, it is important to perform all the studies needed to design detector concepts able to satisfy the needs of the extensive physics program and this workshop happens at a crucial time in the process.
In this workshop, the current status of the most recent advances in the R&D for the accelerator and detectors, will be presented. In addition, there will be sessions dedicated to the experimental and theoretical developments for the various physics topics, from Higgs and electroweak precision measurements to flavour physics (including top) and BSM sensitivities. Plenary sessions will be devoted to overall summaries of the current status of the various aspects, while the parallel sessions will focus on specific areas.
The workshop aims at intensifying French and Italian collaboration and participation to the FCC feasibility study through detailed studies on physics possibilities and the constraints that these entail on the detectors, and through accelerator and detector concepts studies and R&D.
The workshop will happen at a crucial time towards the preparation of the final document to be provided as input to the next European Strategy so we look forward to new inputs and contributions from the community at large.

Starts 4 Nov 2024, 10:00
Ends 6 Nov 2024, 17:00
Europe/Rome

Venice
Palazzo Cavalli-Franchetti ,
S. Marco, 2847,
30124 Venice

4-6 Nov., Venice
https://agenda.infn.it/event/37960/

Conclusions

- FCC-ee fills the need for a highest precision EW/Higgs factory
- Second-highest luminosity at Z, W and H@240 GeV of all proposed factories
- Based on 60 years of experience with circular e^+e^- colliders, some of which currently in operation, hence no need for a large demonstrator facility
  - R&D on components focused on improved performance, increased efficiency, industrialization, cost aspects, sustainability and minimizing environmental impact
- FCC uses current CERN infrastructure; FCC-hh will reuse FCC-ee infrastructure
- FCC integrated programme offers long-term vision for global HEP at precision and energy frontiers, interlinked with large-scale advanced technology R&D programmes
  - FCC-ee, FCC-hh hadron collider (100 TeV pp, AA), FCC-eh option, …
- Strong international support & participation are crucial for success of ongoing Feasibility Study & for FCC project to go ahead !

Thank you!

Status of FCC global collaboration

increasing international collaboration as a prerequisite for success

150
Institutes

32
Companies

34
Countries

EC
H2020

Transfer line FCC-ee (option with SPS for FCC-hh)

LINAC and Injection Tunnels

- Designed to enable injection either from the HE Linac sited at Prevessin of from the SPS as pre-booster
- Single tunnel with spur to enable anti-clockwise 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.)