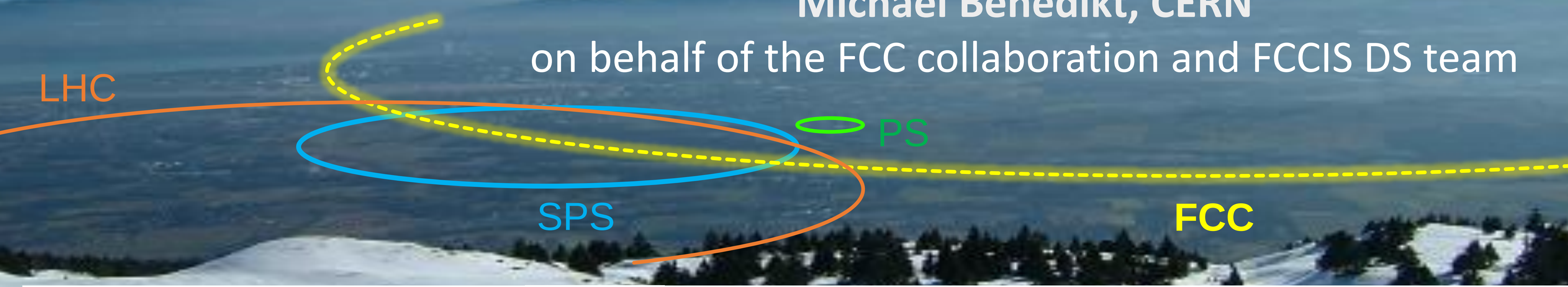
Future Circular Colliders (FCC) Feasbility Study Status

US – FCC Workshop, 24 April 2023, BNL

Michael Benedikt, CERN
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 | 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, contact number 101086276; and by the Swiss **CHART** program*

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

photo: J. Wenninger

European Strategy for Particle Physics

Recommendations of the 2020 update of the European Strategy for Particle Physics (ESPP):

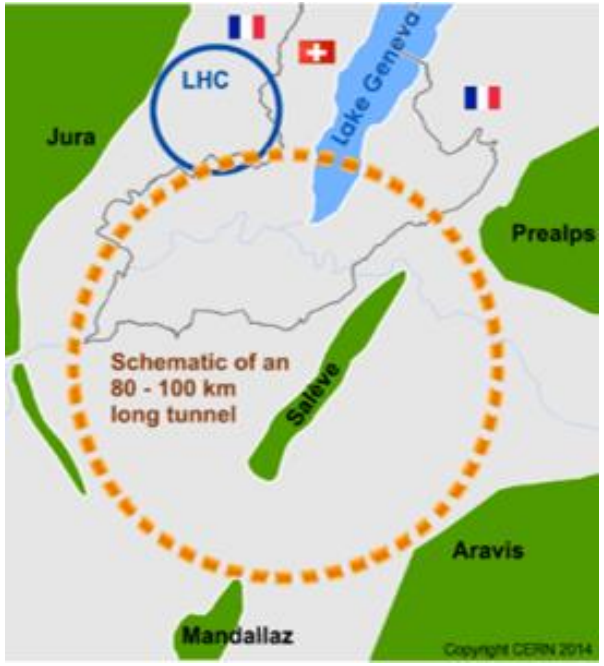
- Full exploitation of the high-luminosity LHC upgrade
- An **electron-positron Higgs factory is the highest-priority next collider**. For the longer term, the European particle physics community has the ambition to operate a **proton-proton collider at the highest achievable energy.**
- Europe, together with its international partners, should investigate the **technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.**

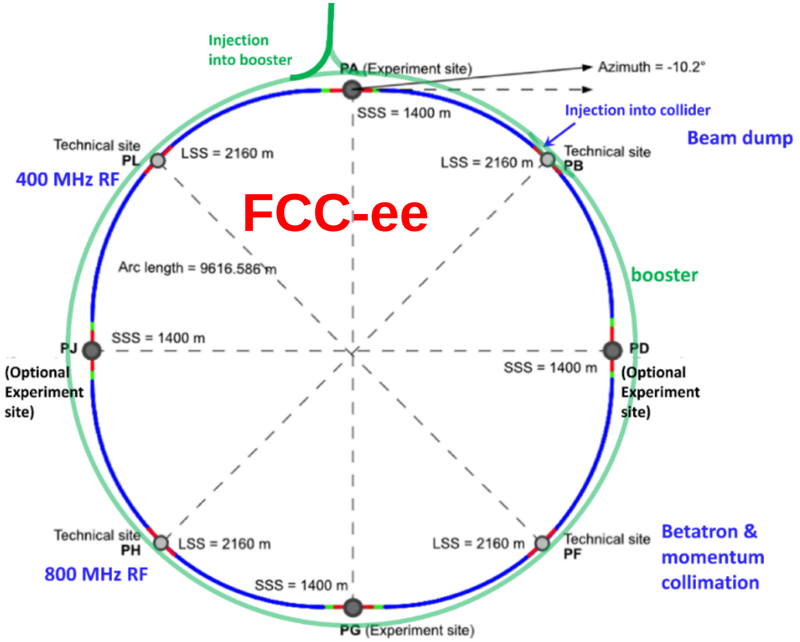
- **FCC Feasibility Study is one of the main recommendations of the 2020 update of the European Strategy for Particle Physics**

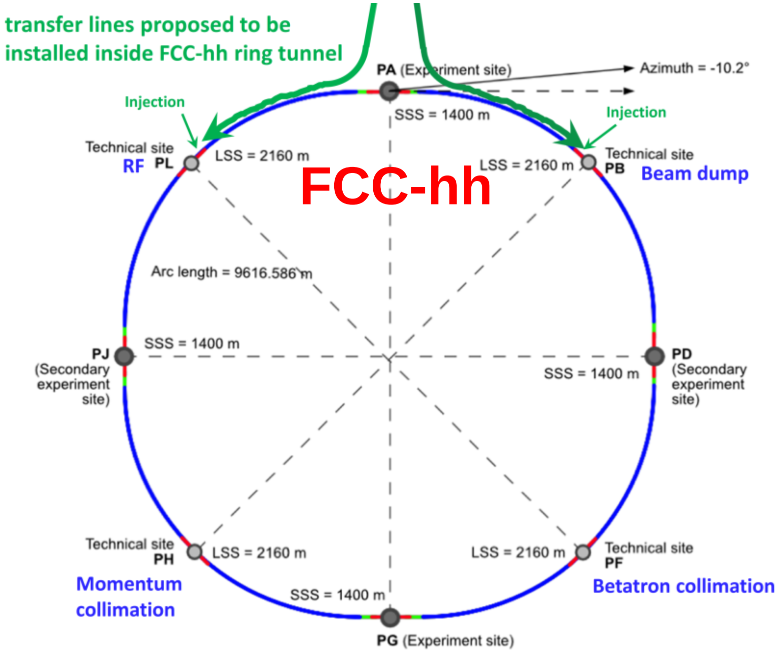
FCC integrated program
inspired by successful LEP – LHC programs at CERN

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

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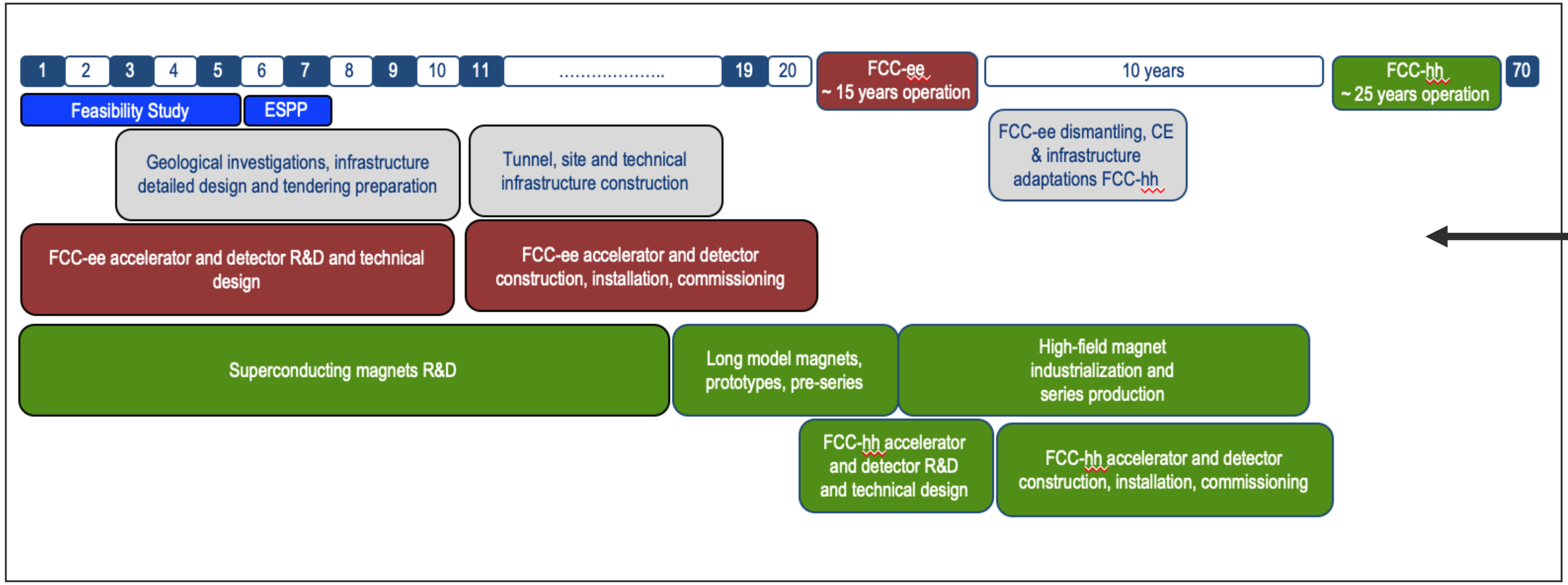
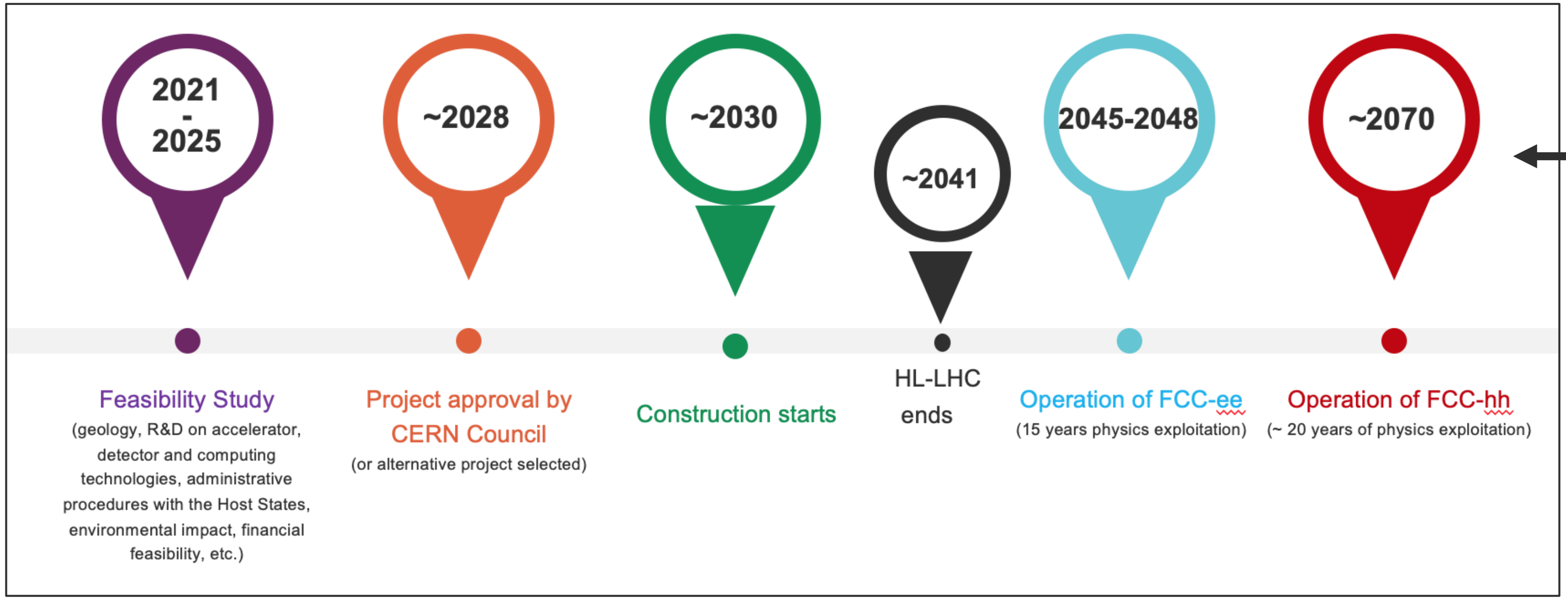
FCC timeline



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

Technical schedule:
FCC-ee could start operation **in 2040 or earlier**



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)

F. Gianotti

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

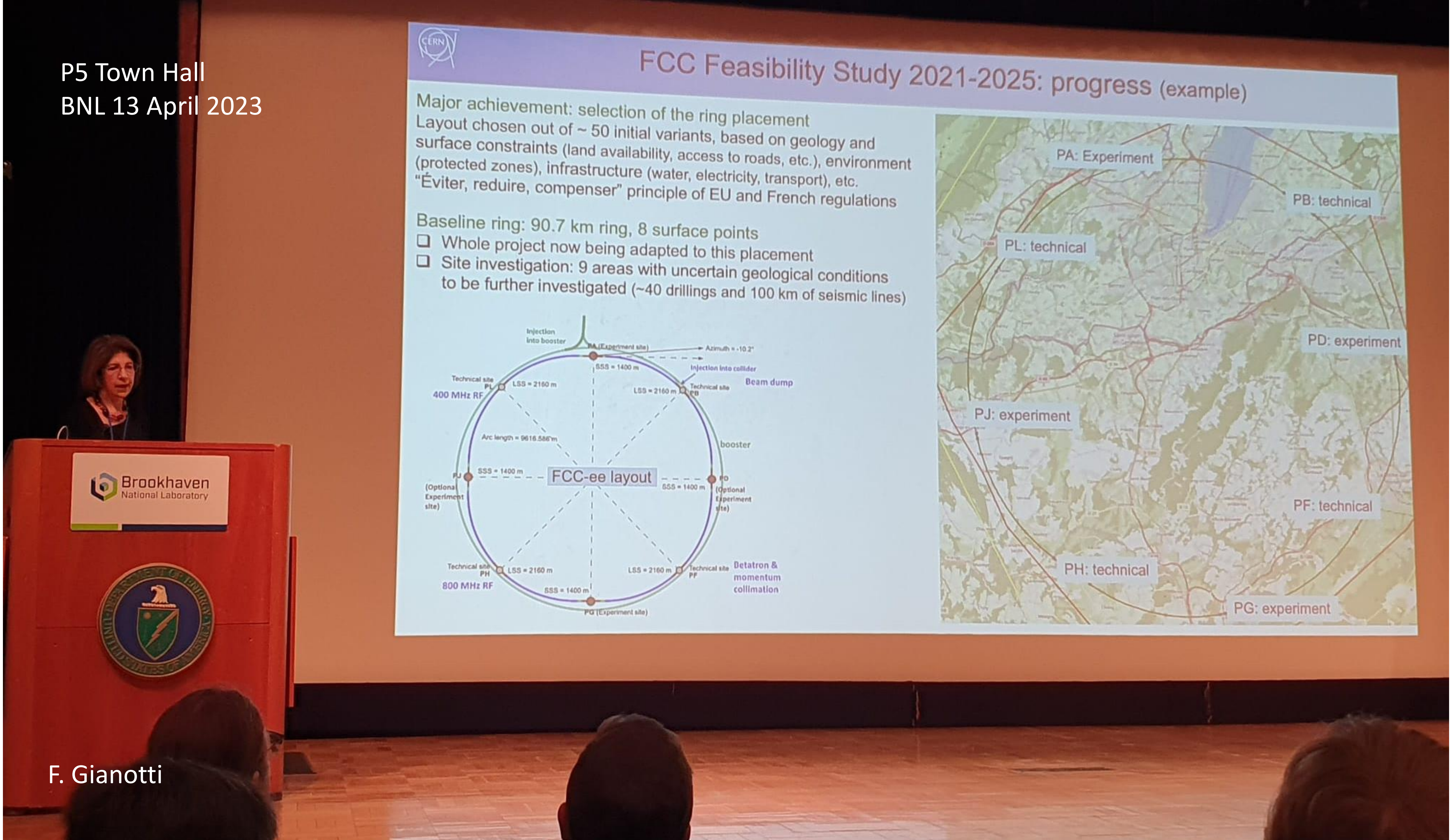
- Demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure
- Pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval
- Optimisation of the design of FCC-ee and FCC-hh colliders and their injector chains, supported by R&D to develop the needed key technologies
- Elaboration of a sustainable operational model for the machine 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 (emphasis on FCC-ee)
- Identification of substantial resources from outside CERN's budget for the implementation of first stage project (tunnel and FCC-ee)
- Consolidation of the physics case and detector concepts and technologies

Feasibility Study funded from CERN budget (~ **35 MCHF/year** over 5 years, including high-field magnet R&D).
Additional funding from the European Commission and collaborating institutes (e.g. CHART collaboration with Switzerland)

Mid-term review end of 2023 → final results in Feasibility Study Report by end of 2025

F. Gianotti

P5 Town Hall
BNL 13 April 2023



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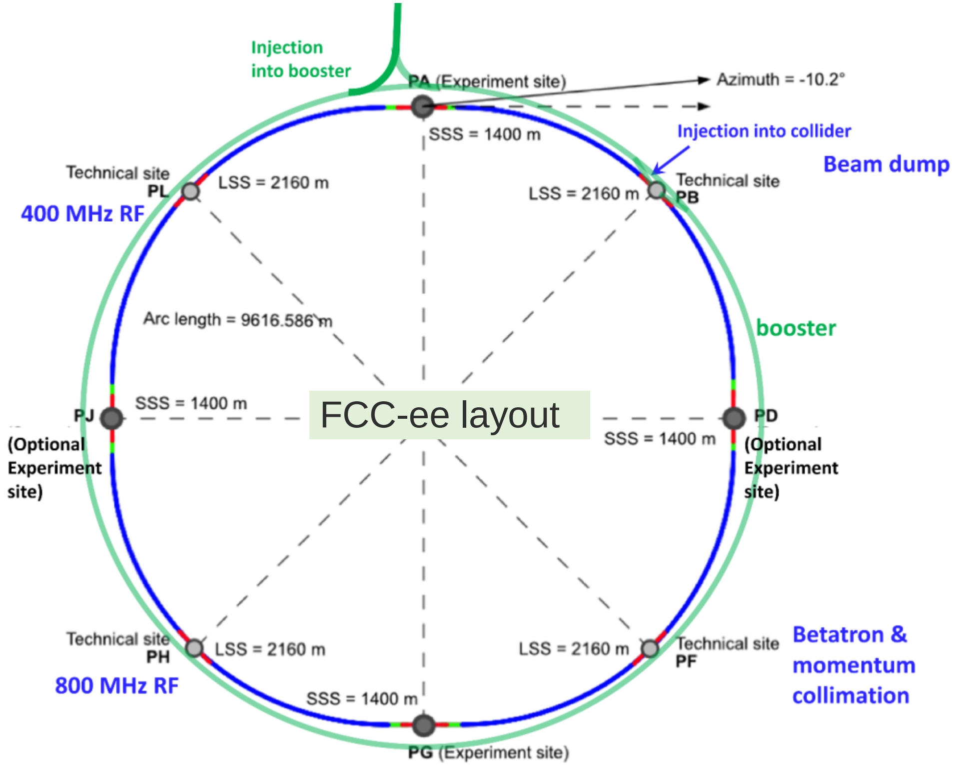
optimized placement and layout

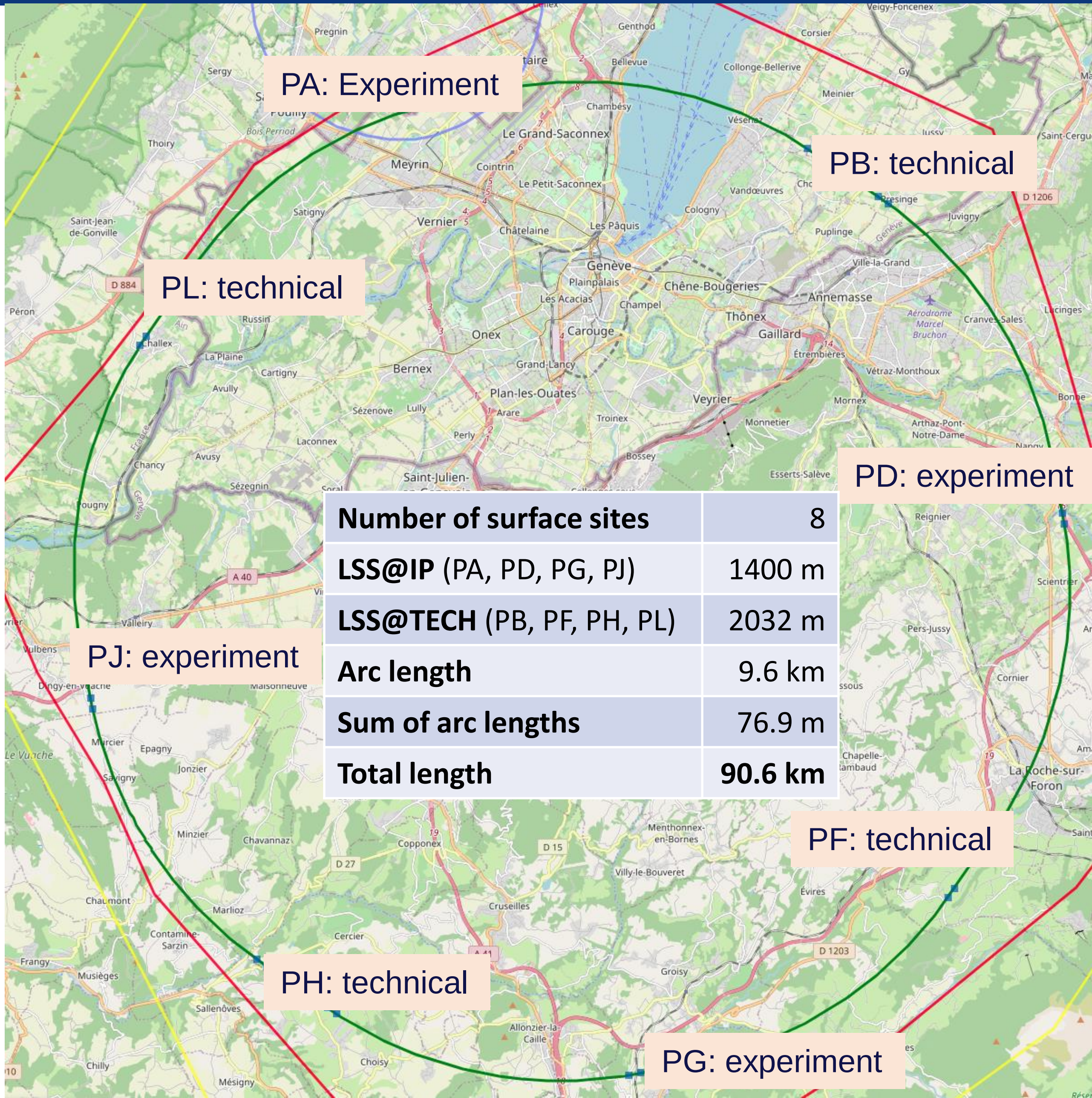
Major achievement: optimization of the ring placement

Layout chosen out of ~ 50 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), etc.
“Éviter, reduire, compenser” principle of EU and French regulations

Baseline ring: 90.7 km ring, 8 surface points

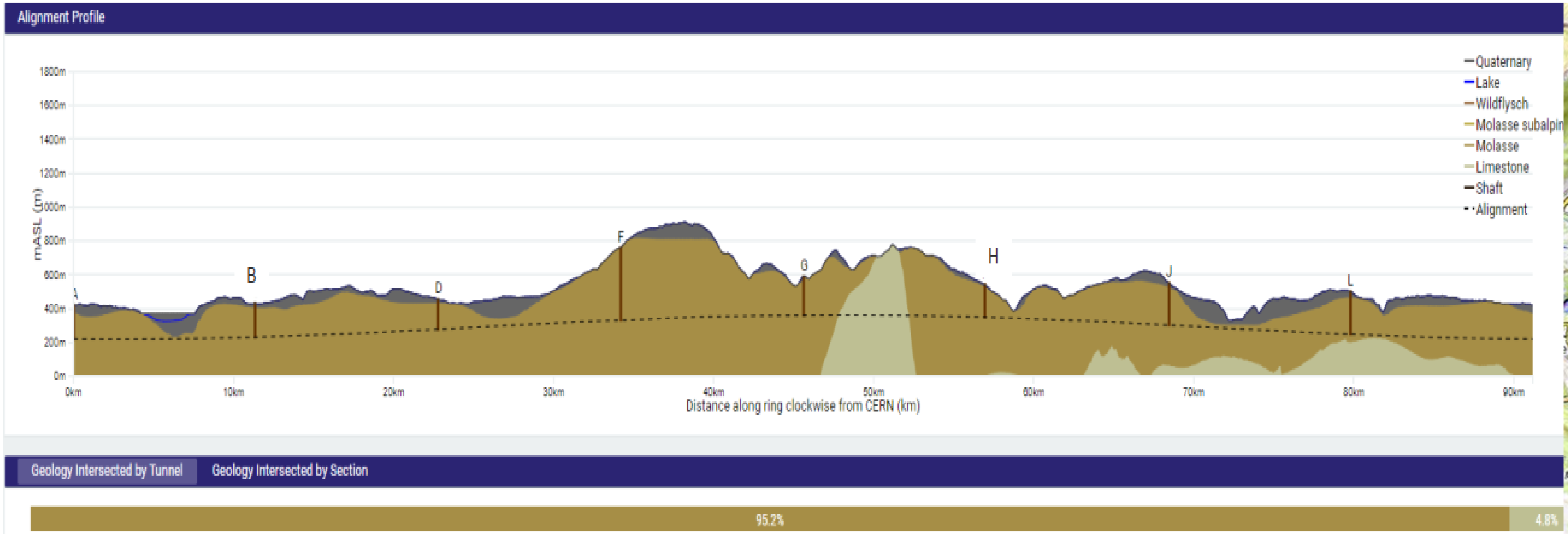
- ❑ Whole project now being adapted to this placement
- ❑ Site investigation: 9 areas with uncertain geological conditions to be further investigated (~40 drillings and 100 km of seismic lines)

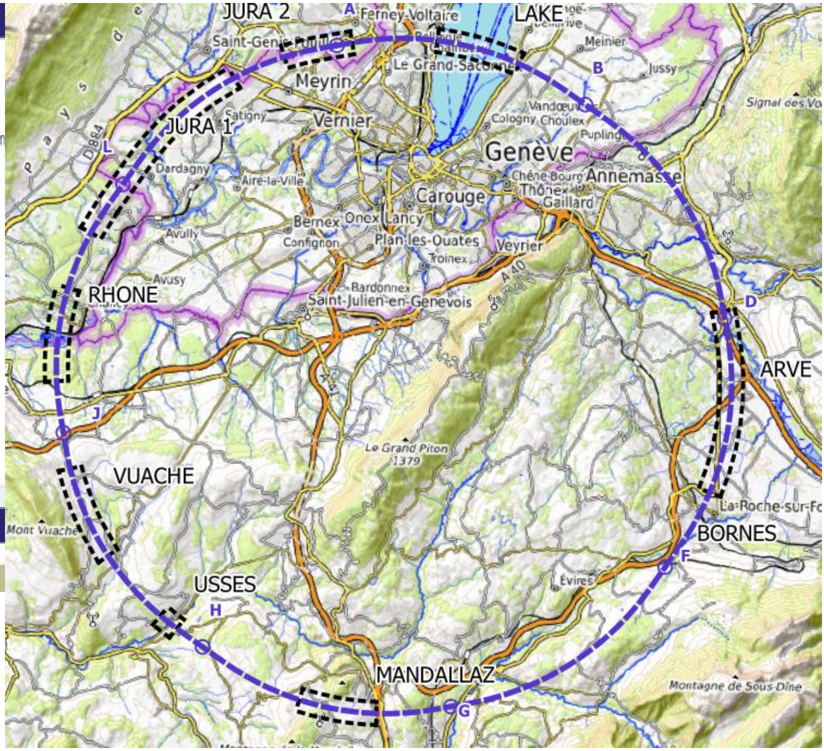




Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.6 km**

FCC implementation - footprint baseline





present baseline implementation

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

site investigations planned for 2024 and 2025 in areas with uncertain geological conditions:

- Limestone-molasse border, karstification, water pressure, moraine properties, water bearing layers, etc.
- ~40-50 drillings, 100 km of seismic lines

Implementation baseline PA31-3.0 91 km

1. **PA – Ferney Voltaire** (FR) – experimental site
2. **PB – Présinge/Choulex** (CH) – technical site
3. **PD – Nangy** (FR) – technical/experimental site
4. **PF – Etaux** (FR) – technical site
5. **PG – Charvonnex/Groisy** (FR) – experimental site
6. **PH – Cercier** (FR) – technical site
7. **PJ – Vulbens/Dingy en Vuache** (FR)

   – technical/experimental site

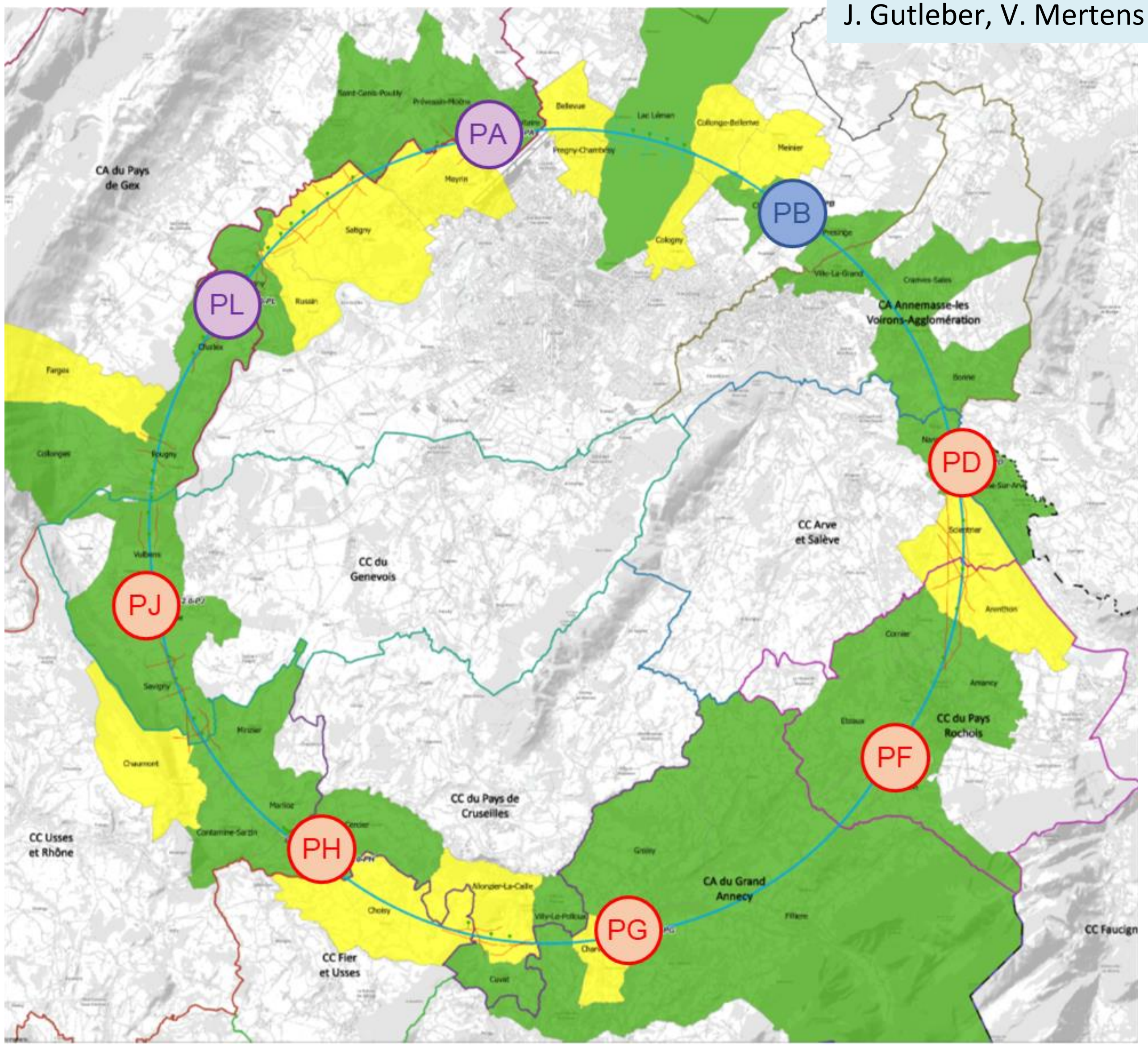
8. **PL – Challex** (FR) – technical site

First meetings with communes concerned in France (31) and Switzerland (10)

Rencontrée

Rendez-vous proposé / programmé

J. Gutleber, V. Mertens



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regional activities from 2023 – 2025

Environmental studies

Techniques classiques de mesures avec des photographies, des inventaires de la faune et de la flore, des analyses de l'eau, de l'air, du trafic routier ainsi que de la pollution sonore et lumineuse existante.

Opportunities for co-construction

Identification des opportunités et synergies Optimiser les emplacements des sites en surface, identifier des opportunités et synergies en vue de créer des retombées pour tous.

Geotechnical investigations

Techniques acoustiques de cartographie du sous-sol au moyen de camions-vibreurs et équipements similaires. Elles permettent d'obtenir une image des couches géologiques sans nécessiter de forages.

Geophysical investigations

Forages exploratoires de petite taille et de courte durée lorsque des données précises devront être relevées sur la stabilité des sols, dans des zones qui représentent des défis particuliers pour l'ouvrage souterrain.

Stage 1: FCC-ee – highest luminosity lepton collider

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Innovation Study

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

2 or 4 interaction points

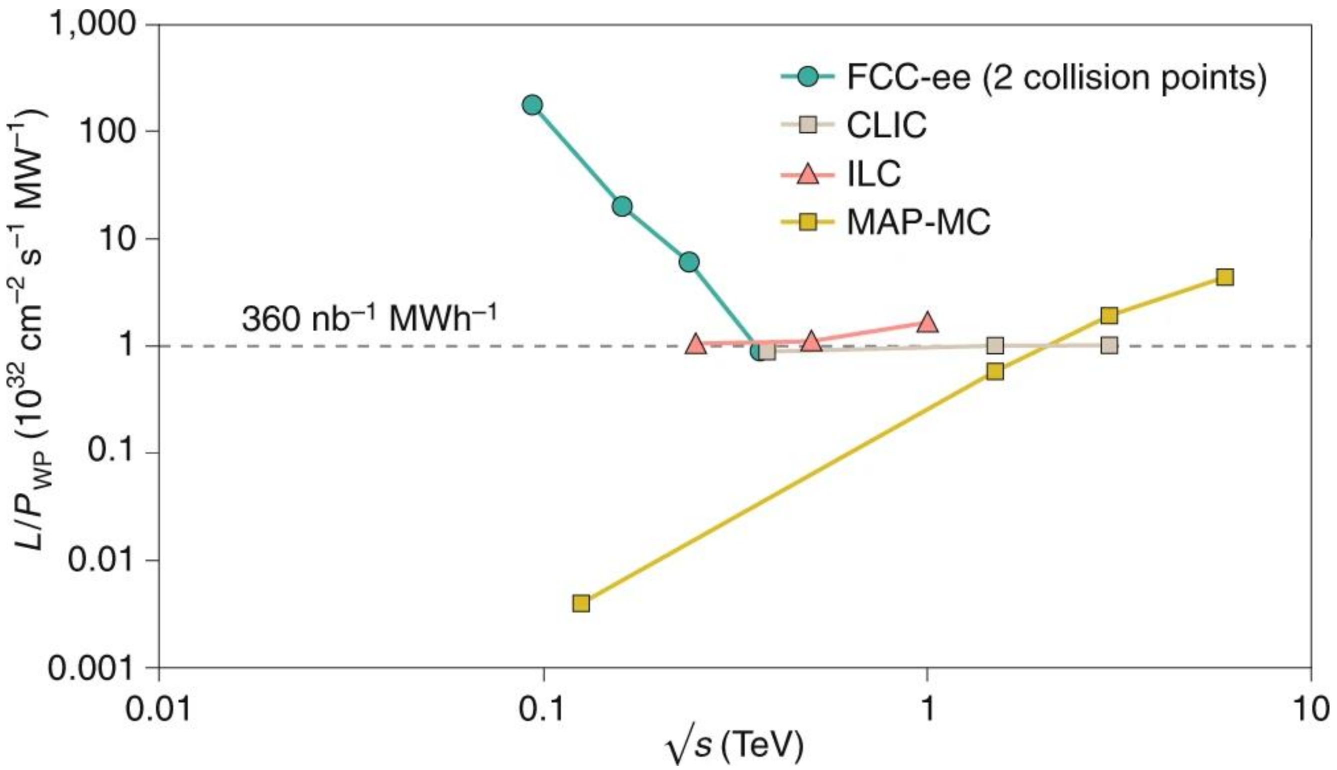
efficient $\mathcal{L}$ from Z to $t\bar{t}$

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

>2.5 ab^{-1} with ~0.5×10^6 H / IP (3y)

>75 ab^{-1} with ~2×10^{12} Z / IP (4y)

luminosity vs. electricity consumption



enormous performance increase: collects LEP data statistics in few minutes

highest lumi/power of all *H* fact. proposals

Nature Physics 16, 402–407 (2020)

FCC-ee: main machine parameters

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F. Gianotti

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

- x 10-50 improvements on all EW observables
- x10 Belle II statistics for b, c, τ
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- 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

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Recently updated

FCC-ee RF parameter table

Number of 800 MHz cavities: 1088
Total number of cavities: 1460

F. Peauger

	Bare cavity in vertical test stand		Jacketed cav w HOM in vert test		Cryomodule (with FPC) in hor. test		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
1-cell 400 MHz	6.9	3.3E+09	6.6	3.15E+09	6.3	3.0E+09	5.7	2.7E+09
2-cell 400 MHz	13.2	3.3E+09	12.6	3.15E+09	12	3.0E+09	10.8	2.7E+09
5-cell 800 MHz	24.5	3.8E+10	23.3	3.64E+10	22.2	3.5E+10	20.0	3.0E+10

15-Feb-23	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	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]	5.72	5.34	10.95	20.01	10.78	20.01	10.78	20.12	20.10
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.00	8.20	18.75	8.08	18.75	8.08	18.85	18.83
#cells	56	140	256	280	520	560	520	2440	3000
# cavities	56	28	128	56	260	112	260	488	600
# CM	14	7	32	14	65	28	65	122	150
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	22	0.2	163	3	158	3	158	23	3
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	2.7E+05	1.1E+06	7.7E+06	1.1E+06	1.5E+07	9.4E+06	3.8E+06	8.3E+07
Detuning [kHz]	8.939	5.126	0.412	0.141	0.096	0.014	0.031	0.032	0.003
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
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		9875.14
cos phi	0.32	0.27	0.35	0.35	0.88	0.88	0.56	0.96	0.87
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

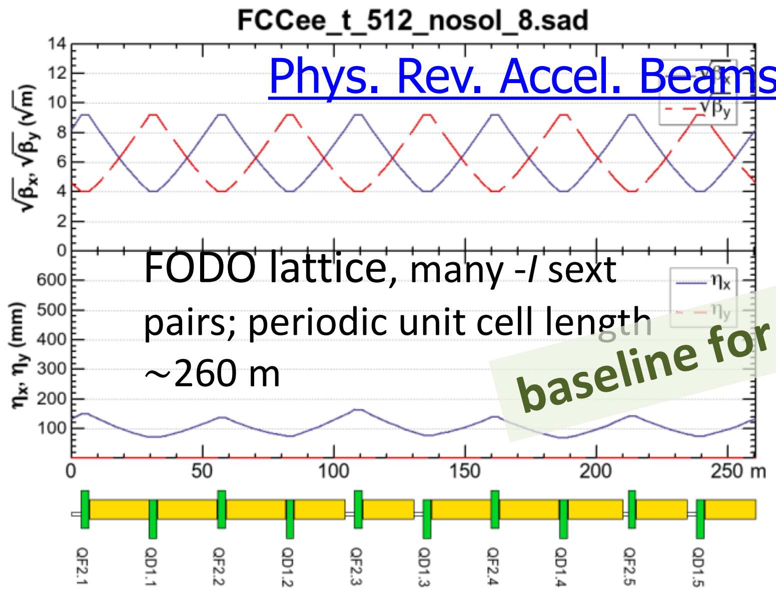
detailed specification, close to state of the art

RF source type	400 MHz - 1 MW klystron	800 MHz - 400 kW klystron	400 MHz - 1 MW klystron	800 MHz - 400 kW klystron	400 MHz - 1 MW klystron	800 MHz - 50 kW SSA	400 MHz - 50 kW SSA	800 MHz - 400 kW klystron	800 MHz - 50 kW SSA
Frequency [MHz]	400	800	400	800	400	800	400	800	800
Pcav [kW]	880	176	385	88	379	44	45	181	8
Prf conditioning [kW]	220	44	96	22	95	11	11	45	2
# cavities / RF sources	1	2	2	4	2	1	1	2	4
# RF sources	112	14	128	14	130	112	260	244	150

FCC-ee collider optics development: 2 options

Short 90/90: $t\bar{t}$, Zh

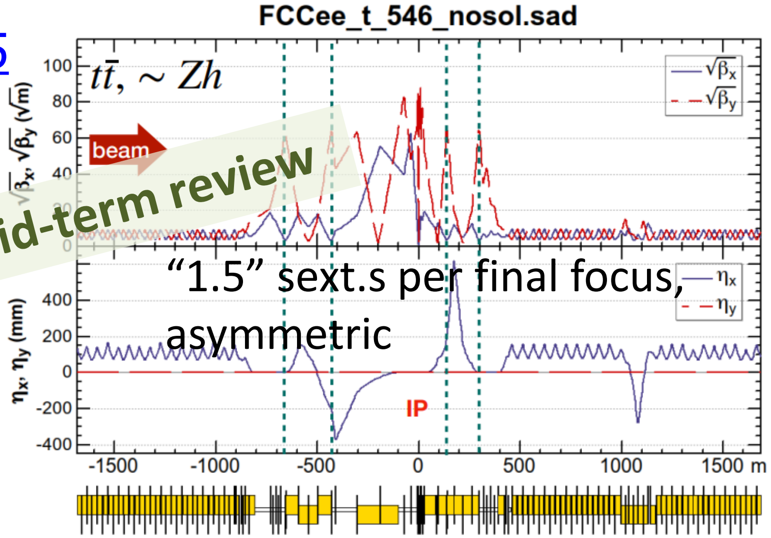
arc



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

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

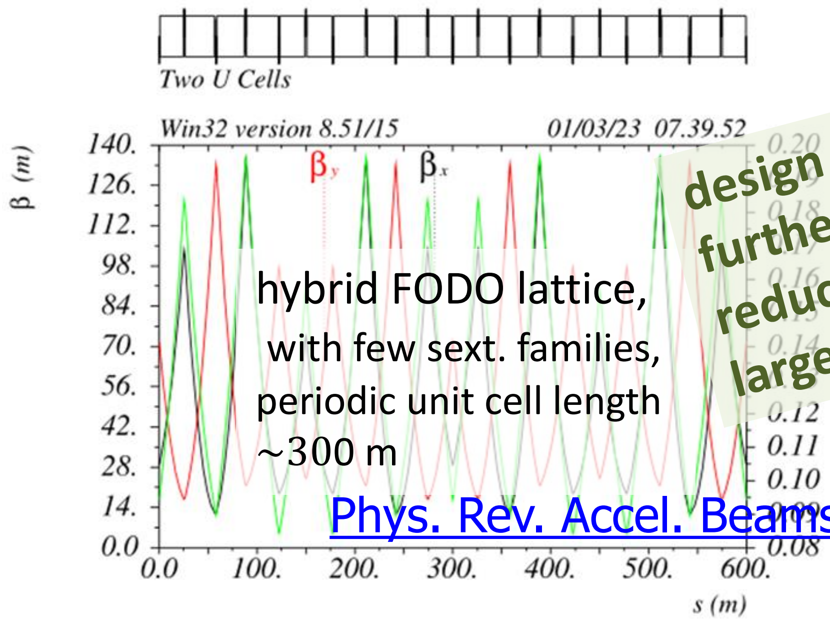
interaction region



"1.5" sext.s per final focus, asymmetric

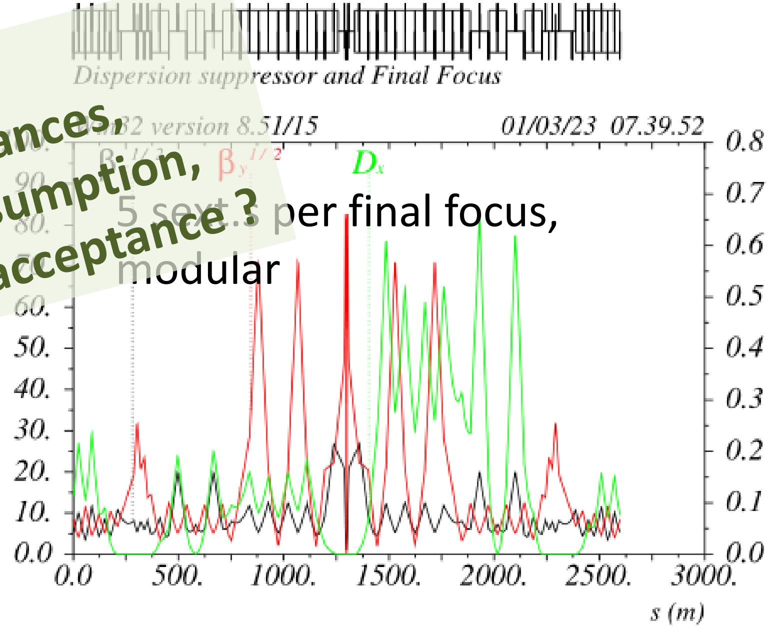
baseline for 2023 FCC mid-term review

K. Oide, 2023 EPS Rolf Wideroe award winner



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

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



5 sext.s per final focus, modular

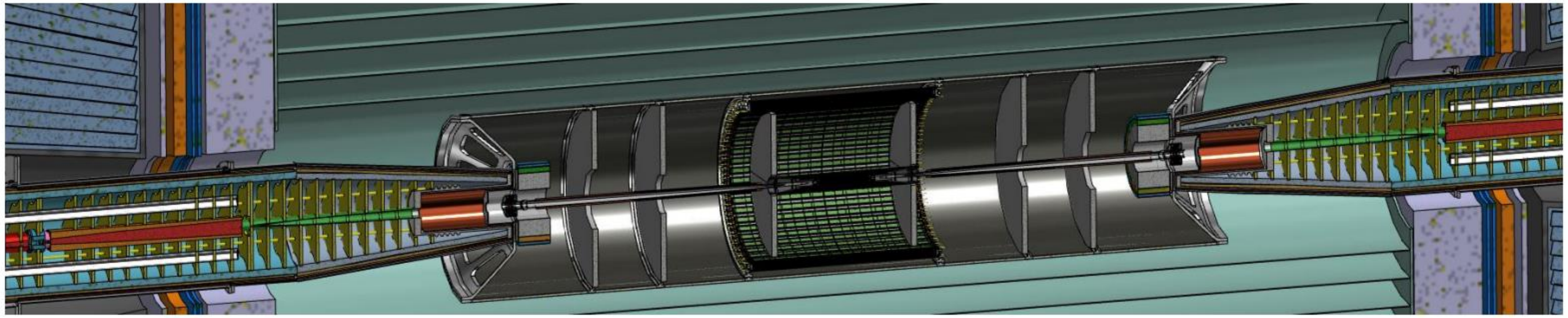
design in progress - further relaxed tolerances, reduced power consumption, larger momentum acceptance ?

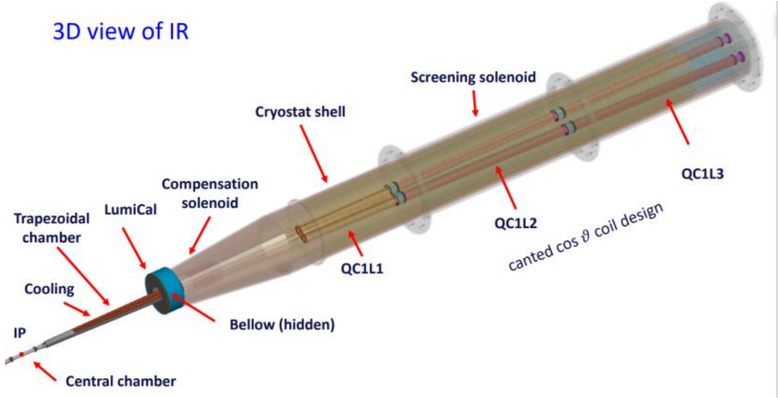
P. Raimondi, 2017 EPS Gersh Budker award winner

FCC-ee MDI developments - examples

Novel outer support tube for central beam pipe and vertex detector

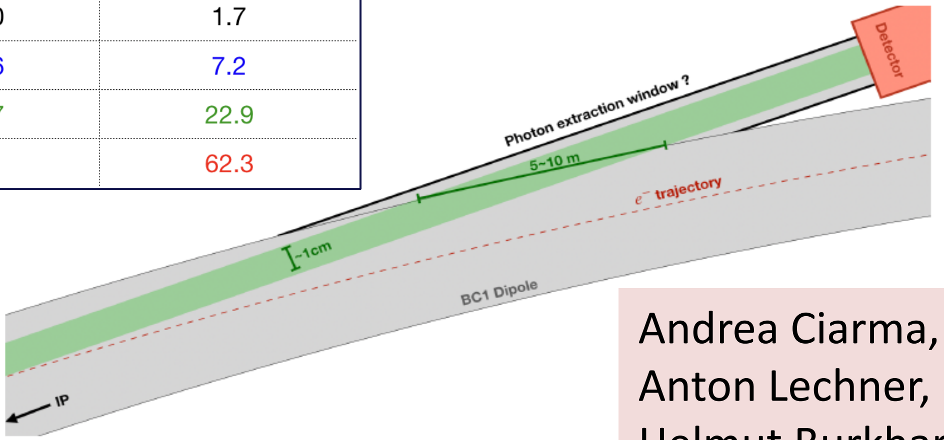
Manuela Boscolo,
Fabrizio Palla,
Filippo Bosi





- 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

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

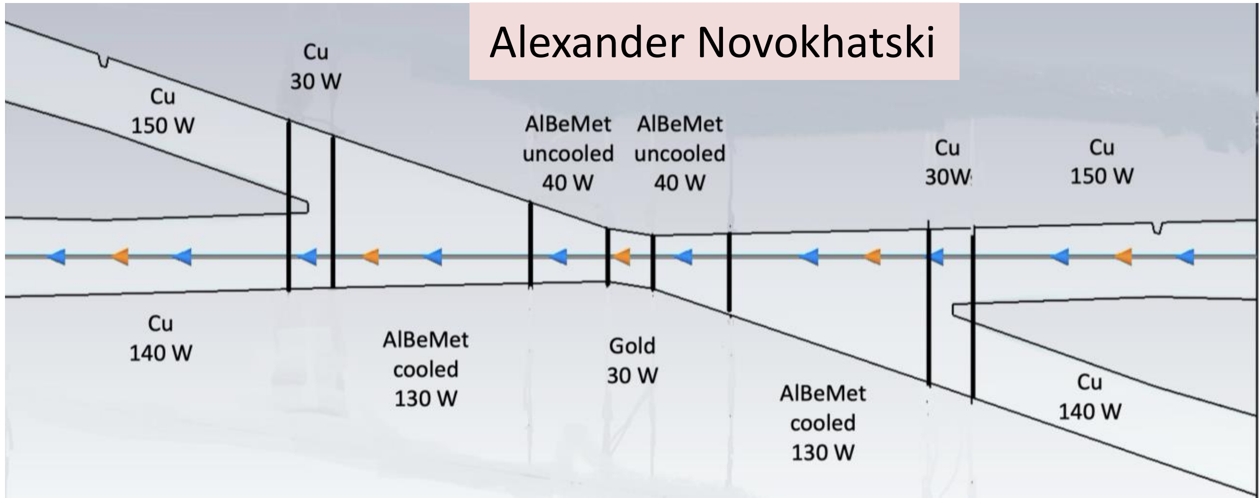


Beamstrahlung dump

Andrea Ciarma,
Anton Lechner,
Helmut Burkhardt,
Manuela Boscolo

IR heat load distribution

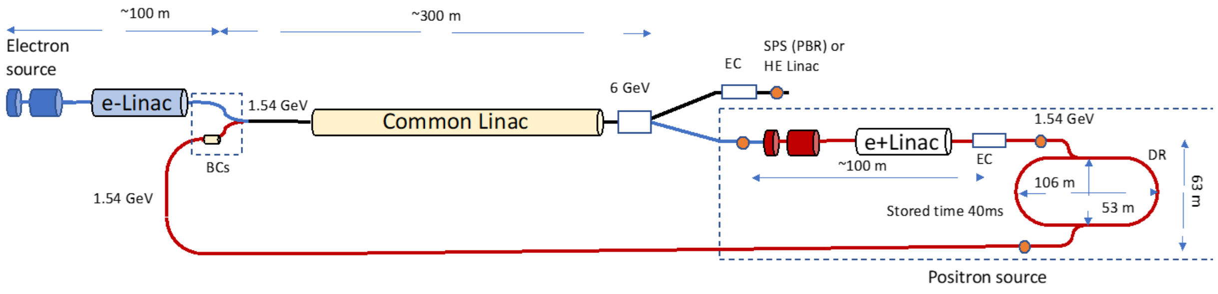
Alexander Novokhatski



FCC-ee injector design, P^3 exp., HTS solenoid

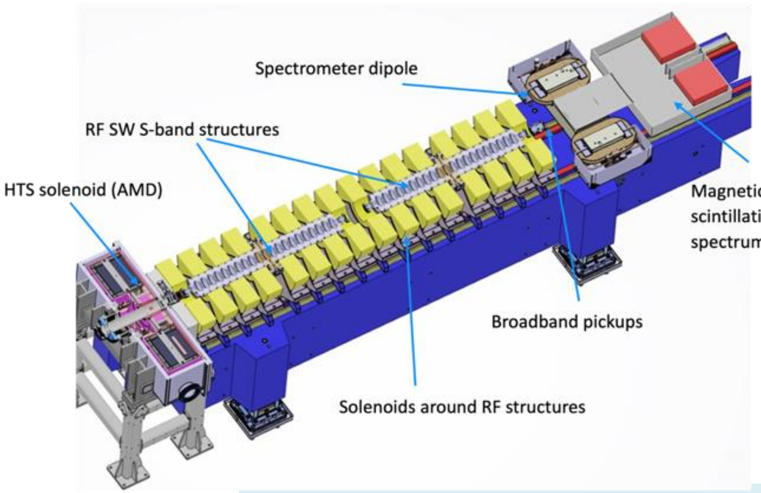
CHART collaboration PSI & CERN with partners CNRS-IJCLab (Orsay), INFN-LNF (Frascati), KEK/SuperKEKB as observer, INFN-Ferrara – radiation from crystal, CEA (FCCIS – booster design)

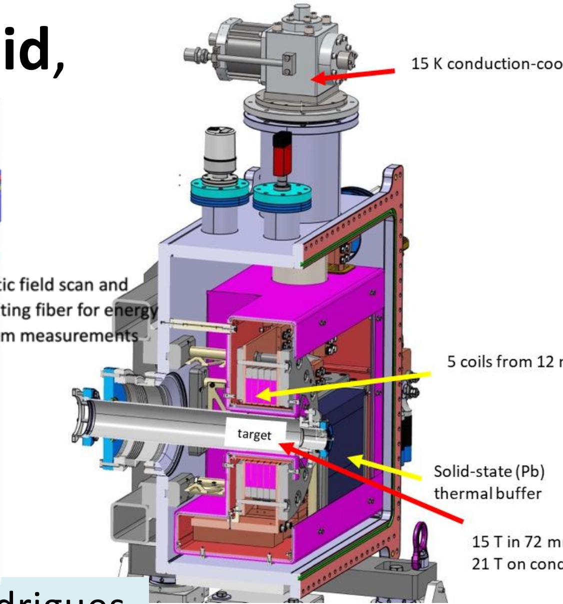
FCC-ee pre-injector layout



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

HTS NI target solenoid,



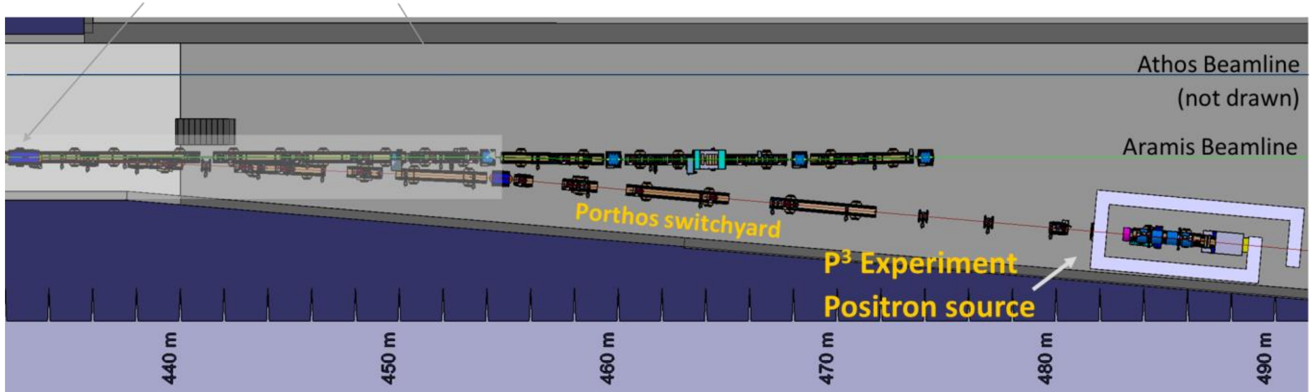


J. Kosse, T. Michlmayr, H. Rodrigues

Goal: demonstrate high-yield positron source concept

Manufacturing Q3’23-Q2’24;

“P^3 Experiment” at PSI’s SwissFEL 2026



FCC-ee accelerator R&D examples

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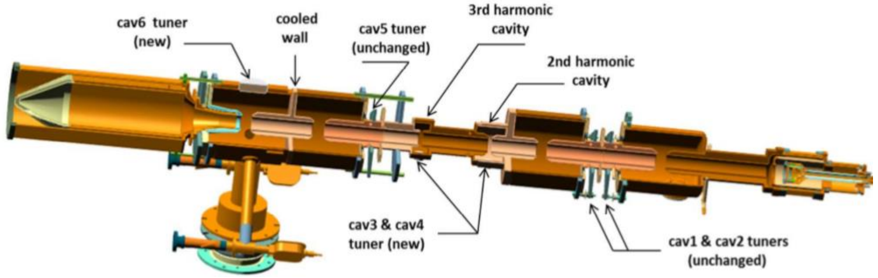
efficient RF power sources (400 & 800 MHz)

I. Syratchev



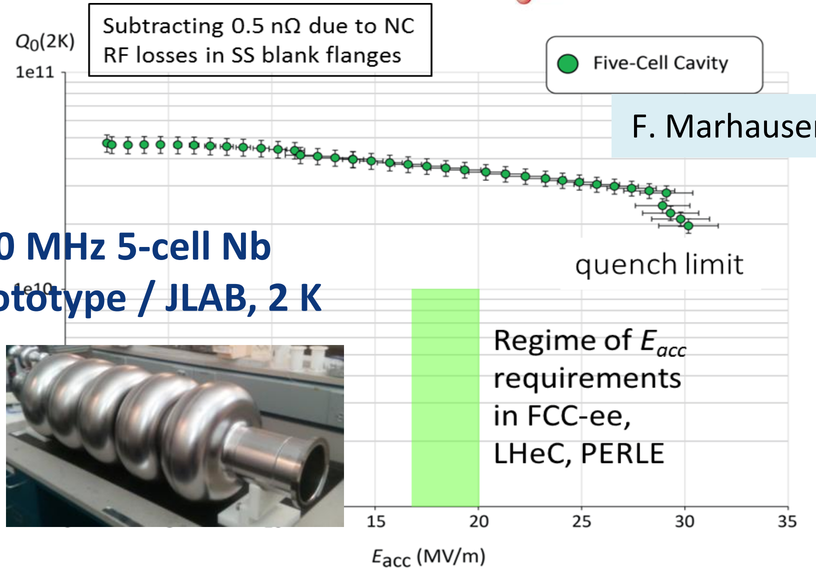
FPC & HOM coupler, cryomodule, thin-film coatings…

efficient SC cavities

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

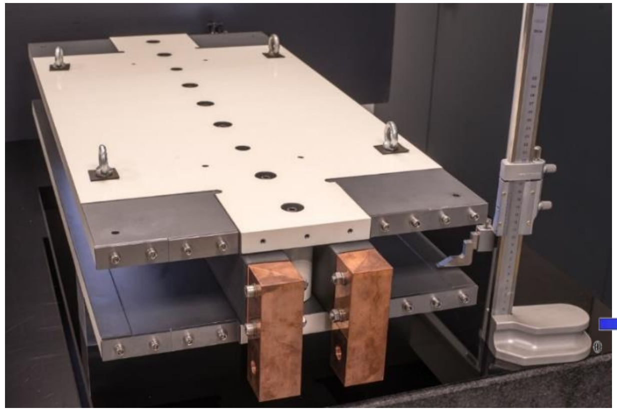
Jefferson Lab

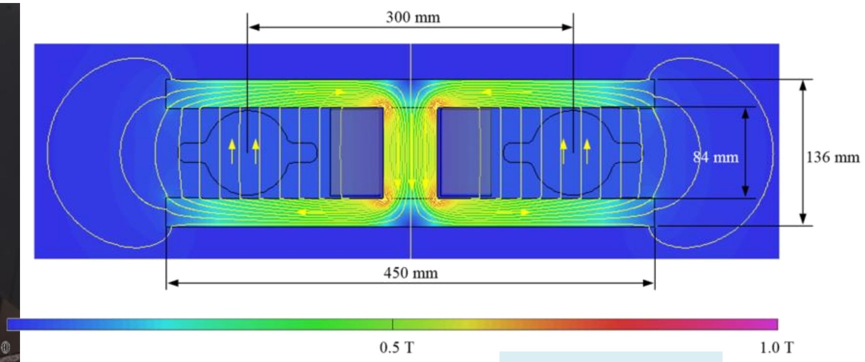
800 MHz 5-cell Nb prototype / JLAB, 2 K



F. Marhauser

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



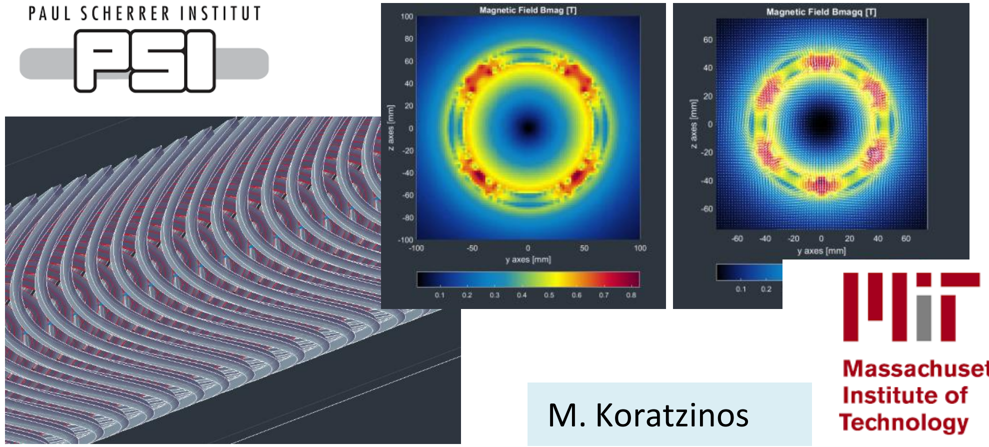


A. Milanese

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

- **Reduce energy consumption** by O(50 MW)

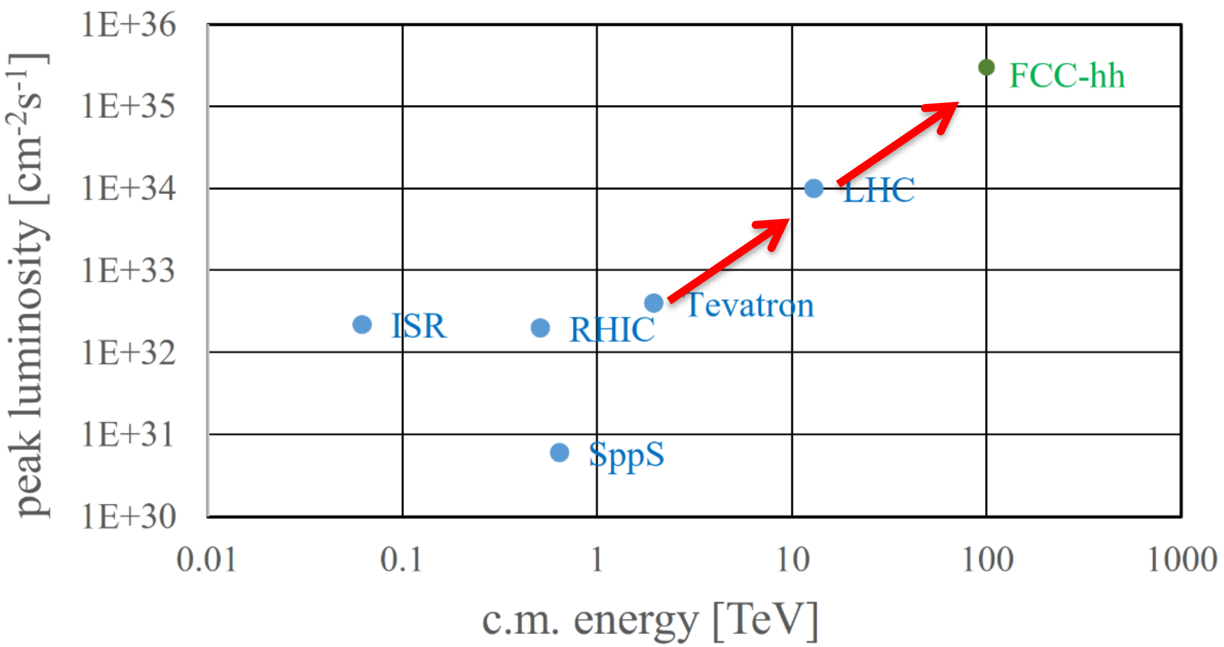
PAUL SCHERRER INSTITUT PSI



Massachusetts Institute of Technology

M. Koratzinos

Stage 2: FCC-hh: highest collision energies



~order of magnitude performance increase in both energy & luminosity wrt LHC

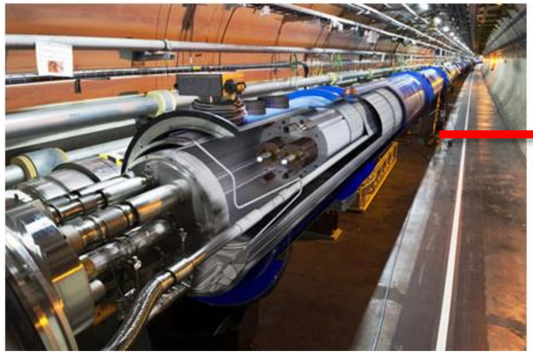
~100 TeV cm collision energy (vs 14 TeV for LHC)

20 ab^{-1} per experiment over 25 years of operation (vs 3 ab^{-1} for LHC)

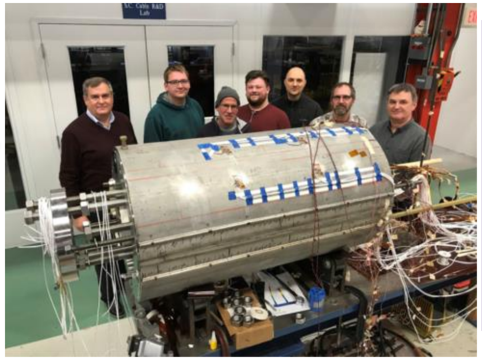
similar performance increase as from Tevatron to LHC

key technology: high-field magnets

from
LHC technology
8.3 T NbTi dipole



via
HL-LHC technology
12 T Nb_3Sn quadrupole



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

HTS technology

Hybrid Nb-Ti/HTS

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FCC-hh: main machine parameters

F. Gianotti

Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

Formidable challenges:

- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 5 MW → cryogenics, vacuum
- ❑ stored beam energy: 8 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

HFM: preparing for FCC stage 2 (FCC-hh)

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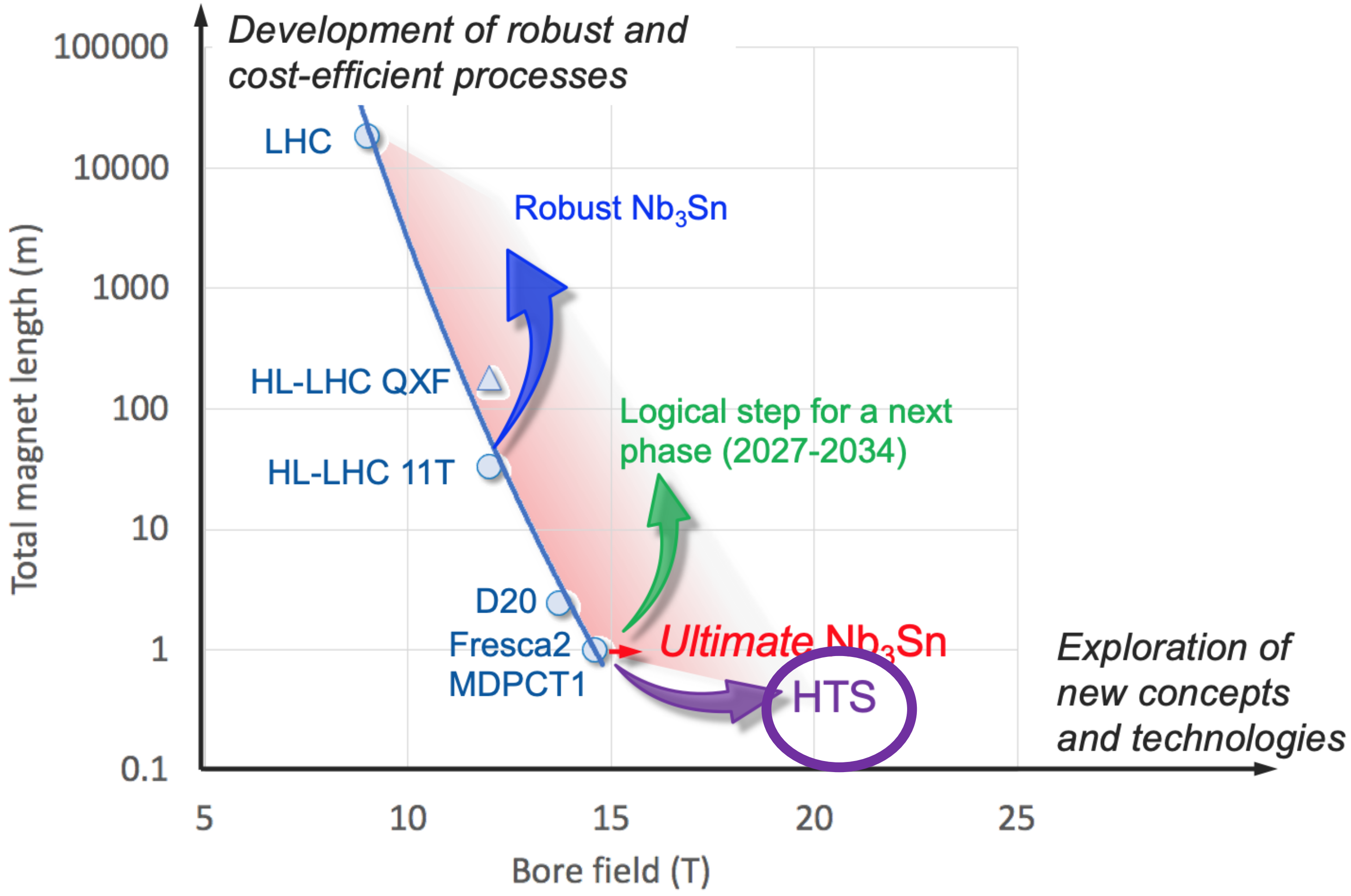
In parallel to FCC studies, High Field Magnet development program as long-term separate R&D project



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

US Electron Ion Collider (EIC)

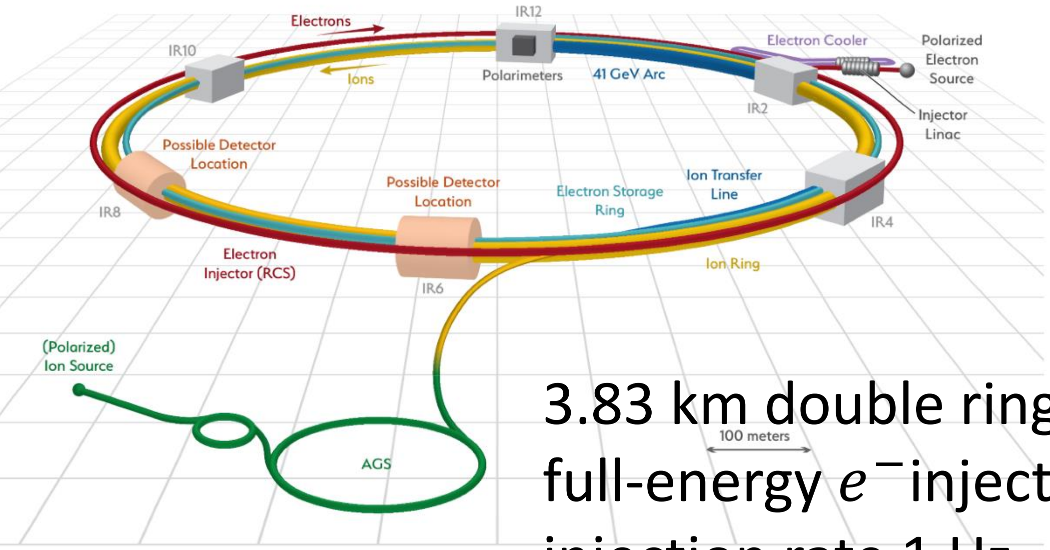
US EIC Electron Storage Ring similar to, but more challenging than, FCC-ee

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**, still evolving

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

The EIC will provide another invaluable opportunity to train 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)**

Mid-Term Review & Cost Review, autumn ‘23

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

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

Infrastructure & placement

- Preferred placement and progress with host states (territorial matters, initial states, dialogue, etc.)
- Updated civil engineering design (layout, cost, excavation)
- Preparations for site investigations

Technical Infrastructure

- Requirements on large technical infrastructure systems
- System designs, layouts, resource needs, cost estimates

Accelerator design FCC-ee and FCC-hh

- FCC-ee overall layout with injector
- Impact of operation sequence: Z, W, ZH, $t\bar{t}$ vs start at ZH
- Comparison of the SPS as pre-booster with a 10-20 GeV linac
- Key technologies and status of technology R&D program
- FCC-hh overall layout & injection lines from LHC and SC-SPS

Physics, experiments, detectors:

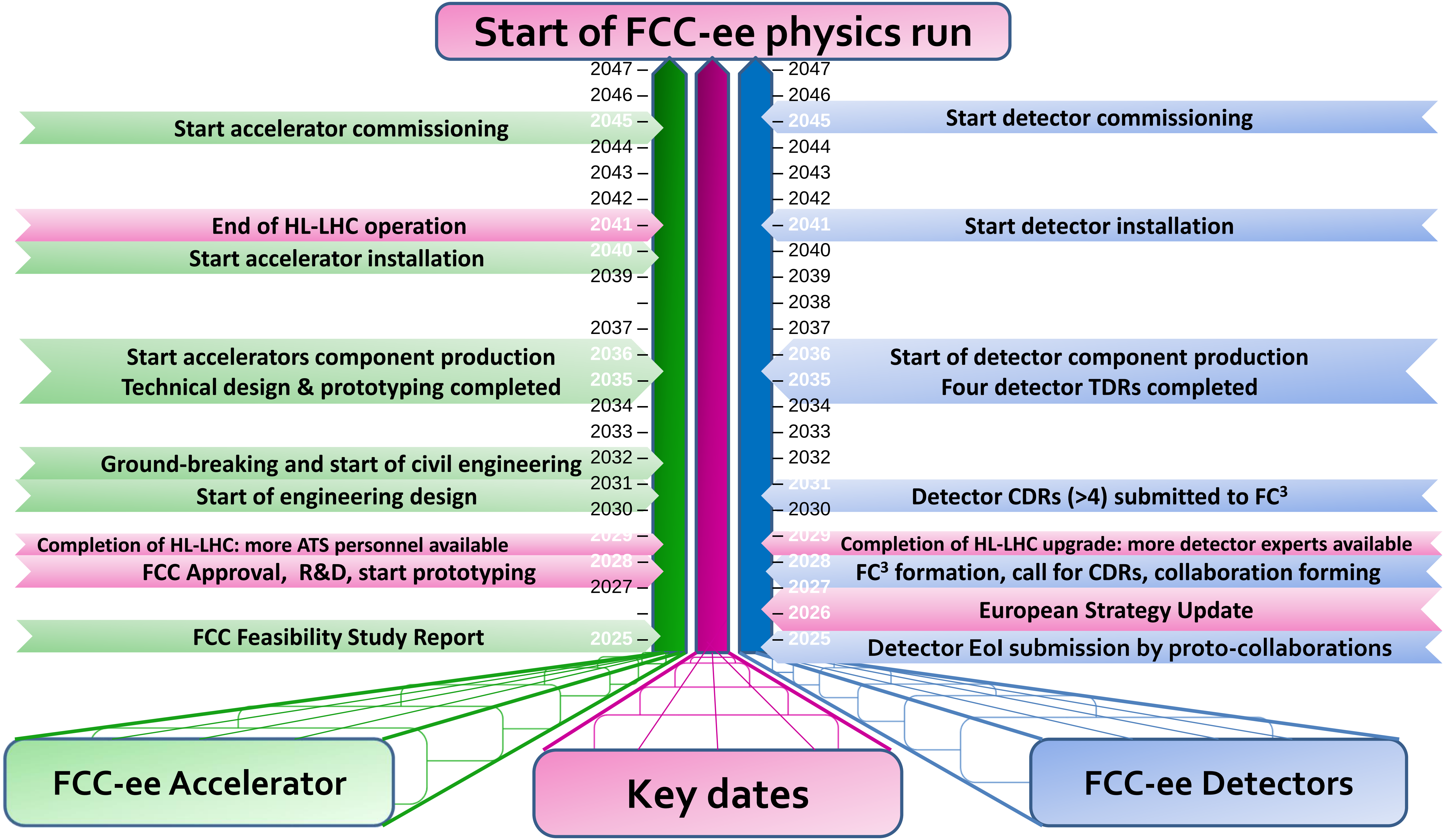
- Documentation of FCC-ee and FCC-hh physics cases
- Plans for improved theoretical calculations to reduce theoretical uncertainties towards matching FCC-ee statistical precision for the most important measurements.
- First documentation of main detector requirements to fully exploit the FCC-ee physics opportunities

Organisation and financing:

- Overall cost estimate & spending profile for stage 1 project

Environmental impact, socio-economic impact:

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


Start of FCC-ee physics run
Start accelerator commissioning
End of HL-LHC operation
Start accelerator installation
Start accelerators component production
Technical design & prototyping completed
Ground-breaking and start of civil engineering
Start of engineering design
Completion of HL-LHC: more ATS personnel available
FCC Approval, R&D, start prototyping
FCC Feasibility Study Report
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Start detector commissioning
Start detector installation
Start of detector component production
Four detector TDRs completed
Detector CDRs (>4) submitted to FC³
Completion of HL-LHC upgrade: more detector experts available
FC³ formation, call for CDRs, collaboration forming
European Strategy Update
Detector EoI submission by proto-collaborations
FCC-ee Accelerator
Key dates
FCC-ee Detectors

FCC FS status summary

Following 2020 European Strategy Update, **the FCC Feasibility Study (FCC FS) was launched in 2021 with full support from CERN Council.**

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

Next milestone is the mid-term review, autumn 2023.

US contributions are essential to advance with the study and prepare towards a future project.

Many areas for collaborations on the accelerator side: **SRF&cryo&powering, beam instrumentation, energy efficient collider and booster magnet systems, MDI including magnet system, beam optics and beam dynamics, injector linac, ... for FCC-ee, and high-field SC magnets (HTS, LTS/Hybrid) towards FCC-hh.**

FCC Week 2023

FUTURE CIRCULAR COLLIDER

Future Circular Collider (FCC) Week 2023, at the **Millennium Conference Centre in London**, United Kingdom from **Monday 5 June to Friday 9 June 2023**.

- Organised with the **support** of the UK Research and Innovation Science and Technologies Facilities Council (STFC) and the EU-funded Horizon 2020 FCCIS project
- **Local partners** : STFC, the University of Cambridge, Imperial College London, King's College London, the University of Manchester, the University of Oxford, Queen Mary University of London, Royal Holloway University of London and University College London

Registration is open !

https://cern.ch/fccweek2023

We look forward to welcoming you to London for what promises to be an exciting and informative event!

thank you ! merci !