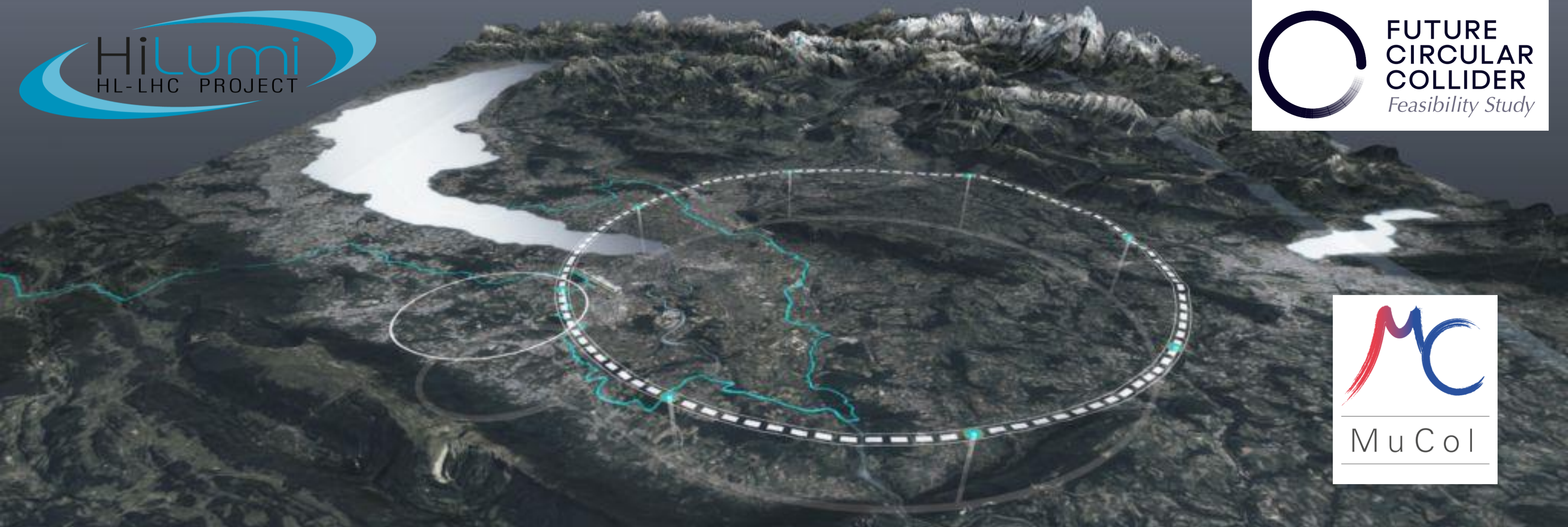
Future Particle Colliders



Event for Early Career Researchers in Particle Physics in Austria, HEPHY, Vienna, 23 May 2024

Alexander Huschauer, with input from M. Benedikt, O. Brüning, D. Schulte, F. Zimmermann, M. Zerlauth
and on behalf of the HL-LHC, FCC and MC communities

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

HiLumi
HL-LHC PROJECT

FCC-ee

FCC-hh

FUTURE CIRCULAR COLLIDER
Feasibility Study

*“The successful completion of the high-luminosity upgrade of the machine and detectors should remain the **focal point of European particle physics**, together with continued innovation in experimental techniques.”*

*“The full physics potential of the **LHC and the HL-LHC**, including the study of flavour physics and the quark-gluon plasma, should be exploited.”*

*“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**.”*

*“Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be **completed on the timescale of the next Strategy update**.”*

Source: https://cds.cern.ch/record/2721370

The Future of US Particle Physics

The Energy Frontier Report

2021 US Community Study
on the Future of Particle Physics

Snowmass 2021, https://inspirehep.net/literature/2514310:

“Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.”

Particle Physics Project Prioritization Panel (P5), 2023,
https://www.usparticlephysics.org/2023-p5-report/index.html:

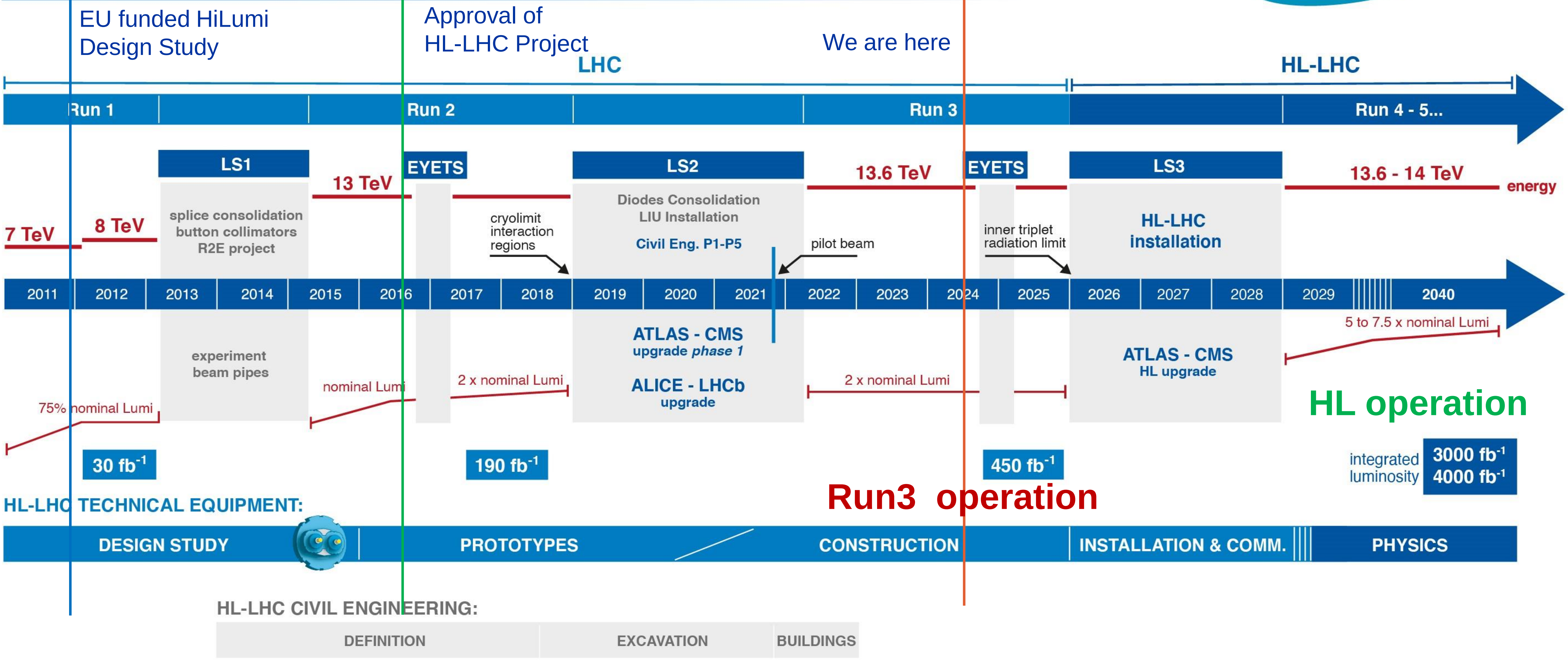
“We advocate substantial US participation in the design and construction of accelerators and detectors for an offshore facility, and we advocate investment of effort to support development of the Future Circular Collider-electron (e^-) positron (e^+) (FCC-ee) and the International Linear Collider (ILC), along with a parallel and increasingly intensive program of R&D pursuing revolutionary accelerator and detector technologies.”

“In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus.”

“At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.”

HL-LHC – the immediate future

LHC / HL-LHC Plan

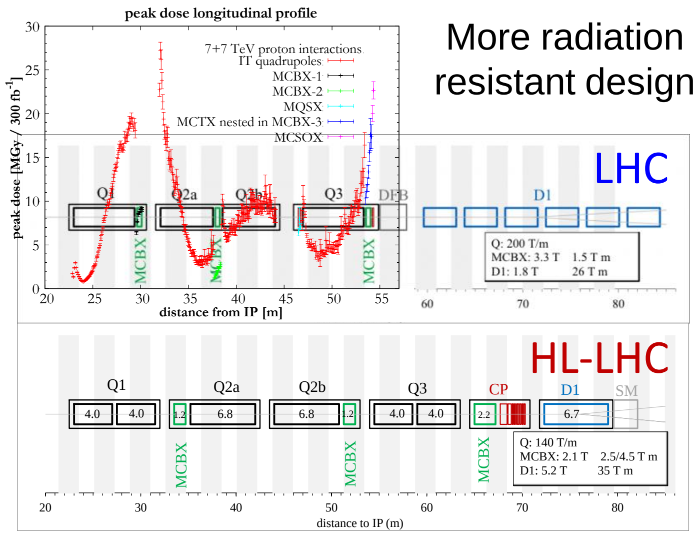


The project is ready for installation start in 2026!

Challenging and technologically intensive upgrade project

1) Upgrade of inner triplets

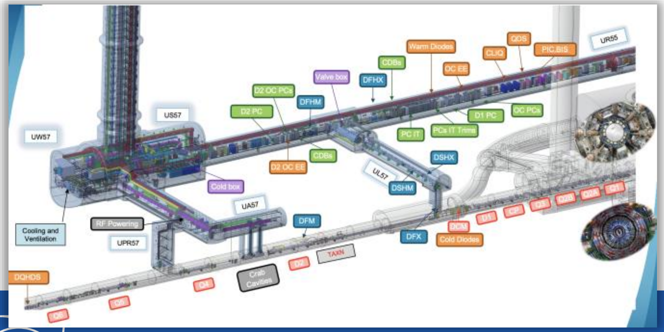
More radiation resistant design

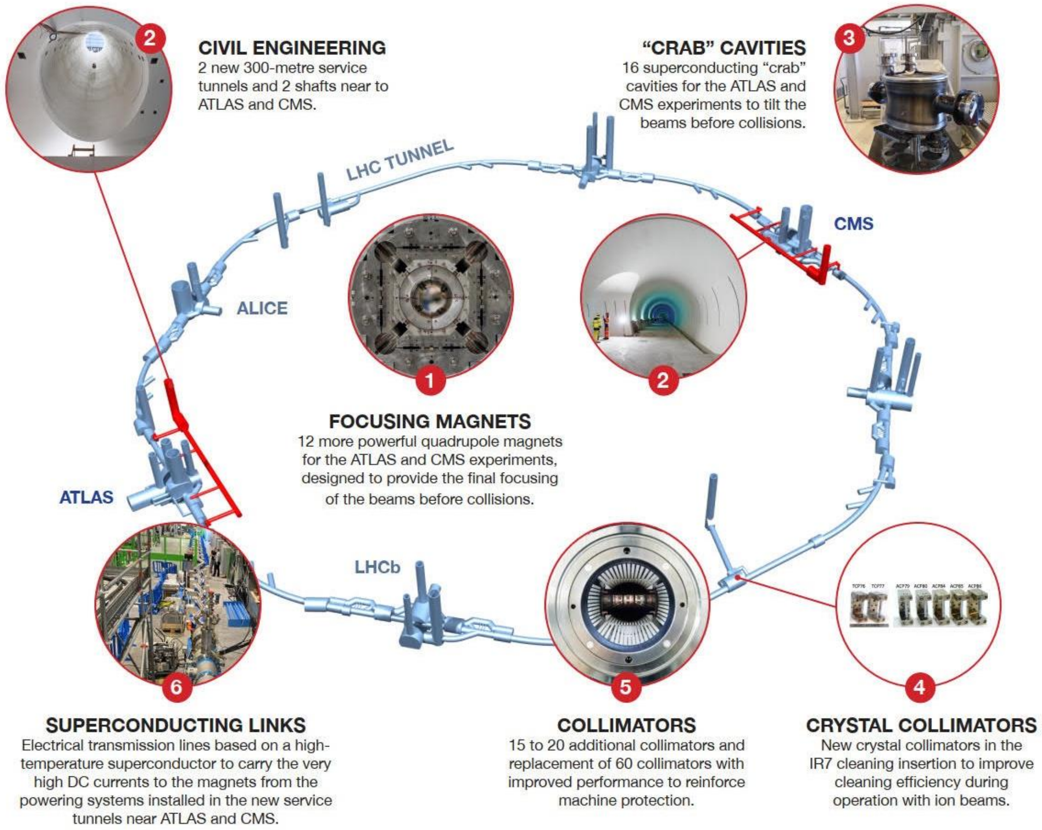


2) Civil engineering

Low R2E regions, increased accessibility

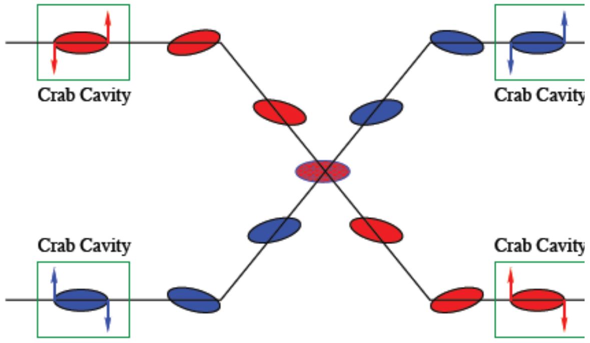
→ 100 m between converters and magnets





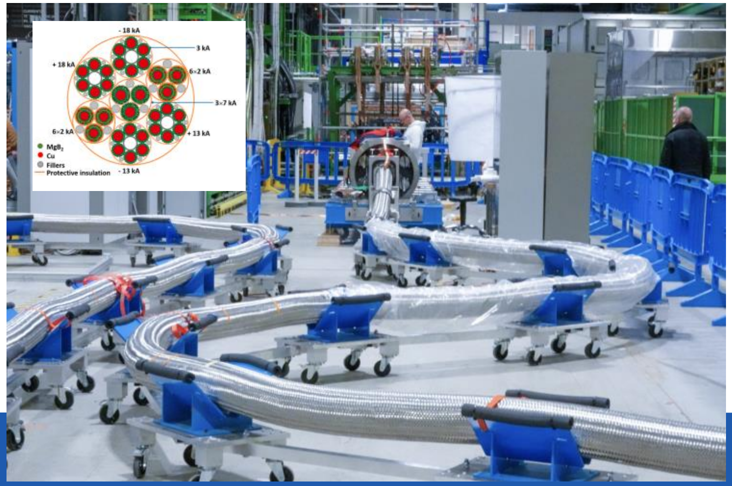
3) Crab cavities

Challenging compact cavity design

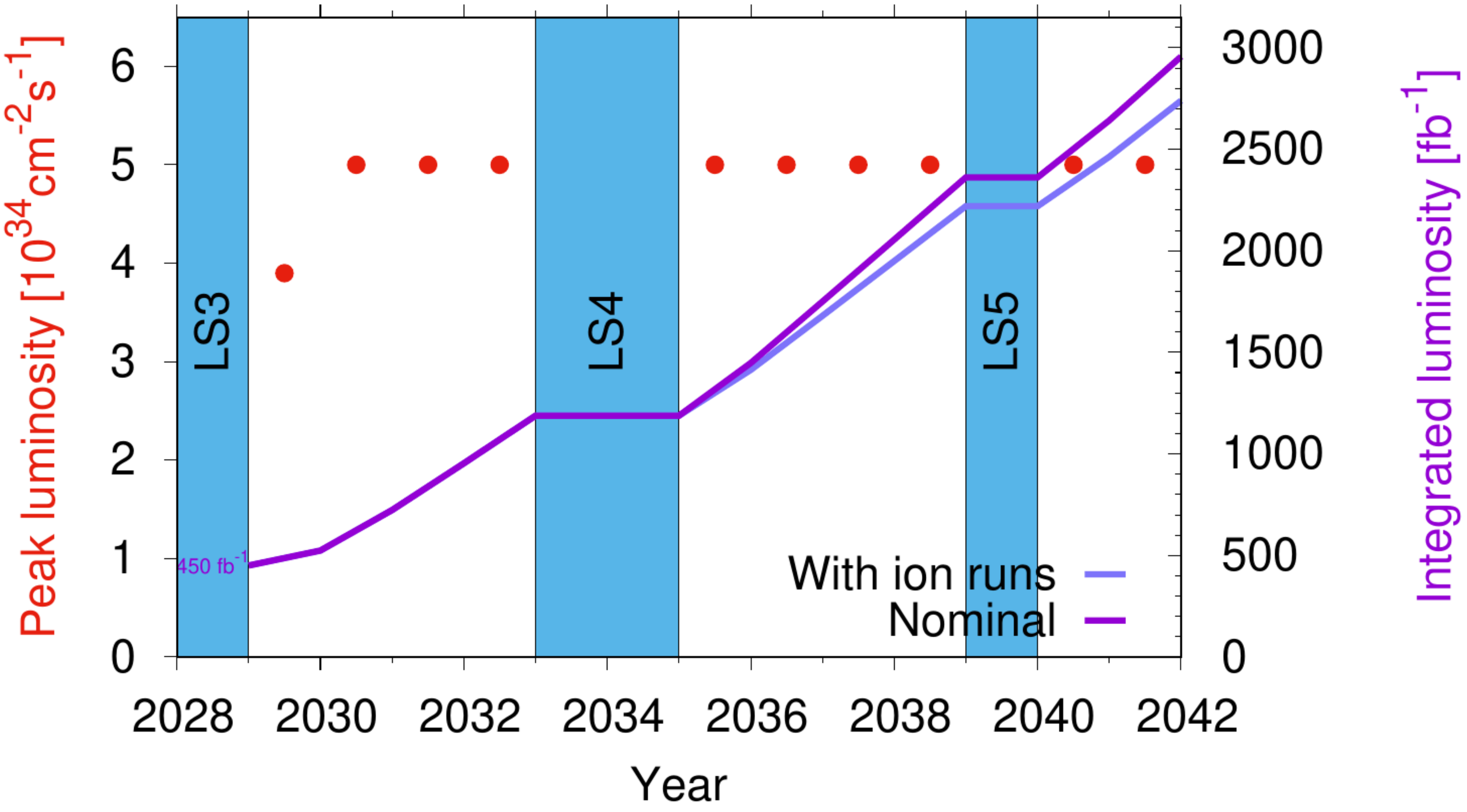


6) Flexible superconducting links

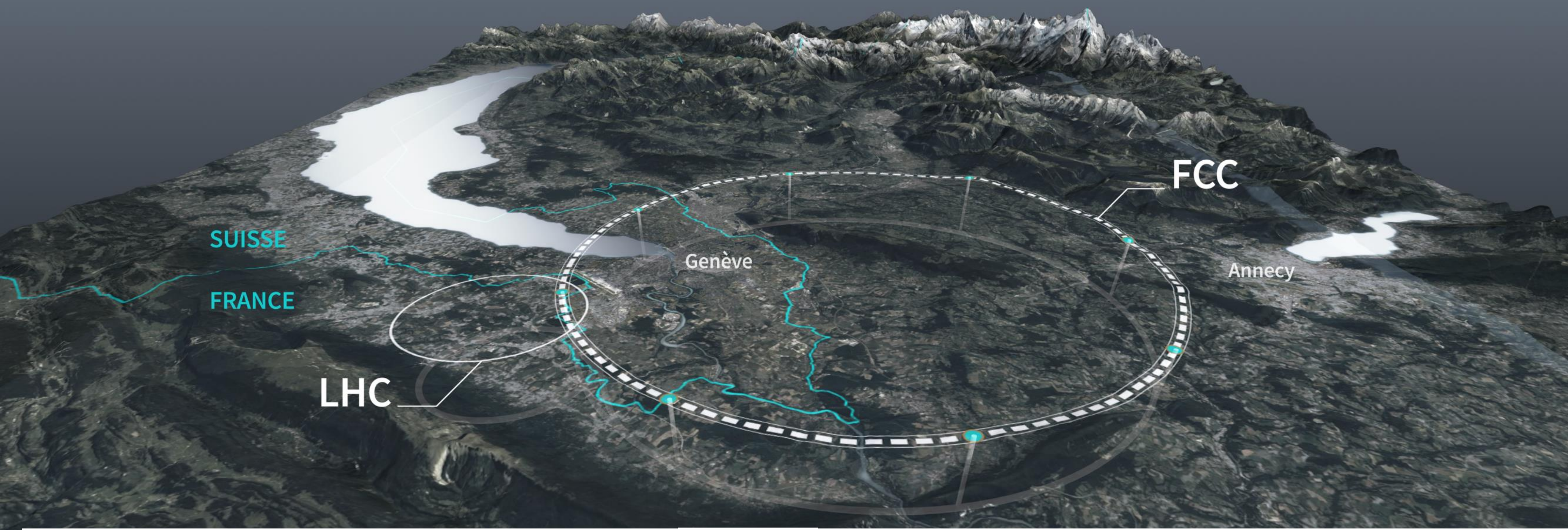
MgB_2: > 100 kA @ 25K



HL-LHC integrated luminosity – about 10 x the LHC performance



Status of the FCC Feasibility Study



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

FUTURE CIRCULAR COLLIDER

Why FCC ?

F. Gianotti

1) Physics : best overall physics potential of all proposed future colliders

- FCC-ee : **ultra-precise** measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
- FCC-hh : **only** machine able to explore next **energy frontier** directly (~ x10 LHC)
- Heavy-ion collisions and, possibly, ep/e-ion collisions
- **4 collision points** → robustness; increased dataset for same machine power; specialized experiments for maximum physics outpu

2) **Timeline**

- **FCC-ee technology is mature** → construction can proceed in parallel to HL-LHC operation and physics can start few years after end of HL-LHC operation → 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 (HTS)**
  - **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 with the size of the CERN community** (4 major experiments)

Is it feasible? Isn't it too ambitious?

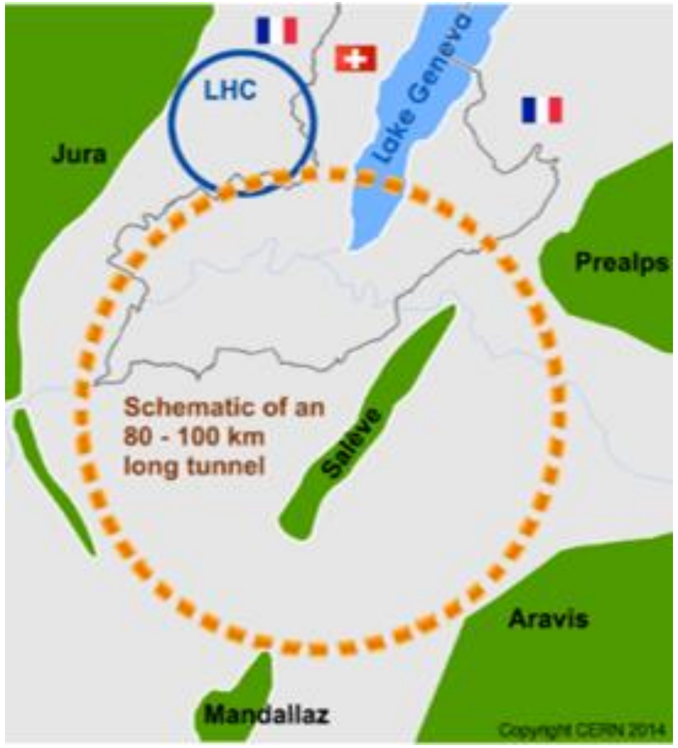
-- The mid-term review will show the status of the Feasibility Study, including the funding model.
-- **FCC is big and audacious project, but so were LEP and LHC when first conceived** → they were successfully built and performed far beyond expectation → demonstration of capability of our community to deliver on very ambitious projects with < 20% cost overrun

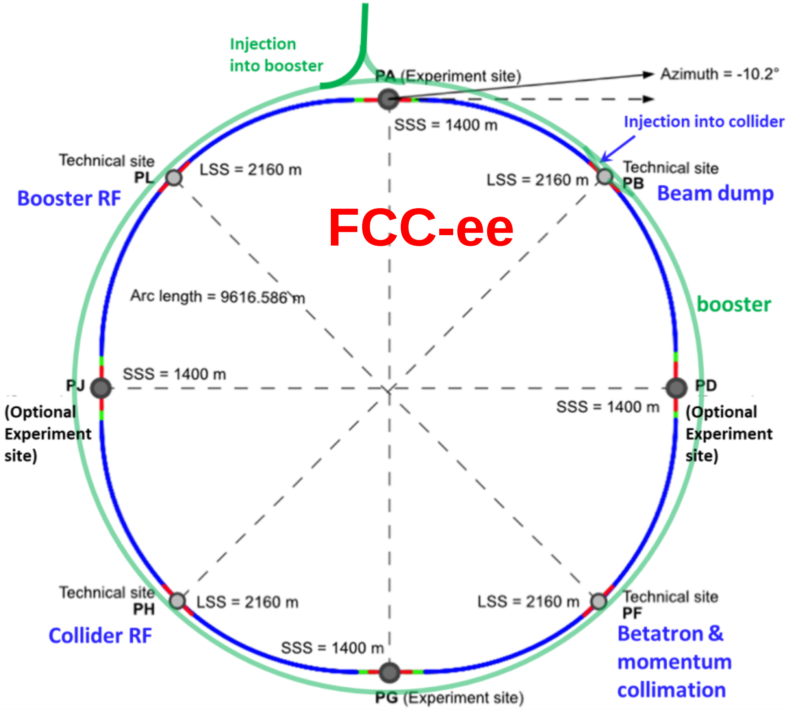
FUTURE CIRCULAR COLLIDER

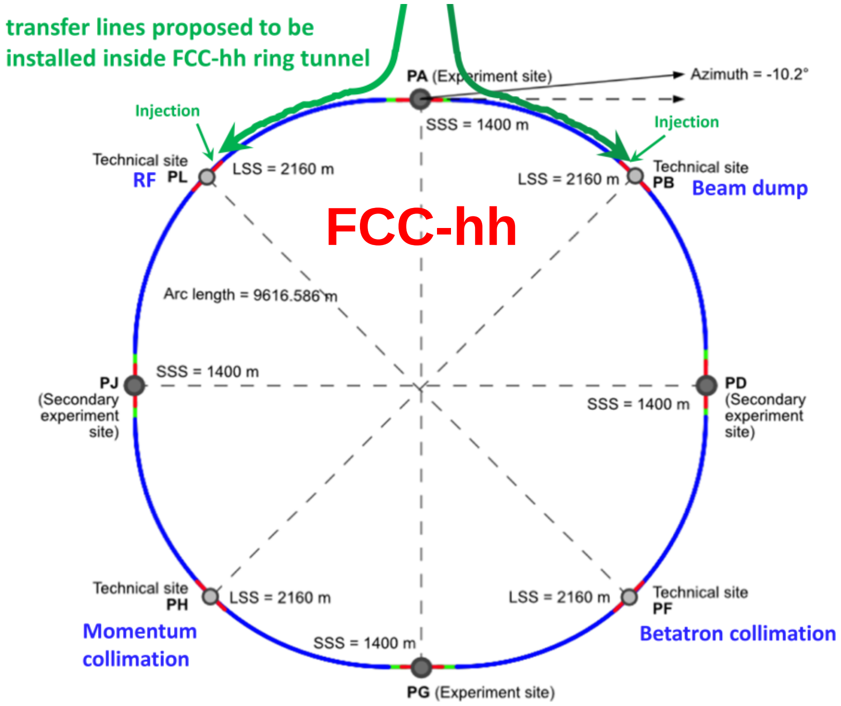
FCC integrated program

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
- 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

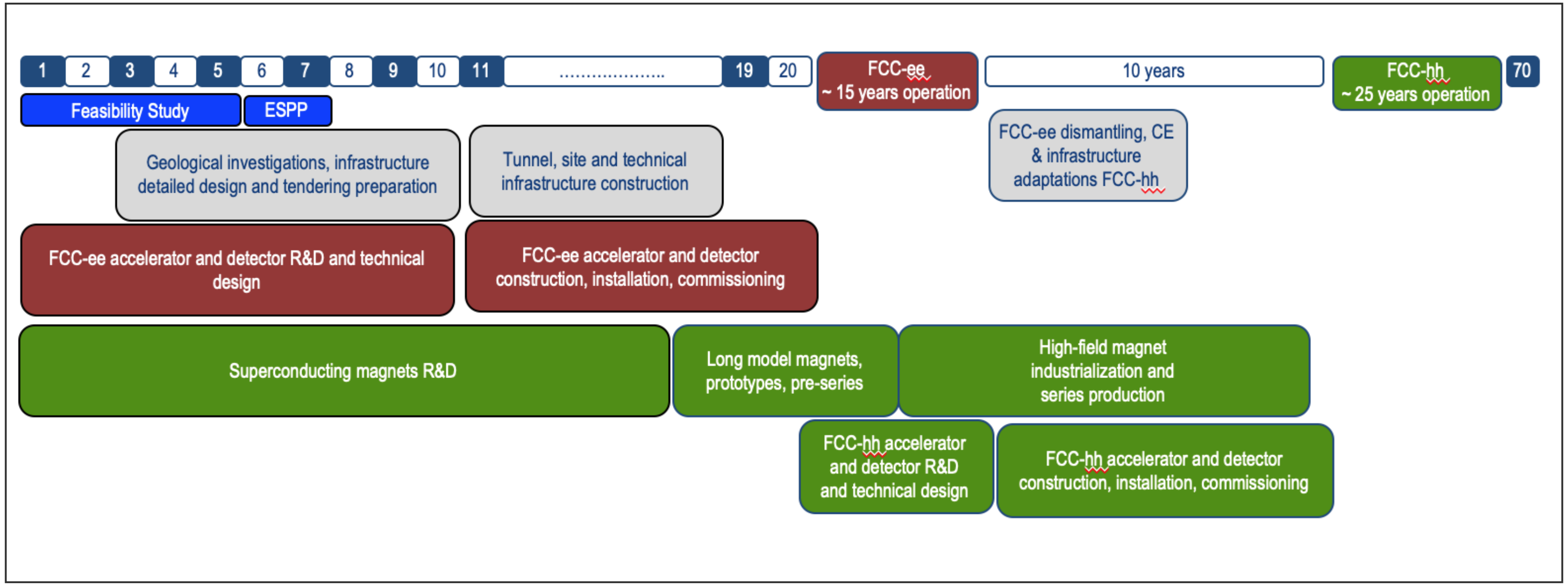






FUTURE CIRCULAR COLLIDER

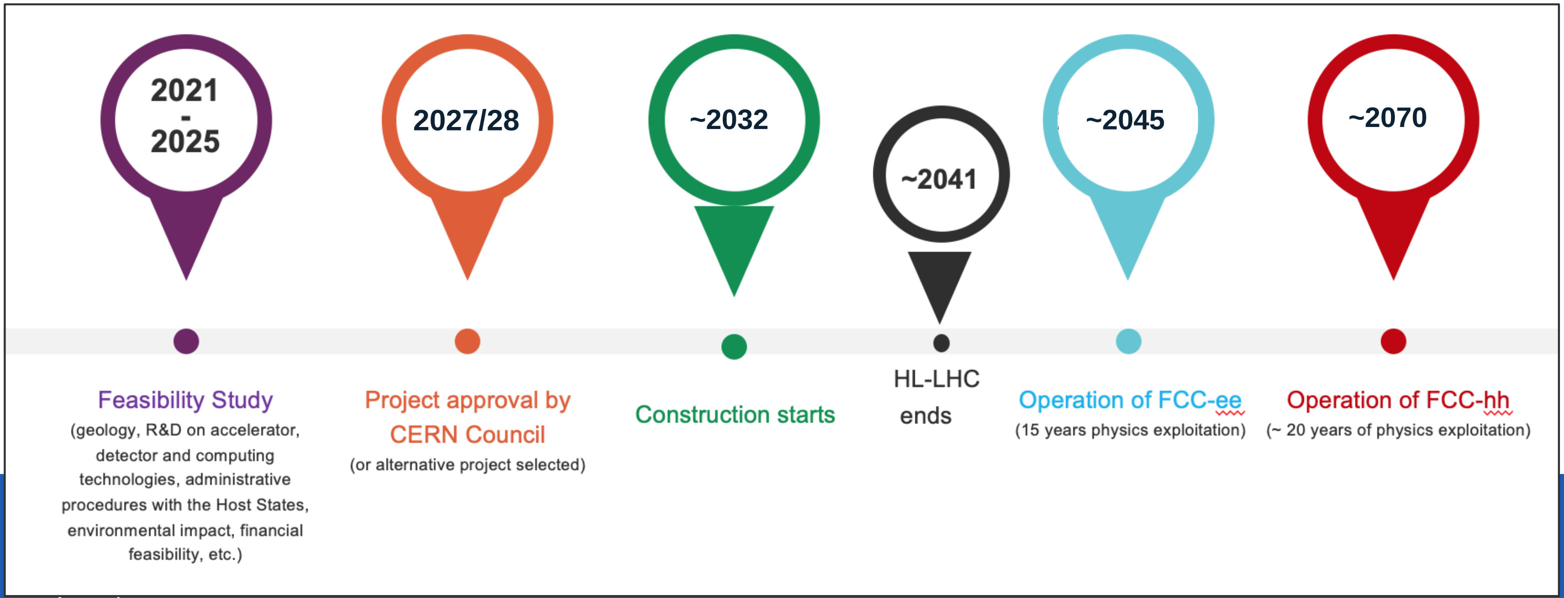
FCC integrated program - timeline



FCC Conceptual Design Study: 2014-2018, leading to CDRs

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



Ambitious schedule taking into account:

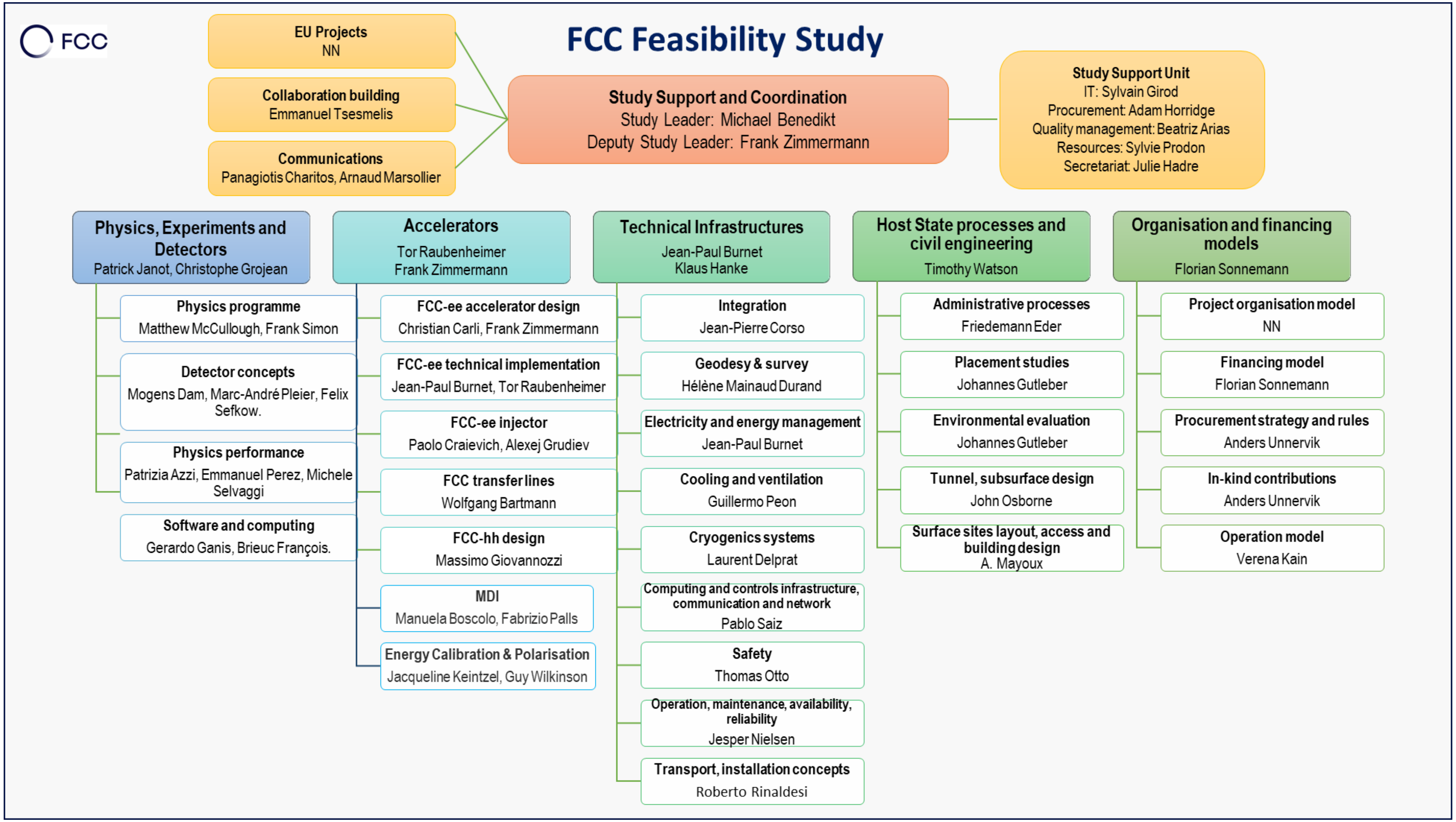
- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041
- ❑ **<u>project preparatory phase</u> with adequate resources immediately after Feasibility Study**

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.

Goal: Complete Feasibility Study Report by March 2025 as input for ESPPU

FCC organigram shows important Austrian involvement

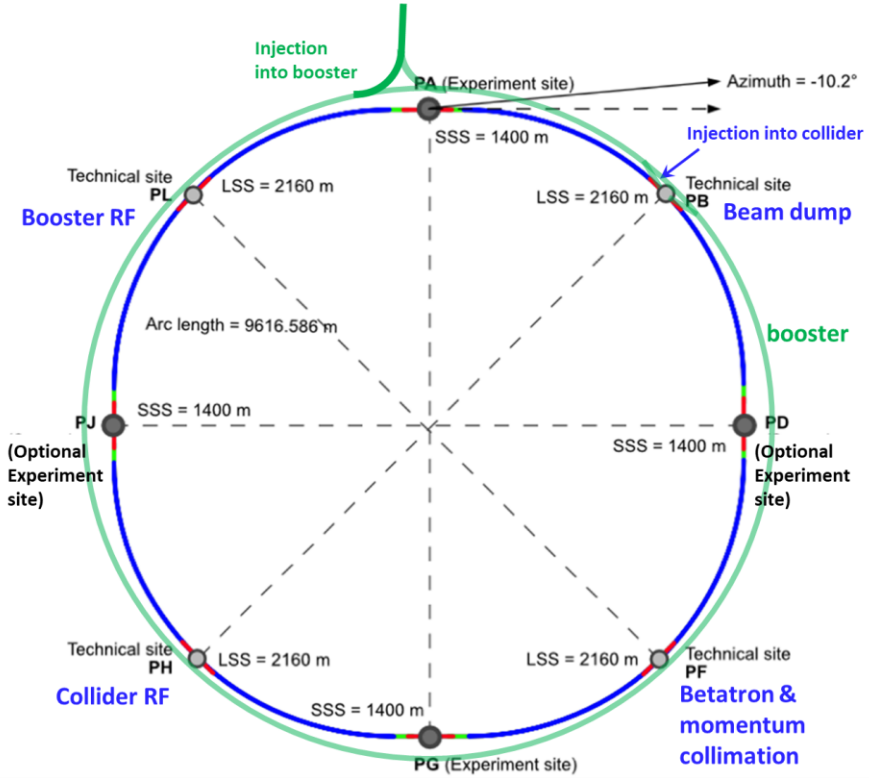


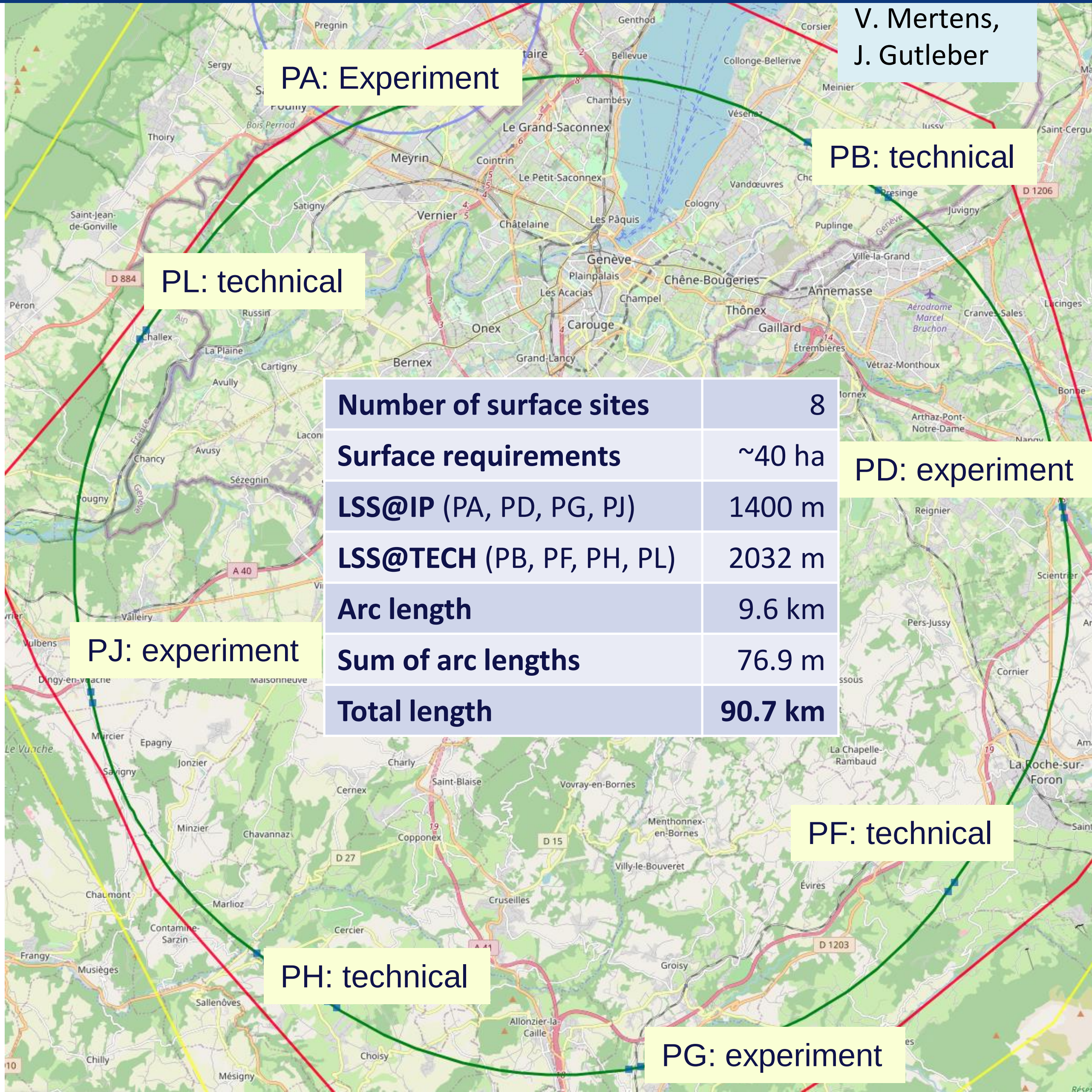
Optimized placement and layout for feasibility study

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

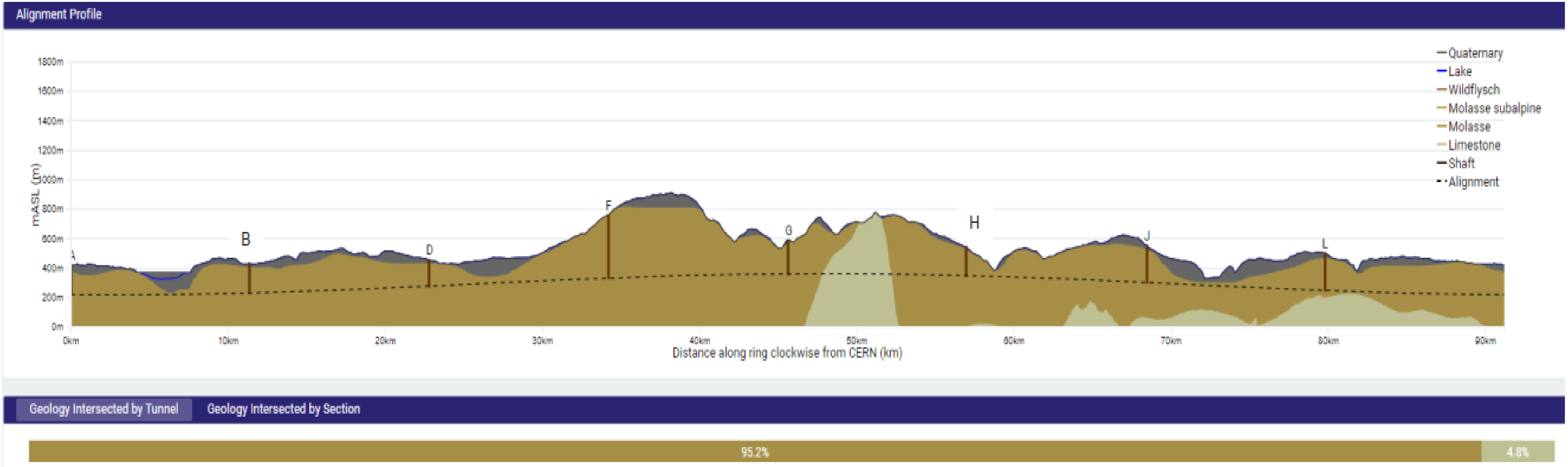
Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement





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**

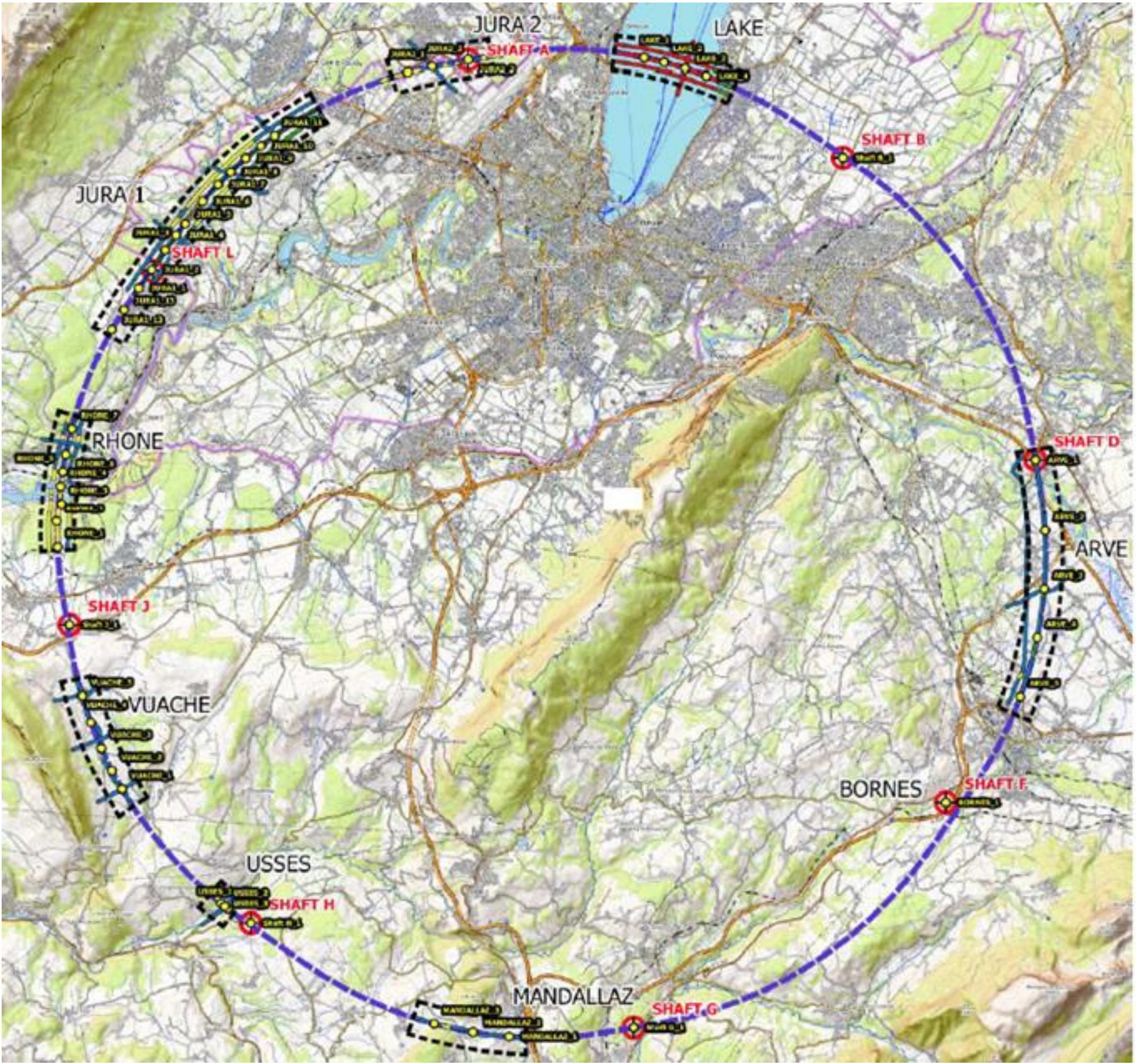
FCC tunnel implementation



Tunnel implementation summary

- 91 km circumference
- 95% in molasse geology for minimising tunnel construction risks
- Site investigations in zones where tunnel is close to geological interfaces: moraines-molasse-limestone

Status site investigations



- **Site investigations in areas with uncertain geological conditions:**
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022.
- **Contracts Status:**
  - Contract for engineering services and role of Engineer during works, active since July 2022
  - Contracts for drillings and seismics in final negotiation round.
  - Start of work in June 2024.

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

Drilling works on the lake

OpenSky Laboratory: demonstrate molasse reuse cases

GOAL: demonstrate the feasibility to transform Molasse (excavated material) into fertile soil.

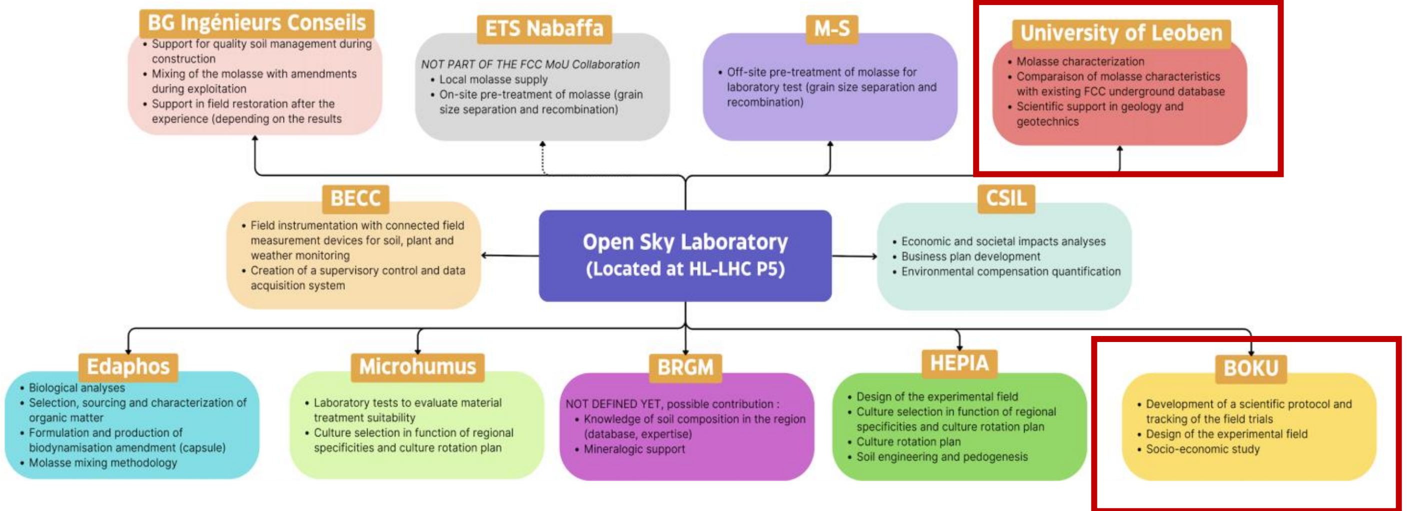
- **Project launched in January 2024**
- **10000 m^2 near LHC P5 (CMS) in Cessy, France.**

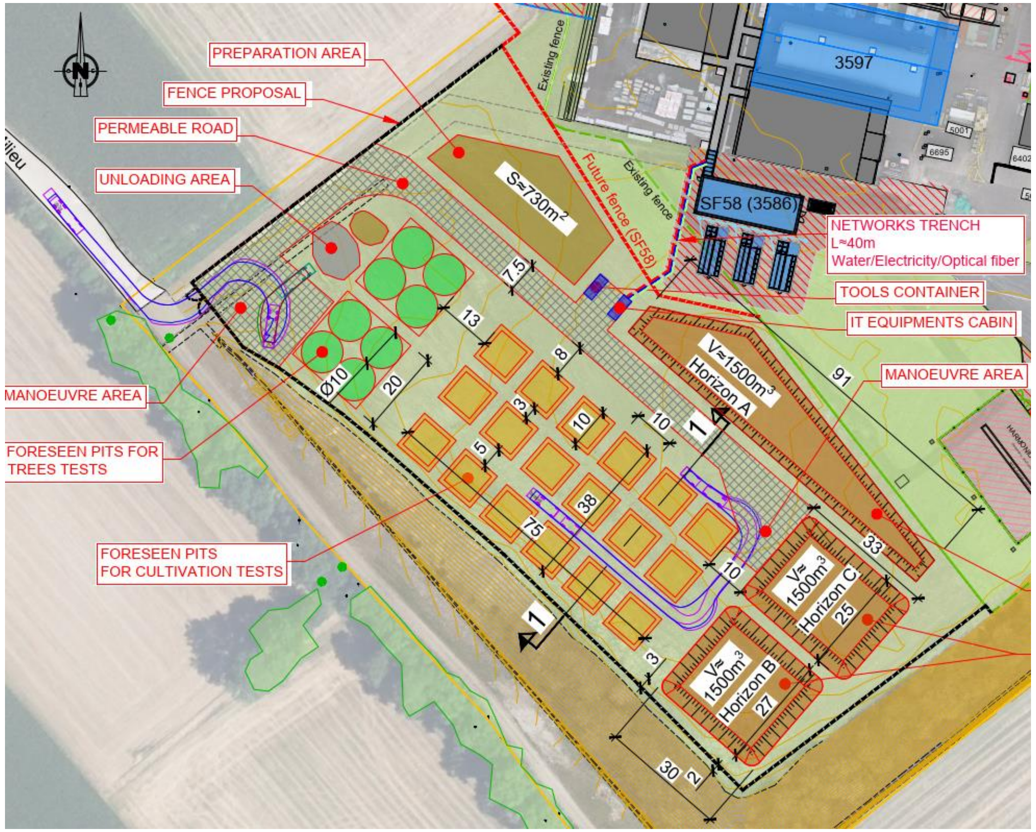
Project phases:

1) Laboratory tests to **identify** the **most suitable mix** of molasse and amendments.

2) **Field tests** in a **controlled environment** (plants selected in function of regional specificities and possible soil reuse cases)

International collaboration with partners from academia and industry specialised in agronomy, soil paedogenesis, phytoremediation





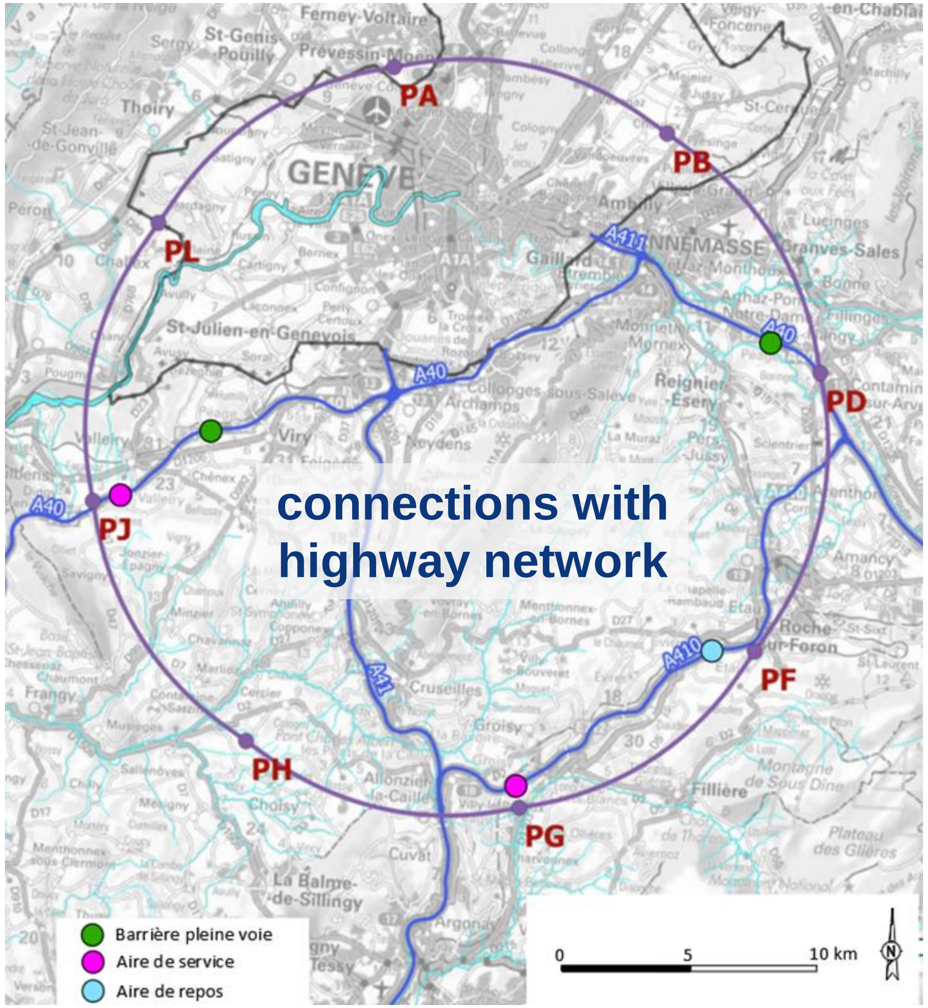
Status - March 2024:

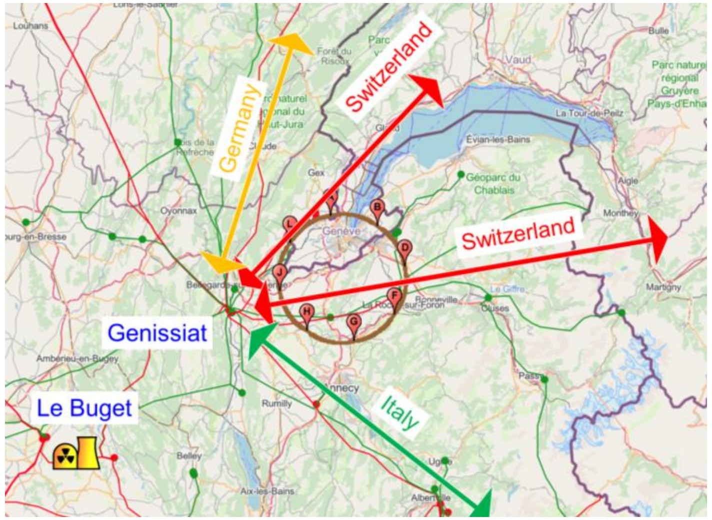
- **Project approved at CERN level**
- **Collaboration agreements being signed**
- **Definition of the laboratory and field tests**

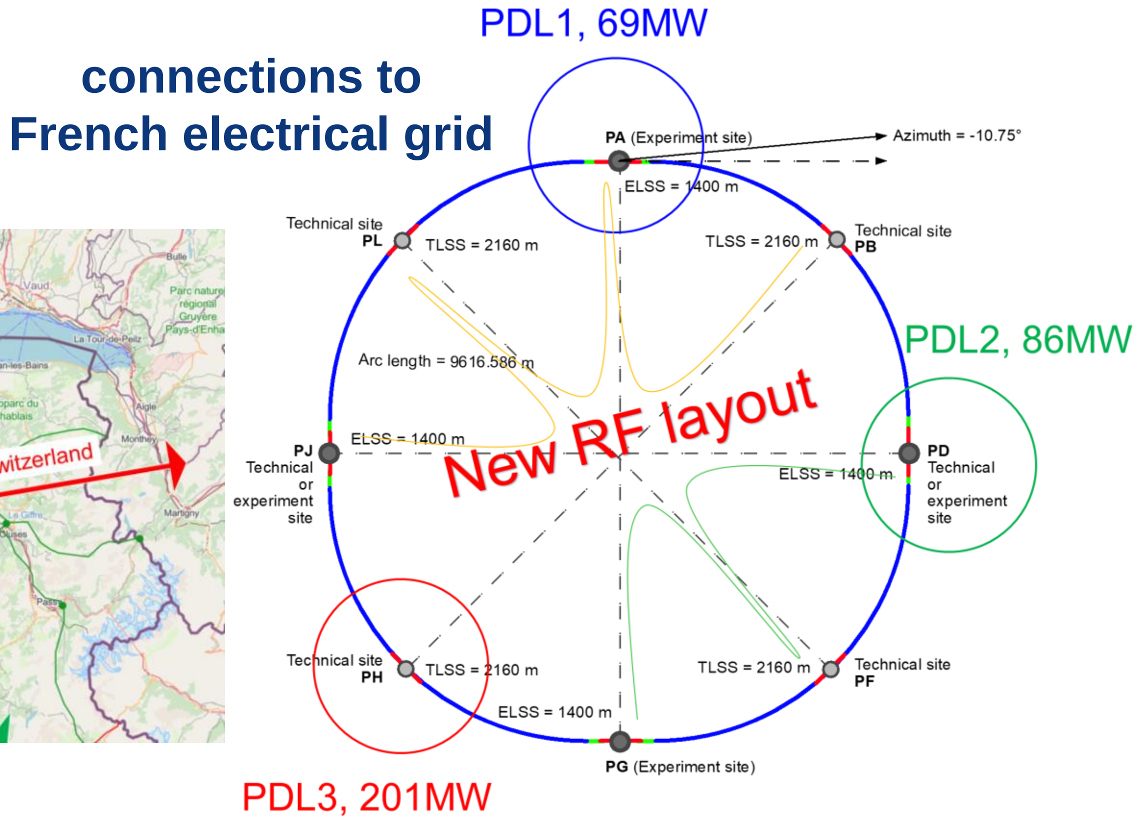
FUTURE CIRCULAR COLLIDER

Connections with regional infrastructure

- **Road accesses developed for all 8 surface sites**
- **Four possible highway connections defined**
- **Less than 4 km new departmental roads required**







- **Electrical connection concept studied 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**
- **R&D efforts aiming at further reduction of the energy consumption of FCC-ee and FCC-hh**

FUTURE CIRCULAR COLLIDER

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

Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

- 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

F. Gianotti

FUTURE CIRCULAR COLLIDER

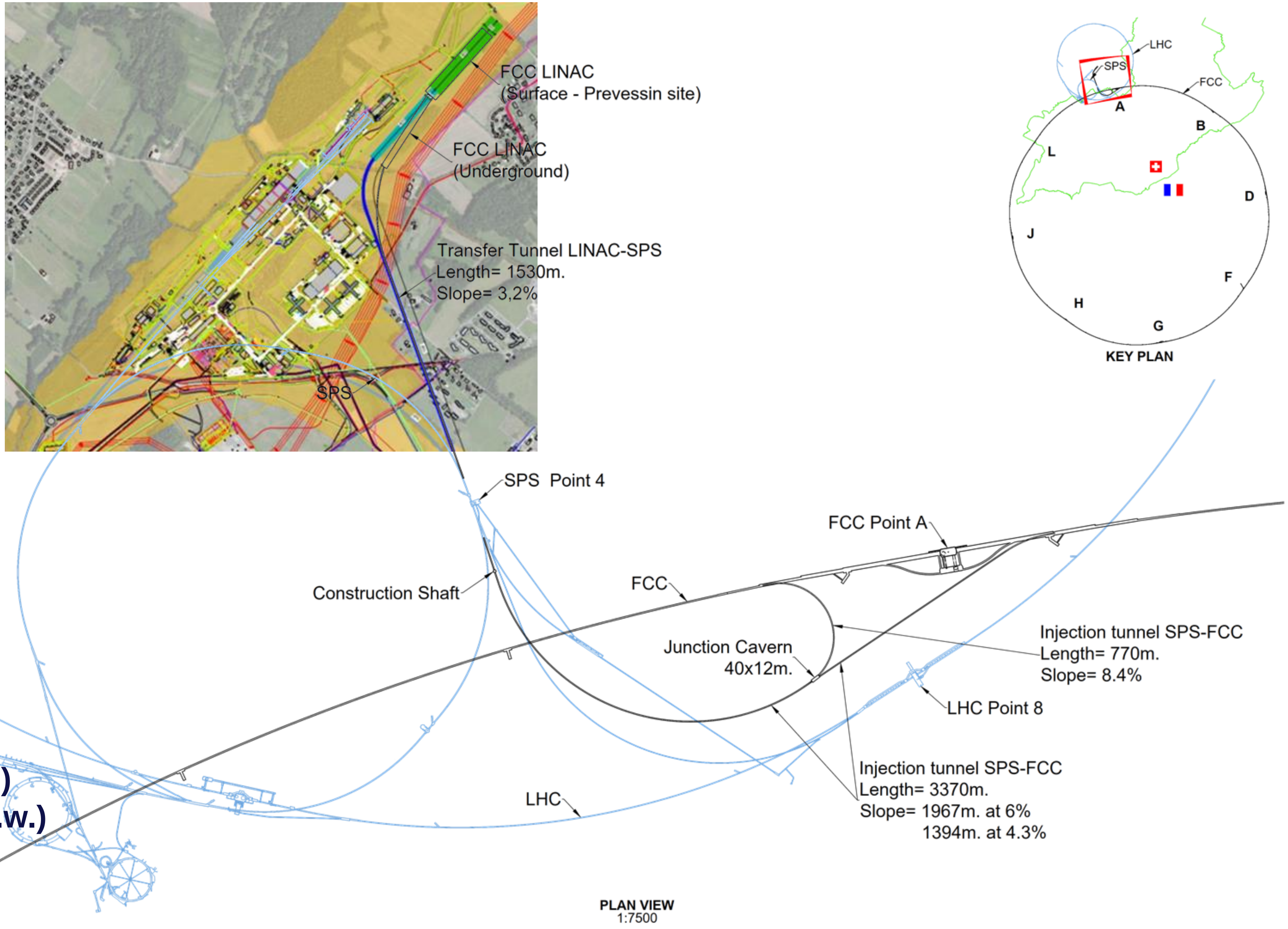
Transfer line FCC-ee (option with SPS for FCC-hh)

LINAC and Injection Tunnels

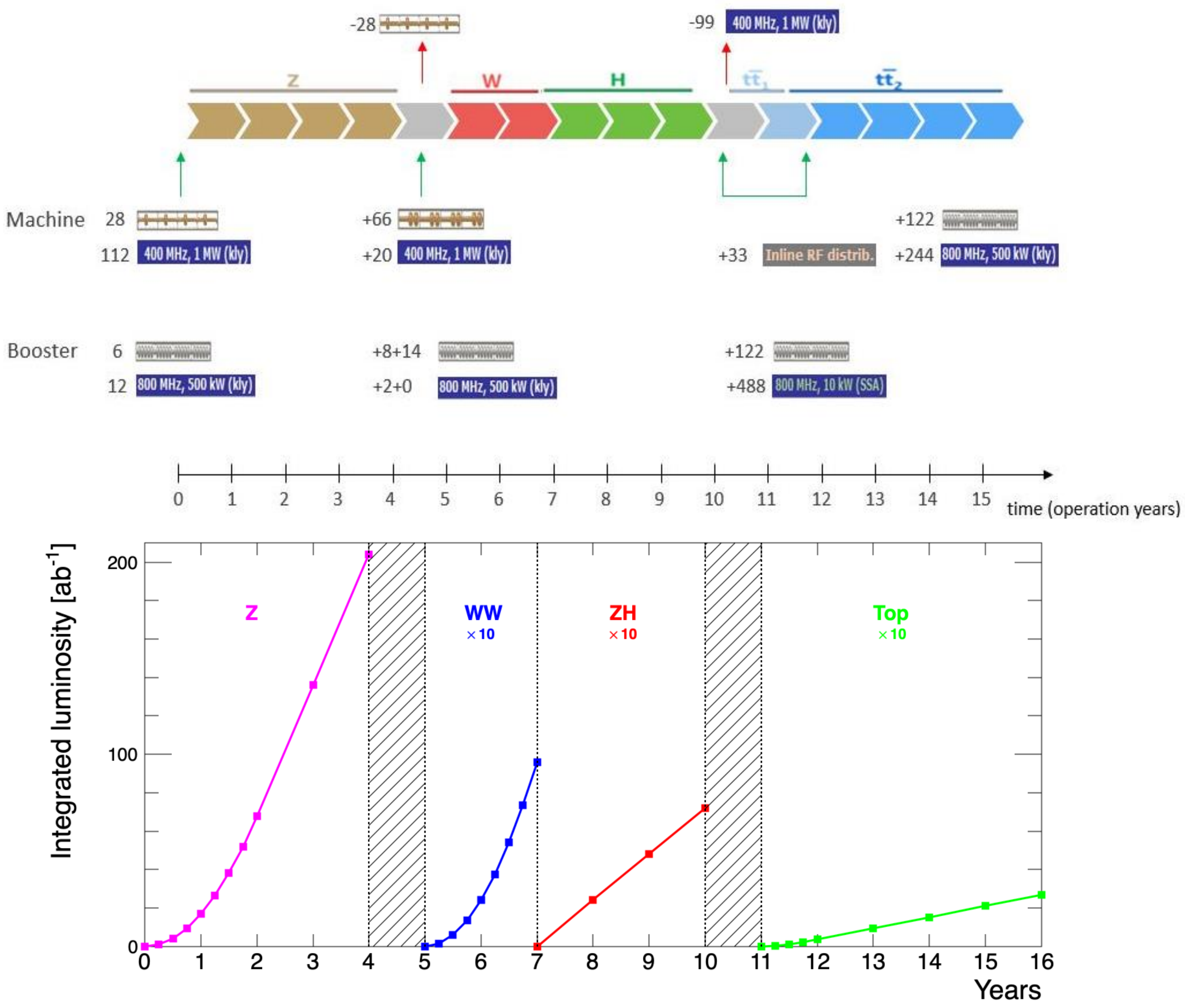
- **Injector with ~20 GeV HE Linac sited on surface at CERN-Prevessin site**

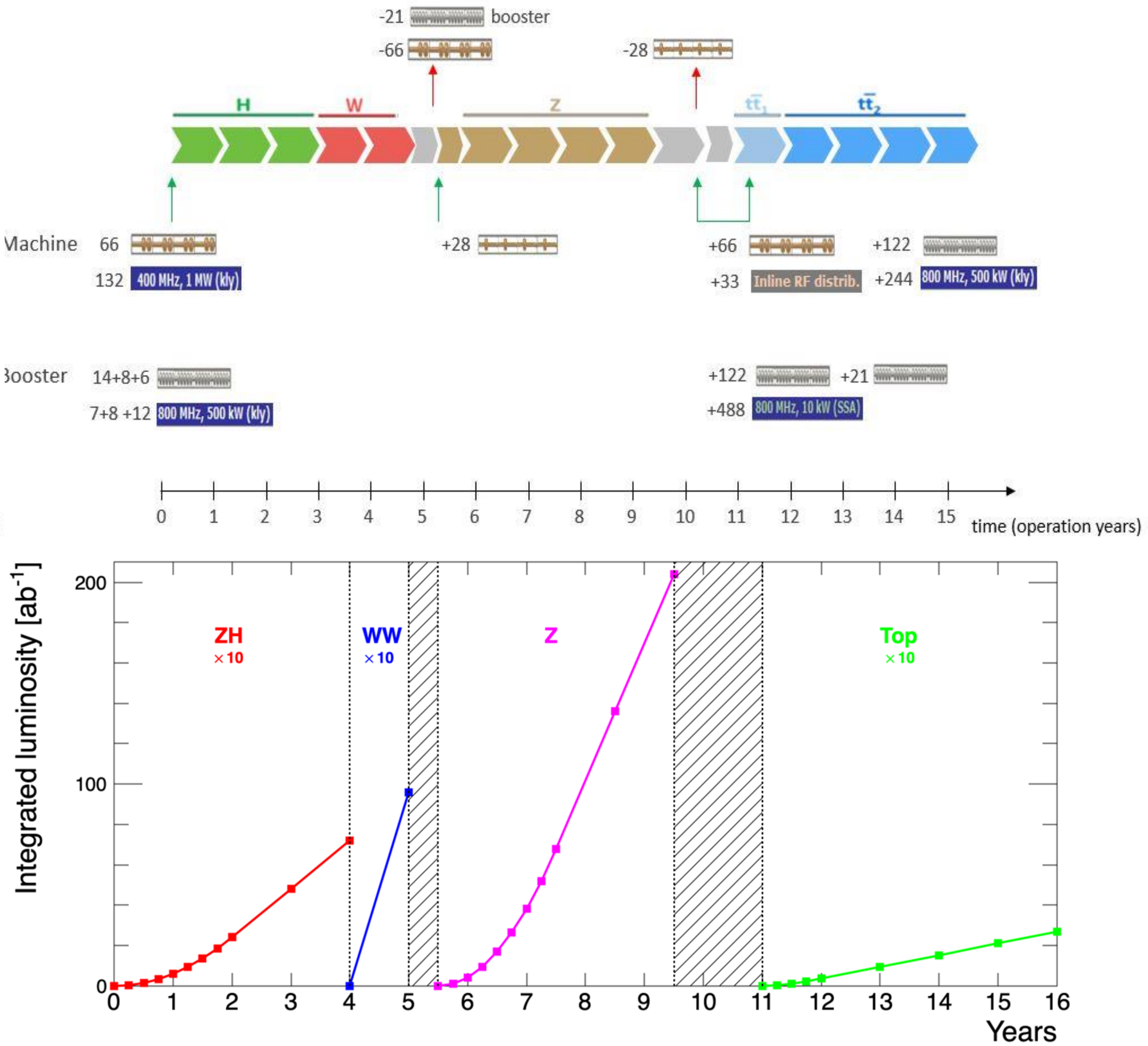
- **Single transfer tunnel to FCC Booster with spur to enable anti-clockwise injection**

- **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.)**



Operation sequences for FCC-ee and RF configuration





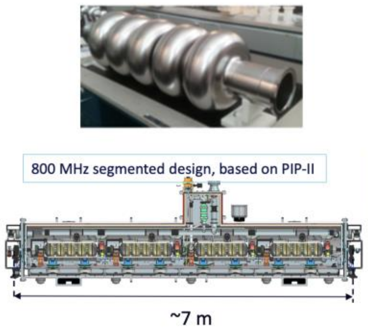
- **Evolution of RF configuration of collider and booster with beam energies and physics operation points**
- **Long-term R&D for SRF, in particular for the 800 MHz system**

FCC-ee R&D activities – just a few examples

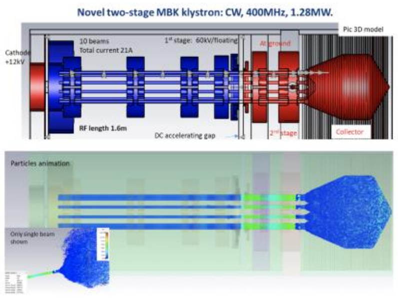
RF system R&D is key for increasing energy efficiency of FCC-ee

- Nb on Cu 400 MHz cavities, seamless cavity production, coating techniques
- Bulk Nb 800 MHz cavities, surface treatment techniques, cryomodule design
- RF power source R&D in synergy with HL-LHC.

800 MHz cavity and CM design
collaborations with **JLAB and FNAL**



high-efficiency klystron R&D
in collaborations with **THALES & CANON**



400 MHz cavity production
in collaboration with **KEK**

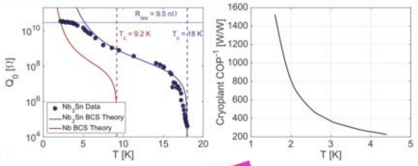
SRF: seamless cavities & thin film coating

C. Pira

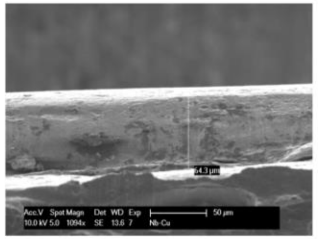
Seamless production

First seamless multicell by spinning

Move from Nb @2K to Nb_3Sn @4.5 K would reduce cryogenic power by a factor of 3

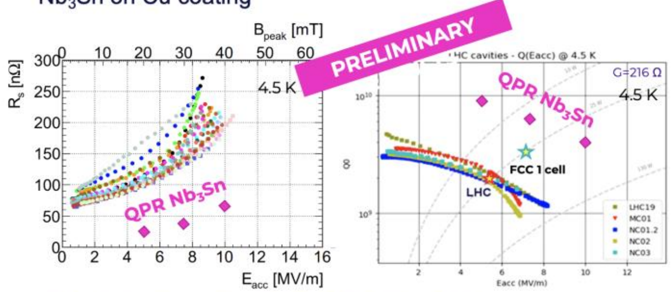


Nb on Cu coating



SEM micrograph of the film cross section

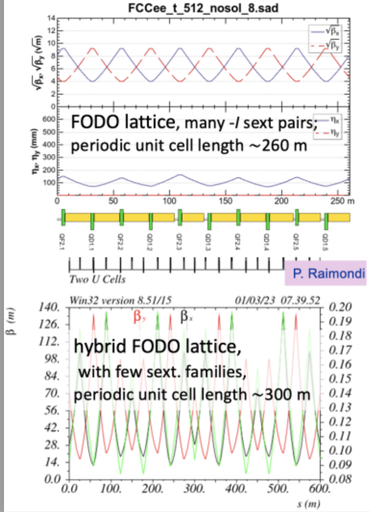
Nb_3Sn on Cu coating



Equivalent to a Q of 9*10⁹ @5 MV/m @4.5 K
Almost 1 order of magnitude better than LHC !
Room for improvement

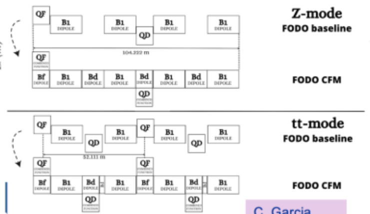
FCC-ee optics baseline & further evolution(s)

regular arc K. Oide

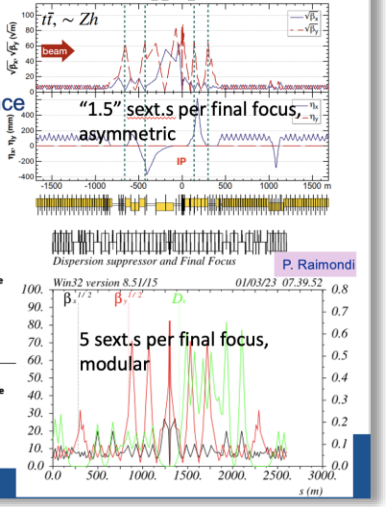


optimisation goals:

- reduced power consumption
- lower SR energy loss
- increased momentum acceptance
- relaxed tolerances
- larger dynamic aperture
- simplified powering schemes

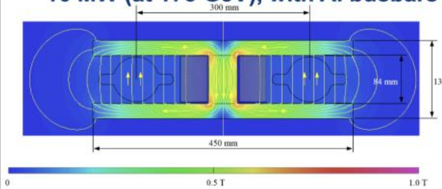


interaction region K. Oide

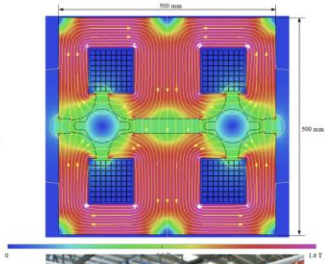


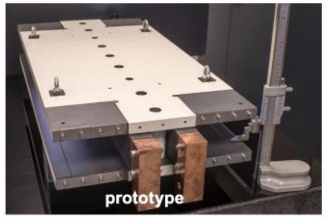
Prototypes of FCC-ee low-power magnets

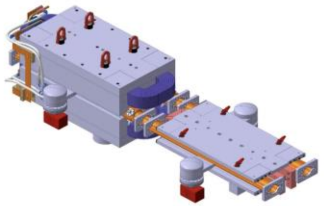
Twin-dipole design with 2× power saving
16 MW (at 175 GeV), with Al busbars

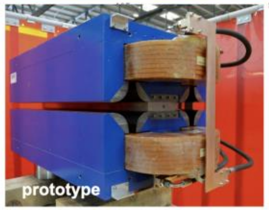


Twin F/D arc quad design with 2× power saving 25 MW (at 175 GeV), with Cu conductor









even more efficient alternative magnet designs are being explored

FUTURE CIRCULAR COLLIDER

FCC-hh

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
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

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 ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)
- Final word about WIMP dark matter

F. Gianotti

FUTURE
CIRCULAR
COLLIDER

FCC – a truly global collaboration

The CERN Council reviewed the work undertaken in a fruitful meeting on 2 February 2024.
It congratulated and thanked all the teams involved in the study for the excellent and significant work done so far and for the impressive progress, and looks forward to receiving the final report in 2025.

150 Institutes

32 Companies

33 Countries

EC H2020

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

FUTURE CIRCULAR COLLIDER

Participating institutes from Austria

Country	Institute		City
Austria	HEPHY	Physics, Detectors	Vienna
Austria	University of Natural Resources and Life Sciences (BOKU)	Reuse of excavation material	Vienna
Austria	University of Graz	Physics	Graz
Austria	Technical University Vienna (TU WIEN)	Accelerators, Technologies, Mechanical Engineering	Vienna
Austria	University of Applied Sciences - Technikum Wien	Technologies	Vienna
Austria	University of Leoben	Tunneling Reuse of excavation material	Leoben
Austria	Österreichisches Institut für Wirtschaftsforschung (WIFO)	Economic and socio-economic studies	Wien
Austria	Johannes Kepler University (JKU)	Technologies	Linz
Austria	University of Innsbruck	Detectors	Innsbruck

https://fccis.web.cern.ch/collaboration

FUTURE CIRCULAR COLLIDER

Milestone in 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.

Public Information Event in the Science Gateway

First event in a series of upcoming public meetings to enrich the dialogue between the people living in the region and CERN.

- **On the agenda:**
  - FCC Physics, FCC Regional Implementation
  - Round table with CH and FR representatives
  - Questions & Answers

- **Attendance: Full room (400 people). 350 members of the general public, 10 journalists/photo reporters, 40 invited guests.**

- **Webcast publicly available: https://cds.cern.ch/record/2897074**

FUTURE CIRCULAR COLLIDER

FCC Feasibility Study – far beyond a paper study

- **Completion of FCC Feasibility Study by March 2025 to enable advancing project decision and project start date.**
  - **placement & layout was defined**, and entire project adapted to the new geometry
  - **Ongoing dialogue** with **local-regional** actors and stakeholders extremely important
- **Pre-TDR phase from April 2025 to end-2027**
  - Provide all necessary information to CERN Council for decision on the project **at the end of 2027 or mid-2028**
    - further develop the civil engineering and the technical design all major components, so as to provide a **more detailed cost estimate** with reduced uncertainties
    - Continuation ot **technical R&D activities**.
    - Continuation of site investigations and perform an **overall integration study to specify requirements of technical infrastructure, accelerators and detectors** for subsequent civil engineering design in case the project goes ahead.
    - Launch of **environmental impact study in 2026**
    - Work with host states on **regional implementation development** and authorization procedures.
  - Career opportunities: for this period the CERN management has proposed the opening of 80 staff positions, 40 PhD and 40 post-docs to the Council for approval in June (reminder: Austrian doctoral student program at CERN)

International
MUON Collider
Collaboration

MuCol

Muon Collider

US P5: The Muon Shot

MuCol

International MUON Collider Collaboration

Particle Physics Project Prioritisation Panel (P5) endorses muon collider R&D: ”This is our muon shot”

Recommend joining the IMCC
Consider FNAL as a host candidate

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

SCI AM

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AUGUST 28, 2023 | 10 MIN READ

Particle Physicists Dream of a Muon Collider

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists

nature

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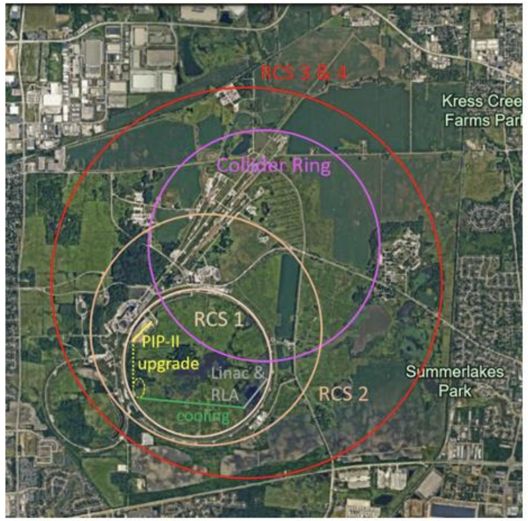
EDITORIAL | 17 January 2024

US particle physicists want to build a muon collider – Europe should pitch in

A feasibility study for a muon smasher in the United States could be an affordable way to maintain particle physics unity.



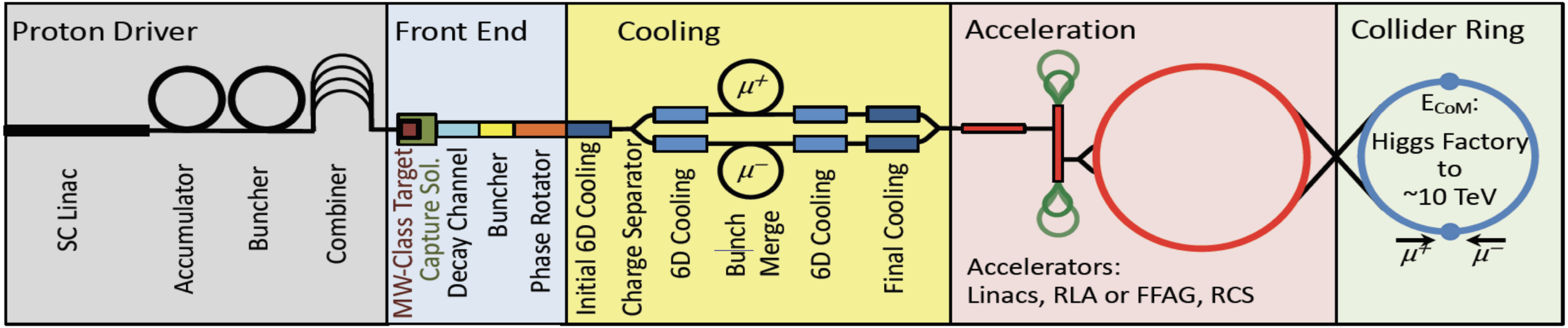
We welcome the US community

Already participation, also in leadership
- Will increase and reorganise in 2024

Ambition of US to host collider is excellent news

Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

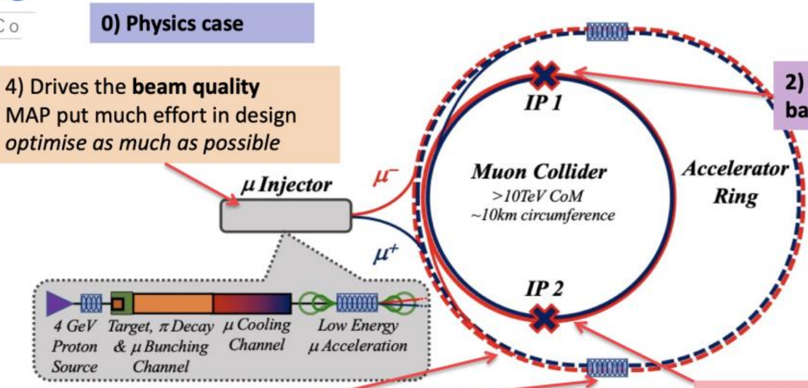
- Combines **precision physics** and **discovery reach**
- Application of hadron collider technology to a lepton collider
- Muon collider promises **sustainable** approach to the **energy frontier**
- limited power consumption, cost and land use

Key Challenges

MuCol

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



2) Beam-induced background

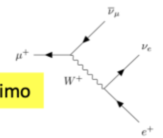
1) Dense neutrino flux
mitigated by mover system
and **site selection**

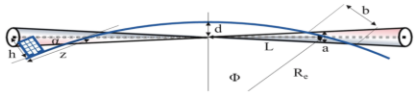
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Muon Decay and Neutrino Flux

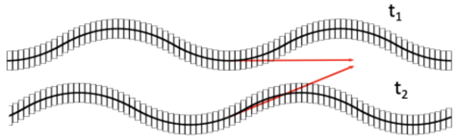
MuCol

Muon decays in collider ring
- Impact on detector ⇒ Daniele, Massimo
- Have to avoid dense neutrino flux





Aim for **negligible impact from arcs**
- Similar impact as LHC
- At 3 TeV this is the case for 200 m depth
- At 10 TeV go from acceptable to negligible with mover system
  - Mockup of mover system planned
  - Impact on beam to be checked



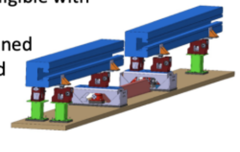
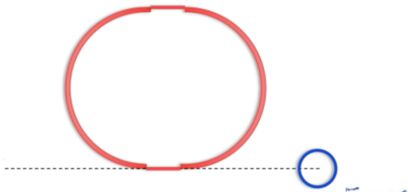


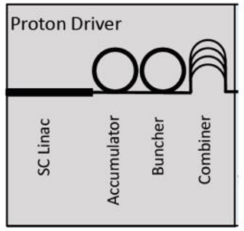
Fig. 7.23: Mock-up of the proposed magnet movement system.

Impact of experimental insertions
- 3 TeV design acceptable with no further work
- But better acquire land in direction of experiment, also for 10 TeV



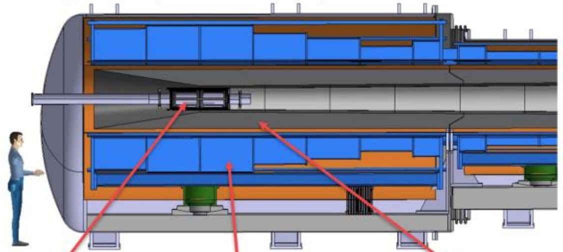
Proton Complex and Target

MuCol



protons → (in target) → pions → (decay) → muons

400 kJ protons to produce 5 x 10^{13} captured muon pairs



5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

ESS and Uppsala are woring on merging beam into high-charge pulses
- Indication is that 10 GeV would be preferred

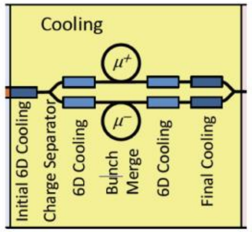
Graphite **Target**

20 T **solenoid**
to guide pions and muons

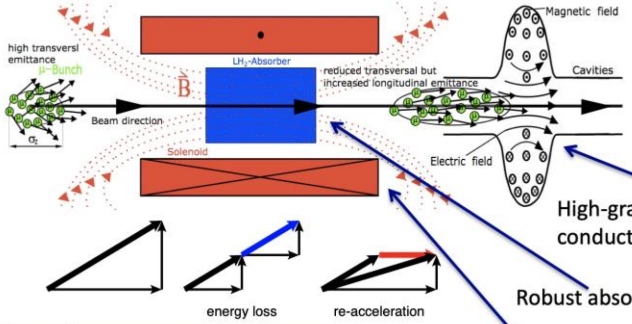
Tunsten shielding
To protect magnet

Muon Cooling Principle

MuCol



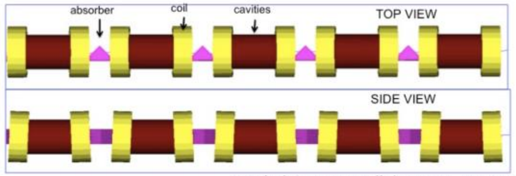
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



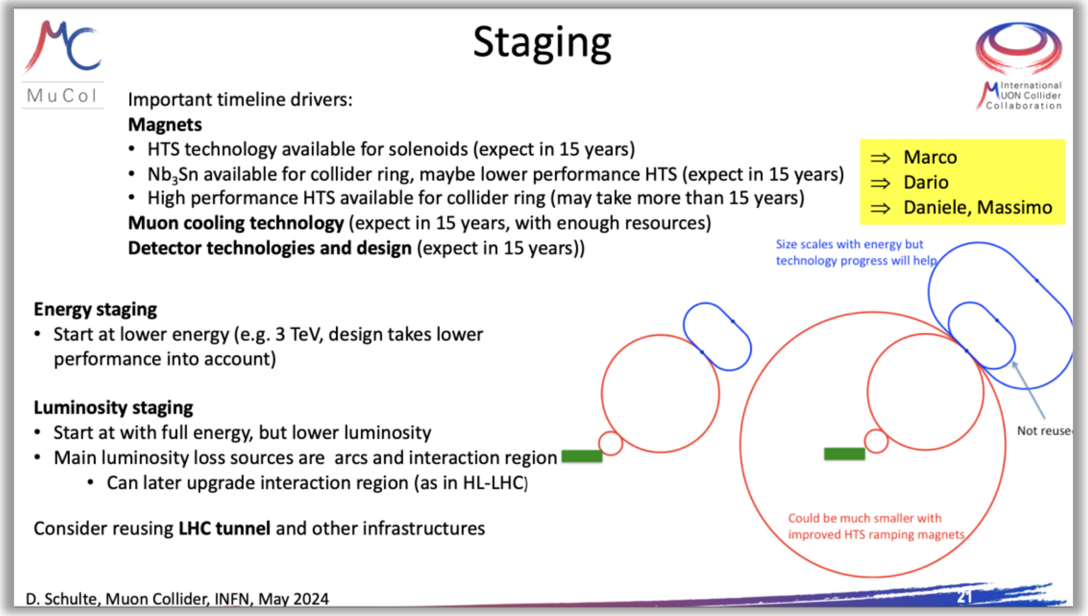
High-gradient normal-conducting cavities

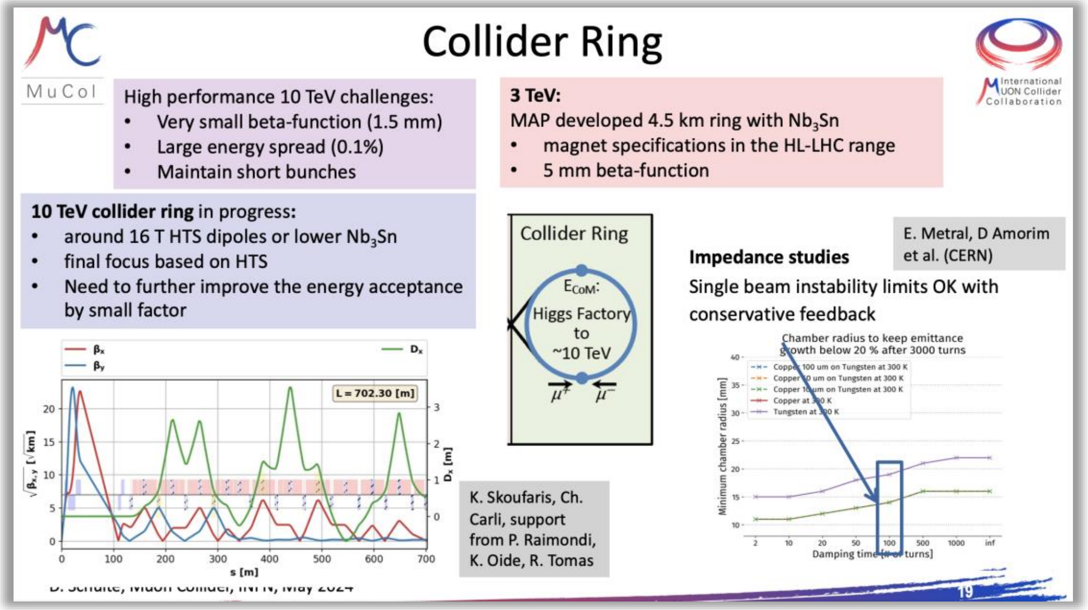
Robust absorbers

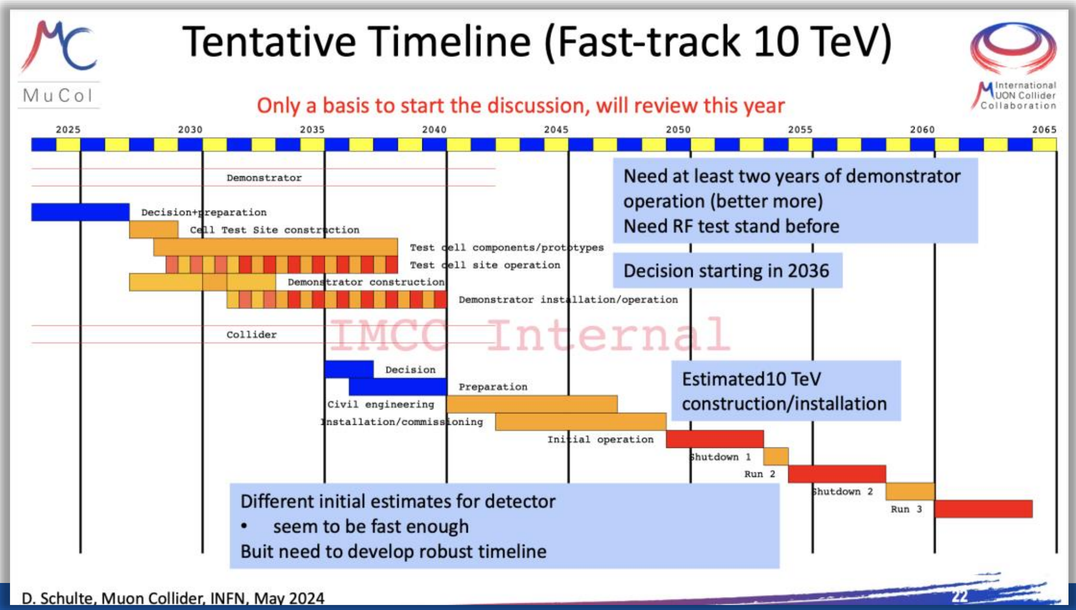
High-field, superconducting solenoid



Principle has been demonstrated in MICE
Nature vol. 578, p. 53-59 (2020)







First collider stage is expected to be operational by 2050

- If the resources ramp up sufficiently
- If decision-making processes are efficient

Conclusions

- **HL-LHC as upgraded CERN flagship will enter into the installation phase in 2026 (LS3)**
  - Operation foreseen until 2041
- **FCC feasibility study for a world-leading HEP infrastructure for 21st century**
  - push the particle-physics **precision and energy frontiers** far beyond present limits
  - Mature FCC-ee design as first stage, springboard for FCC-hh while providing time for development
  - Success of FCC relies on **strong global participation**. Everybody interested is warmly welcome to join the effort!
  - CERN plans to ramp-up activities to allow for timely project start → job opportunities!
- **Muon collider development now also with strong US participation**
  - Challenging technological aspects, potential readiness ~2050 using a staged approach

FUTURE CIRCULAR COLLIDER

FCC Week 2024

Future Circular Collider (FCC) Week 2024, at the **Westin St. Francis in San Francisco.**

From **Monday 10 June to Friday 14 June 2024**.

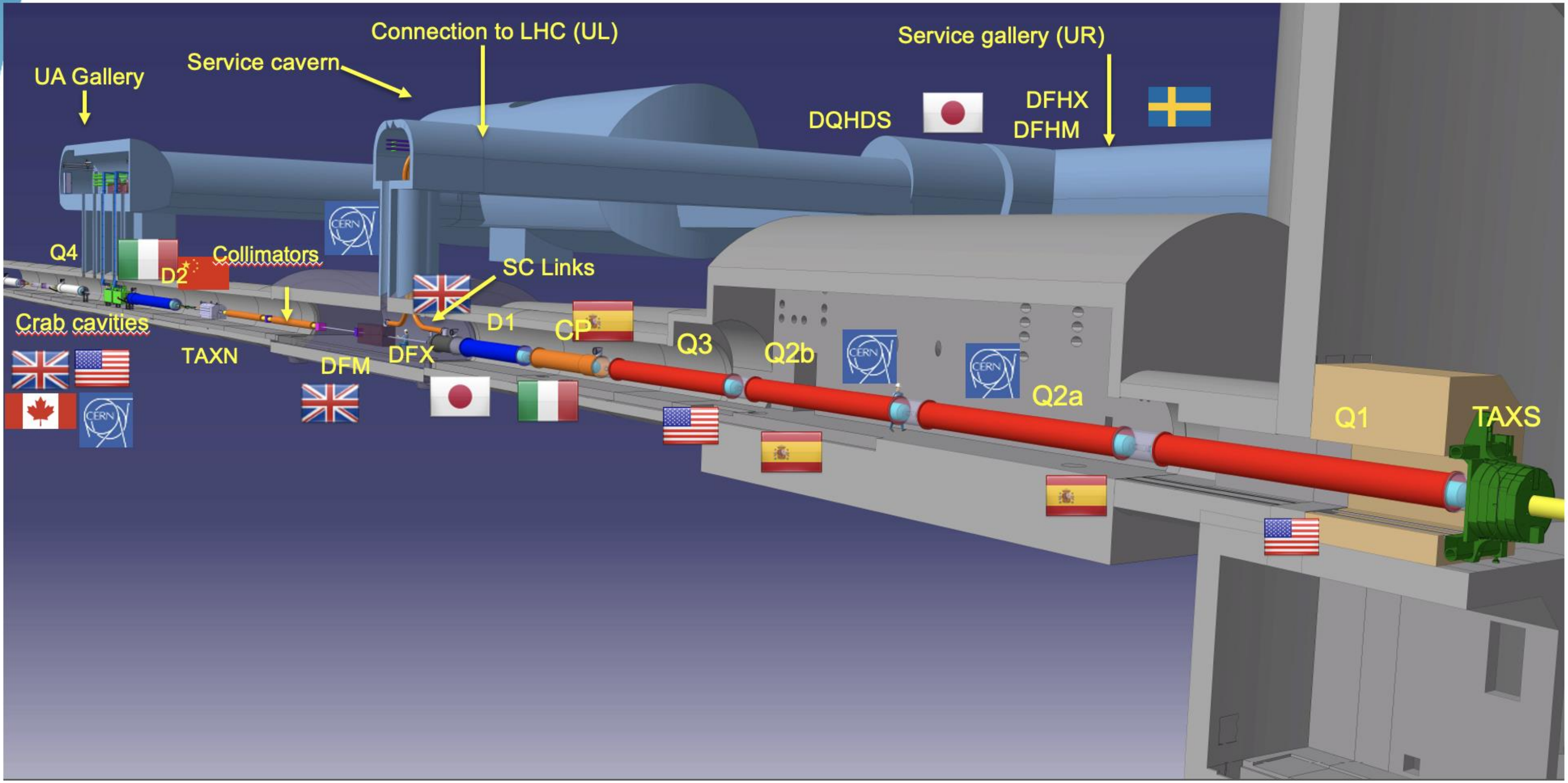
Registration is open !

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

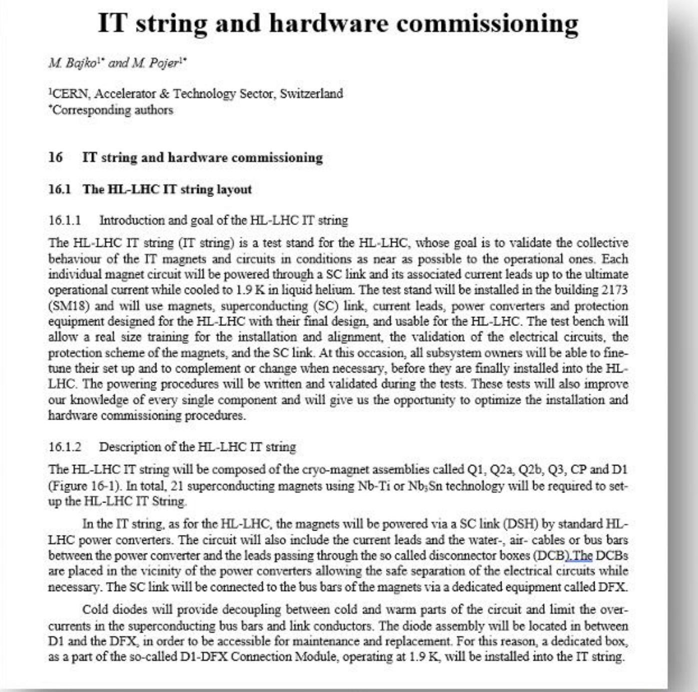
We look forward to welcoming you in San Francisco for what promises to be an exciting and informative event!

Backup material

The realization of HL-LHC is a truly international collaboration



The IT STRING Scope


IT string and hardware commissioning

M. Bajko[1*] and M. Pojer[1*]

[1]CERN, Accelerator & Technology Sector, Switzerland
*Corresponding authors

16 IT string and hardware commissioning

16.1 The HL-LHC IT string layout

16.1.1 Introduction and goal of the HL-LHC IT string

The HL-LHC IT string (IT string) is a test stand for the HL-LHC, whose goal is to validate the collective behaviour of the IT magnets and circuits in conditions as near as possible to the operational ones. Each individual magnet circuit will be powered through a SC link and its associated current leads up to the ultimate operational current while cooled to 1.9 K in liquid helium. The test stand will be installed in the building 2173 (SM18) and will use magnets, superconducting (SC) link, current leads, power converters and protection equipment designed for the HL-LHC with their final design, and usable for the HL-LHC. The test bench will allow a real size training for the installation and alignment, the validation of the electrical circuits, the protection scheme of the magnets, and the SC link. At this occasion, all subsystem owners will be able to fine-tune their set up and to complement or change when necessary, before they are finally installed into the HL-LHC. The powering procedures will be written and validated during the tests. These tests will also improve our knowledge of every single component and will give us the opportunity to optimize the installation and hardware commissioning procedures.

16.1.2 Description of the HL-LHC IT string

The HL-LHC IT string will be composed of the cryo-magnet assemblies called Q1, Q2a, Q2b, Q3, CP and D1 (Figure 16-1). In total, 21 superconducting magnets using Nb-Ti or Nb_3Sn technology will be required to set-up the HL-LHC IT String.

In the IT string, as for the HL-LHC, the magnets will be powered via a SC link (DSH) by standard HL-LHC power converters. The circuit will also include the current leads and the water-, air- cables or bus bars between the power converter and the leads passing through the so called disconnector boxes (DCB).The DCBs are placed in the vicinity of the power converters allowing the safe separation of the electrical circuits while necessary. The SC link will be connected to the bus bars of the magnets via a dedicated equipment called DFX.

Cold diodes will provide decoupling between cold and warm parts of the circuit and limit the over-currents in the superconducting bus bars and link conductors. The diode assembly will be located in between D1 and the DFX, in order to be accessible for maintenance and replacement. For this reason, a dedicated box, as a part of the so-called D1-DFX Connection Module, operating at 1.9 K, will be installed into the IT string.

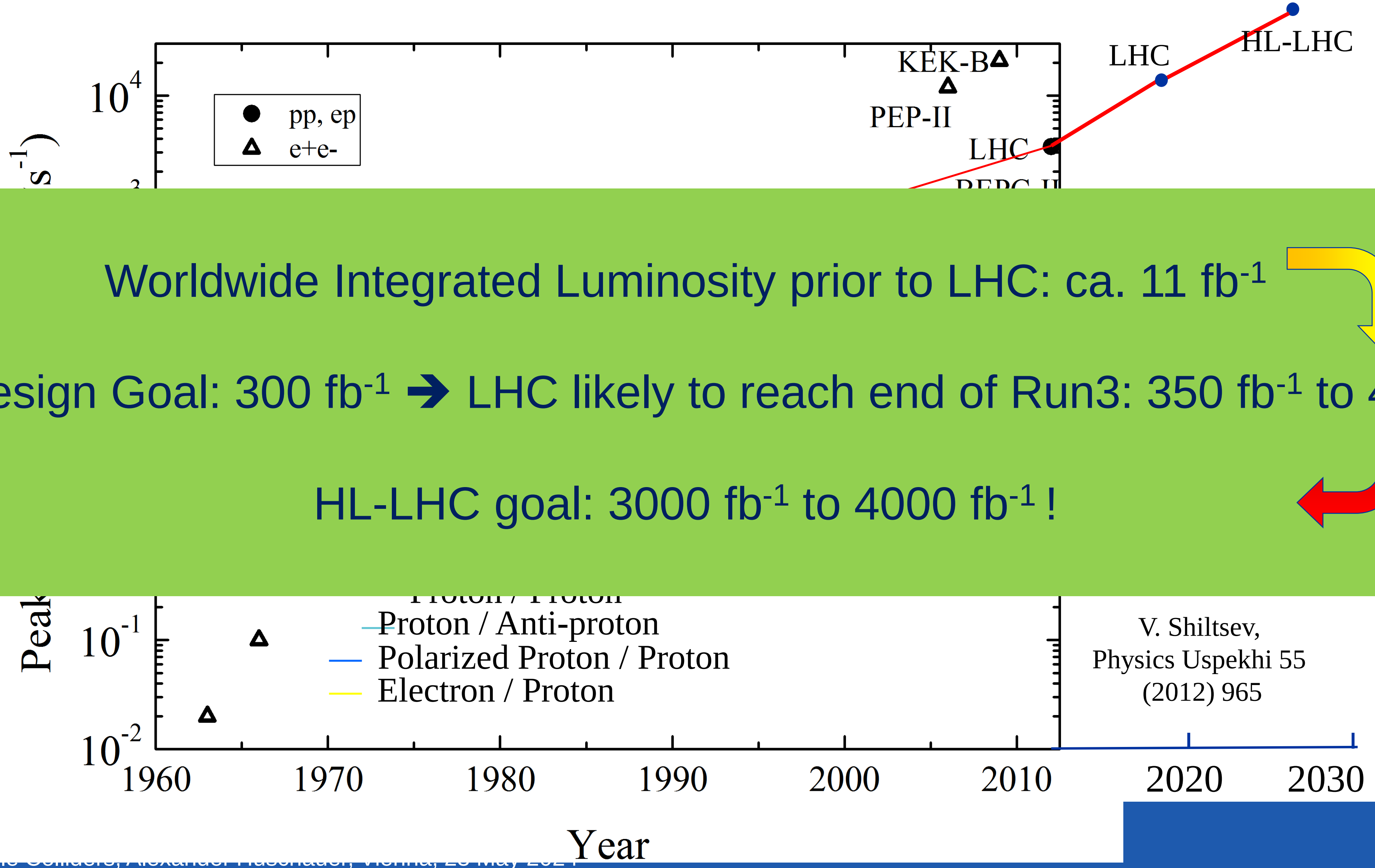
The ***scope*** of the IT STRING is to represent, as best as reasonably achievable in a surface building, the various operation modes to **STUDY and VALIDATE the COLLECTIVE BEHAVIOUR** of the different systems of the HL-LHC's IT zone (magnets, magnet protection, cryogenics of the magnets and of the superconducting link, magnet powering, vacuum, alignment, interconnections between magnets, and the superconducting link itself).

The IT **STRING** will deliver **the first complete experience** of installing and operating the IT zone

Early involvement of OP would be extremely important and beneficial for later commissioning in machine

Ref. HL-LHC IT STRING Scope https://edms.cern.ch/document/1693312/1

Peak luminosities of Hadron colliders



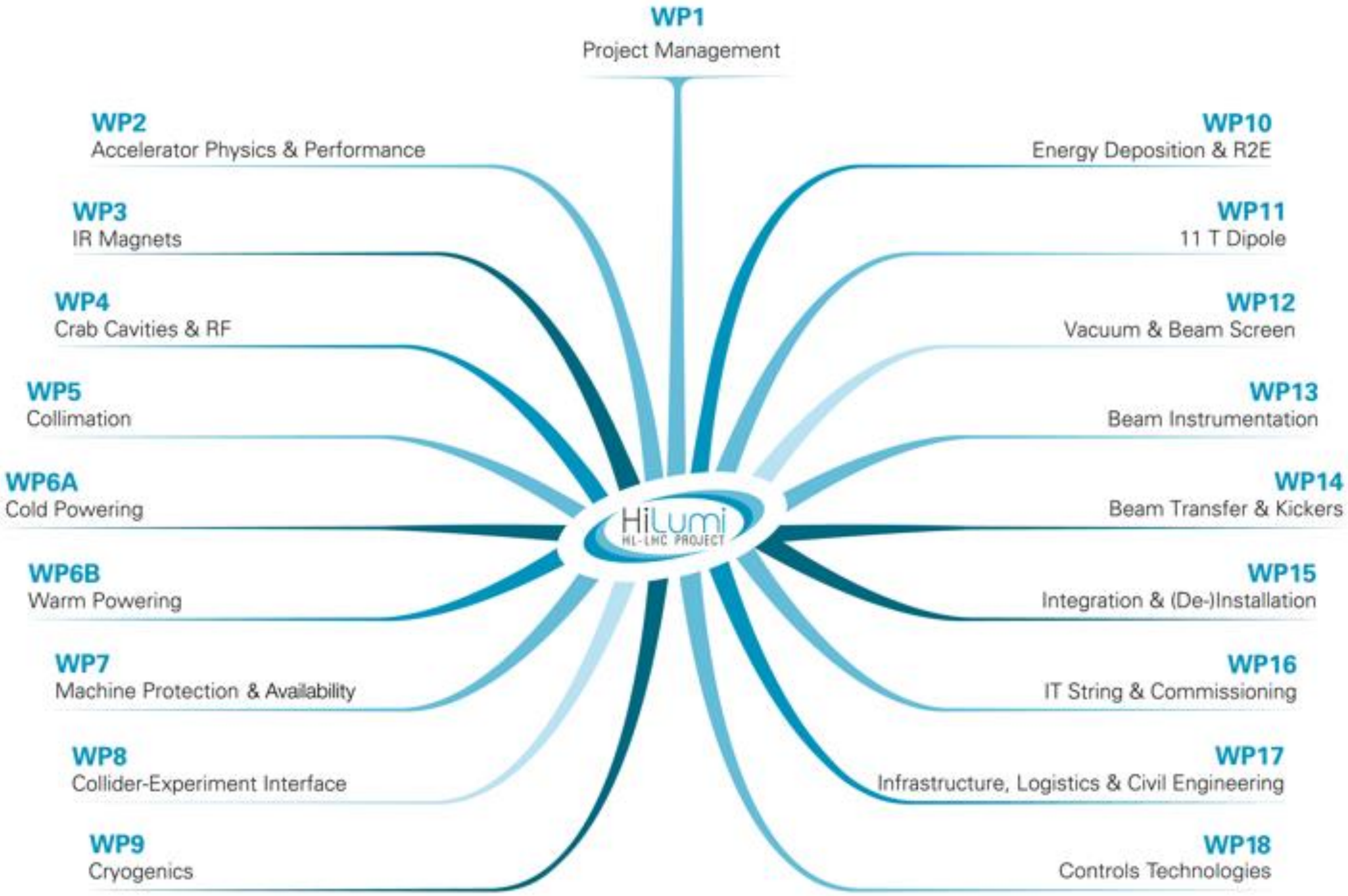
Worldwide Integrated Luminosity prior to LHC: ca. 11 fb^{-1}

x 35

LHC Design Goal: 300 fb^{-1} ➔ LHC likely to reach end of Run3: 350 fb^{-1} to 400 fb^{-1}

x 10

HL-LHC goal: 3000 fb^{-1} to 4000 fb^{-1} !


WP1
Project Management
WP2
Accelerator Physics & Performance
WP3
IR Magnets
WP4
Crab Cavities & RF
WP5
Collimation
WP6A
Cold Powering
WP6B
Warm Powering
WP7
Machine Protection & Availability
WP8
Collider-Experiment Interface
WP9
Cryogenics
WP10
Energy Deposition & R2E
WP11
11 T Dipole
WP12
Vacuum & Beam Screen
WP13
Beam Instrumentation
WP14
Beam Transfer & Kickers
WP15
Integration & (De-)Installation
WP16
IT String & Commissioning
WP17
Infrastructure, Logistics & Civil Engineering
WP18
Controls Technologies
HiLumi
HL-LHC PROJECT

FUTURE CIRCULAR COLLIDER

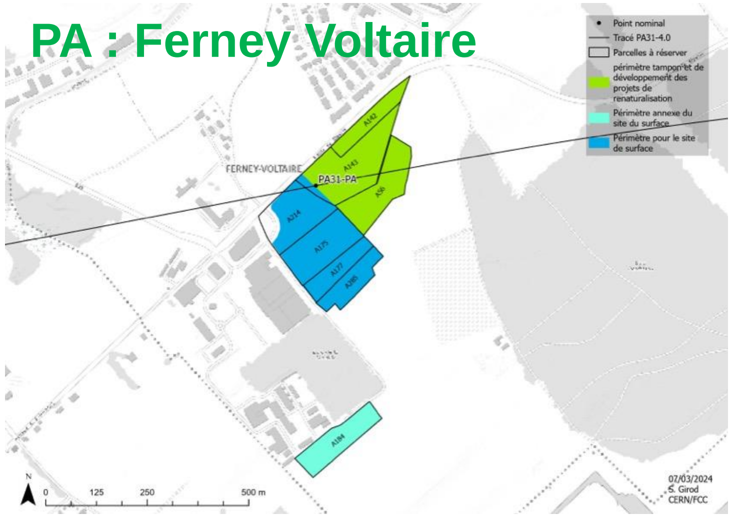
Surface sites development and reservation of land-plots

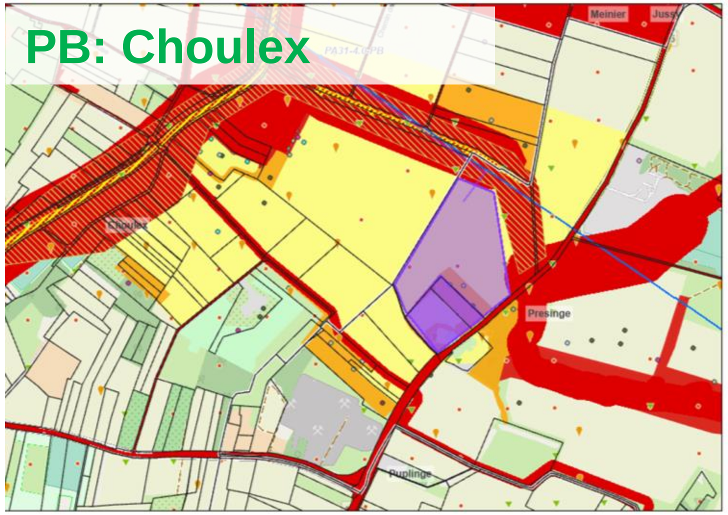
Meetings ongoing with all communes concerned by surface sites to identify individual land-plots for development of surface site layout and land reservation.

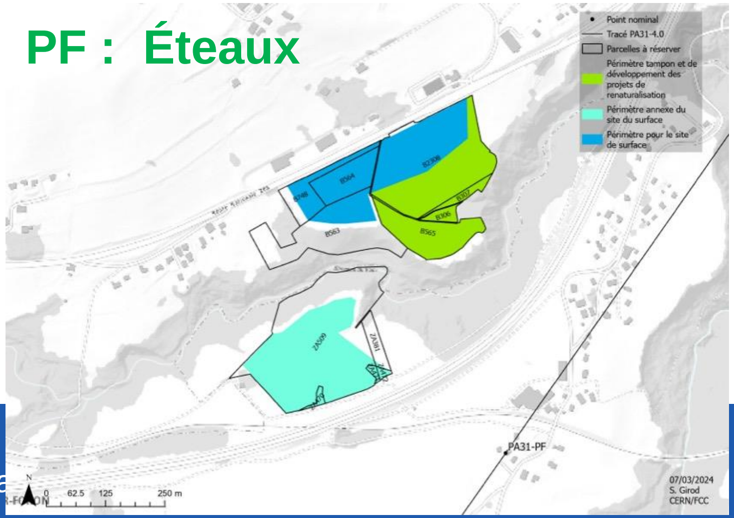
- **PA : Ferney Voltaire: 01/2024**
- **PB: Choulex : 12/2023**
- **PB: Presinge : 01/2024, plenary session with community council 04/2024**
- **PD : Nangy: 05/2024**
- **PF : Éteaux : 03/2024**
- **PG : Groisy / Charvonnex: 04/2024**
- **PH : Marlioz / Cercier : 02/2024**
- **PJ : Vulbens / Dingy en Vuache : 09/2023, 01/2024**
- **PL : Challex: 03/2024, further meetings in Q2/24 to identify best site location**

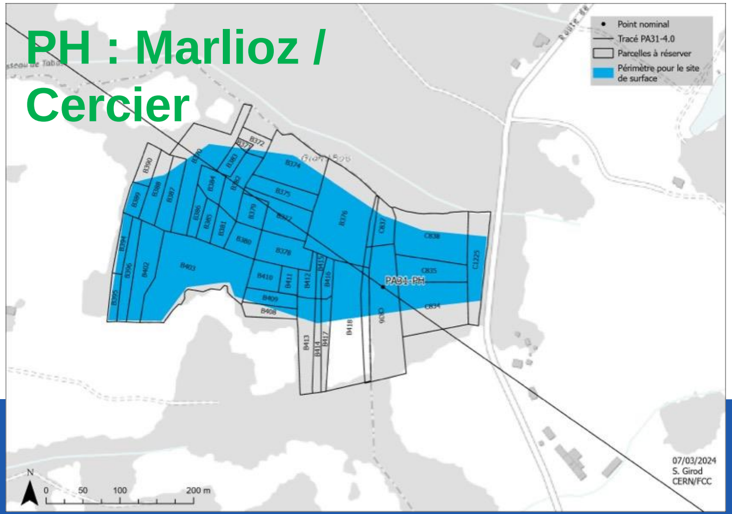
Green: parcelles identified and agreed

Blue: ongoing







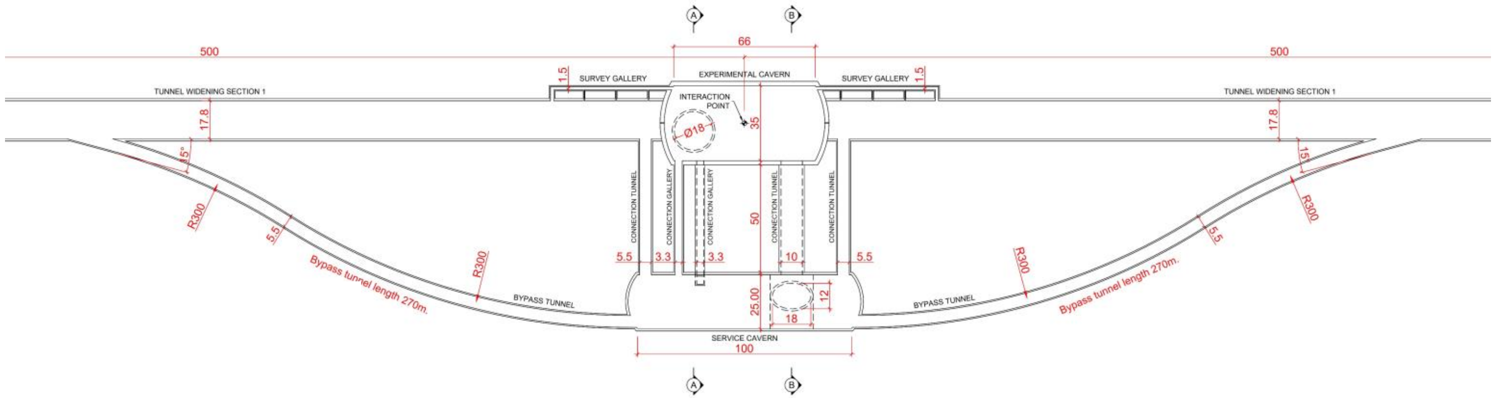


CE underground and surface progress

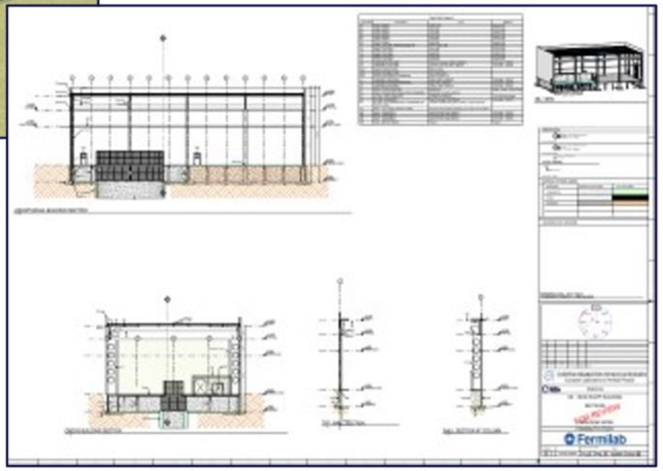
- **Full 3D model of all underground structures as basis for costing and scheduling exercises with external consultant.**

- **Experiment Site (PA)**

PLAN VIEW
1:3000



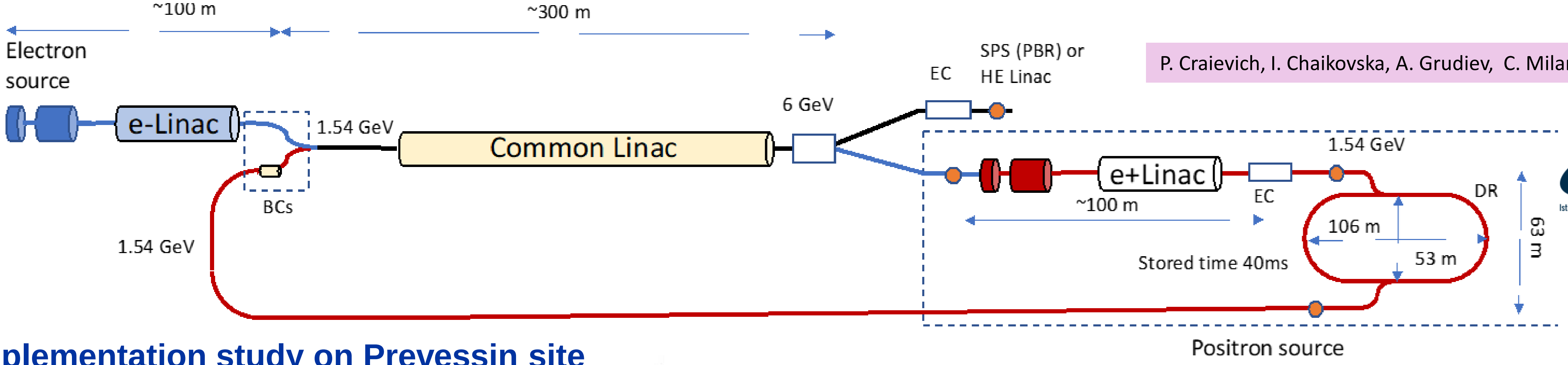
PLAN VIEW
1:1000



Examples of Fermilab Deliverables

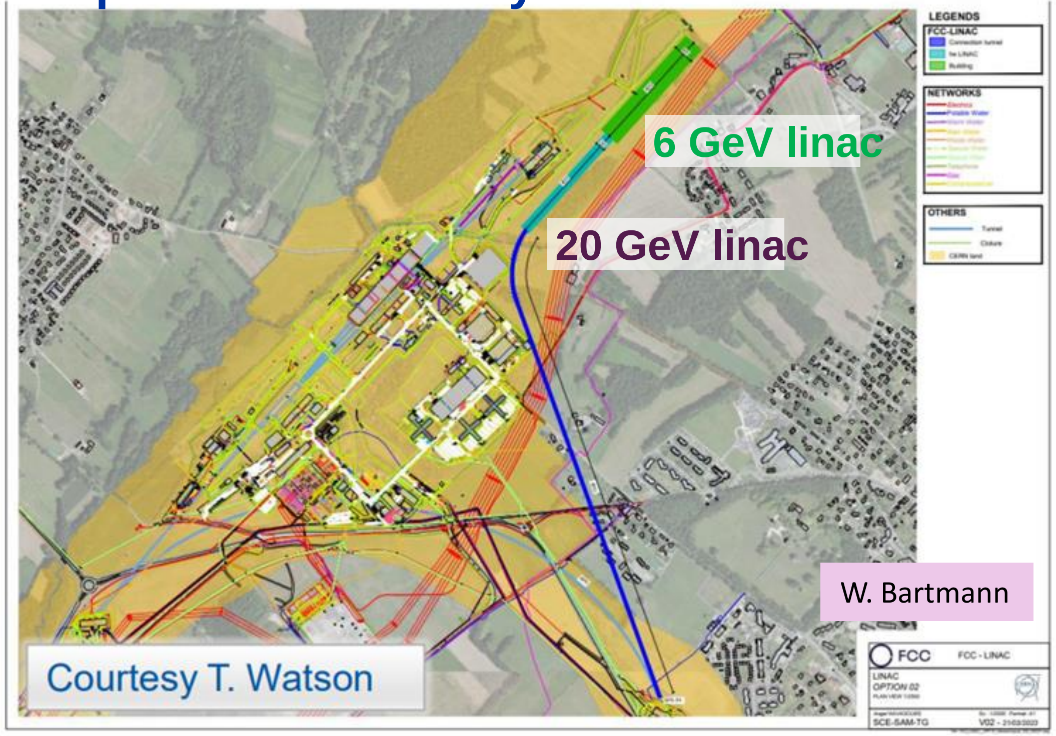
- **Generic study of experiment site and technical site done by FNAL**
- **bills of quantities extracted from FNAL designs**
- **basis for cost estimate by consultant with experience on industrial constructions in CH-FR area.**

FCC-ee injector layout & implementation

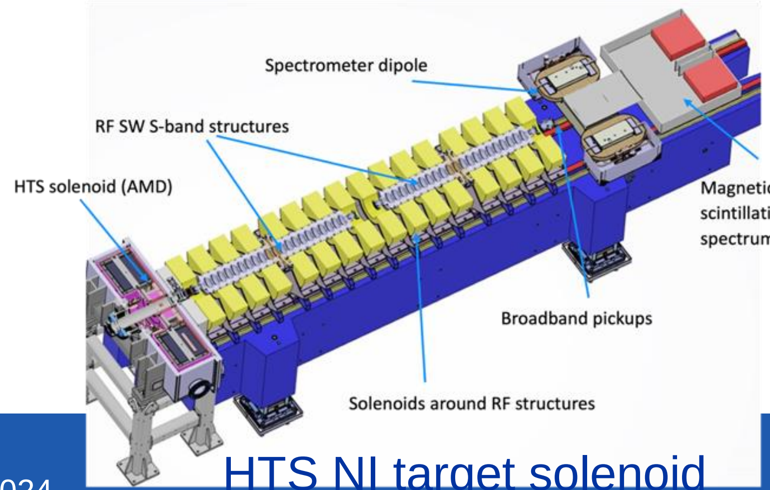


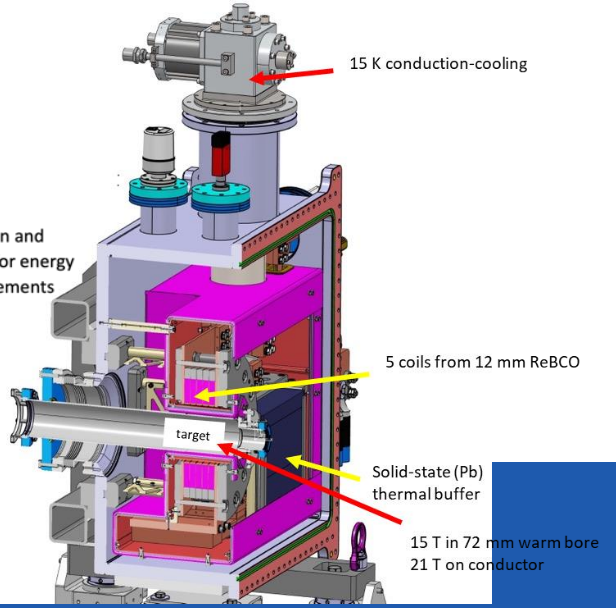
P. Craievich, I. Chaikovska, A. Grudiev, C. Milardi, et al

implementation study on Prevessin site



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





HTS NI target solenoid

J. Kosse, T. Michlmayr, H. Rodrigues

RF R&D activities

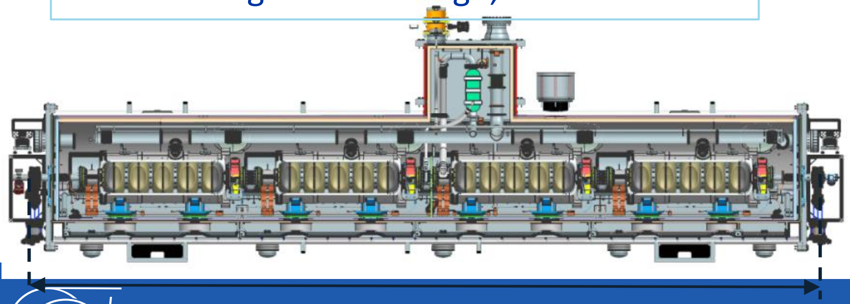
RF system R&D is key for increasing energy efficiency of FCC-ee

- Nb on Cu 400 MHz cavities, seamless cavity production, coating techniques
- Bulk Nb 800 MHz cavities, surface treatment techniques, cryomodule design
- RF power source R&D in synergy with HL-LHC.

800 MHz cavity and CM design

collaborations with **JLAB and FNAL**

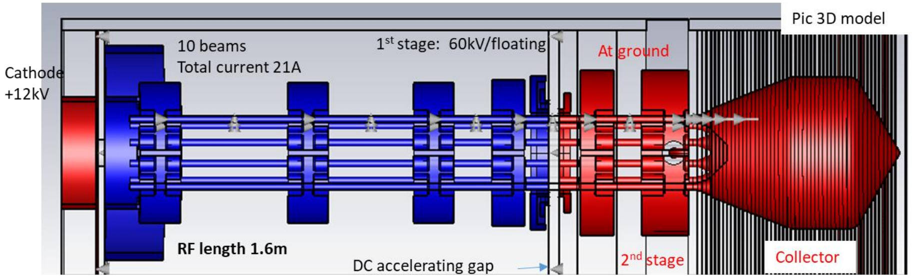
800 MHz segmented design, based on PIP-II

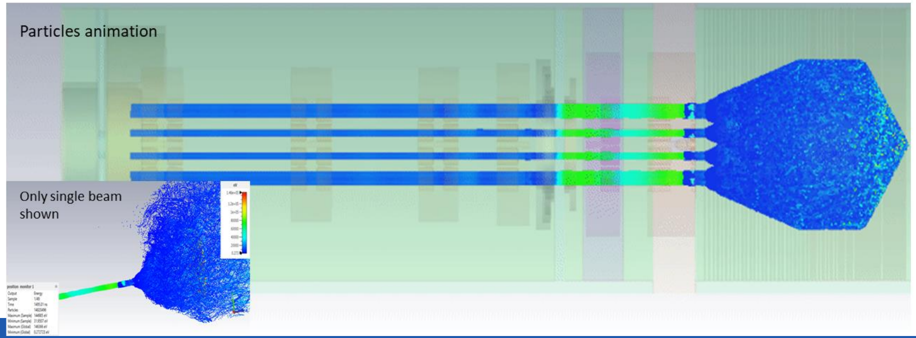


high-efficiency klystron R&D

in collaborations with **THALES & CANON**

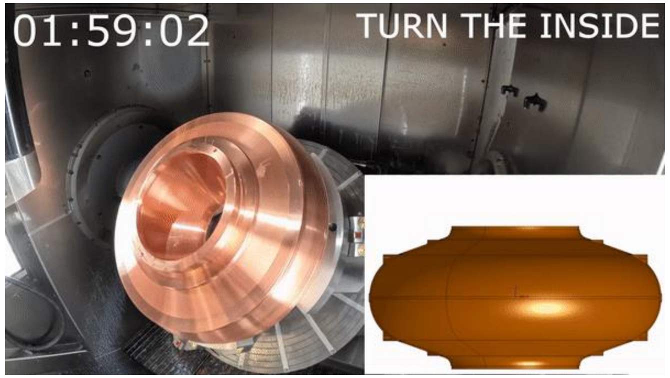
Novel two-stage MBK klystron: CW, 400MHz, 1.28MW.





400 MHz cavity production

in collaboration with **KEK**



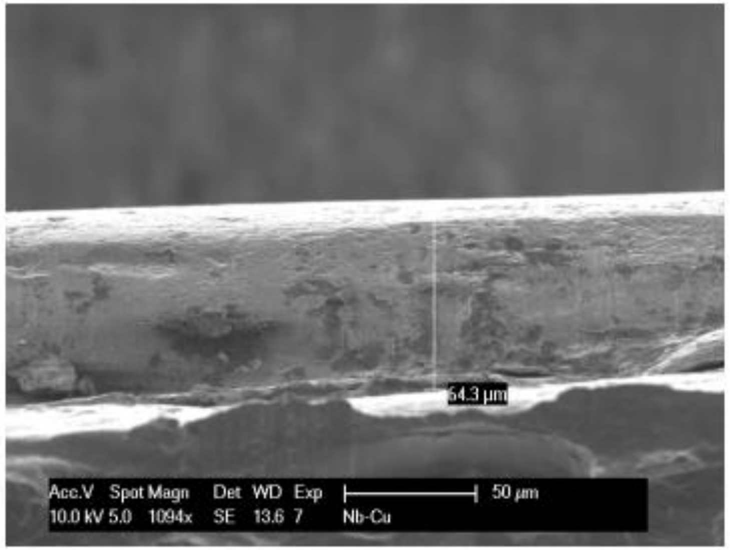
SRF: seamless cavities & thin film coating

C. Pira

Seamless production

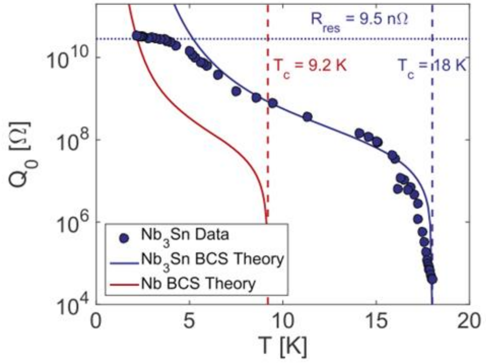
First seamless multicell by spinning

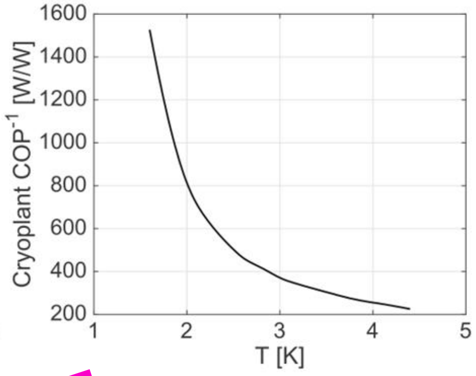
Nb on Cu coating



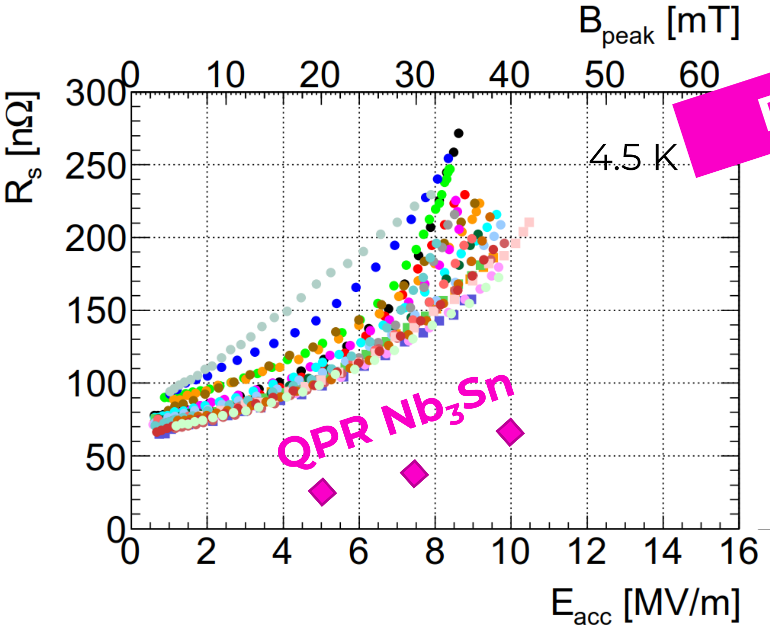
SEM micrograph of the film cross section

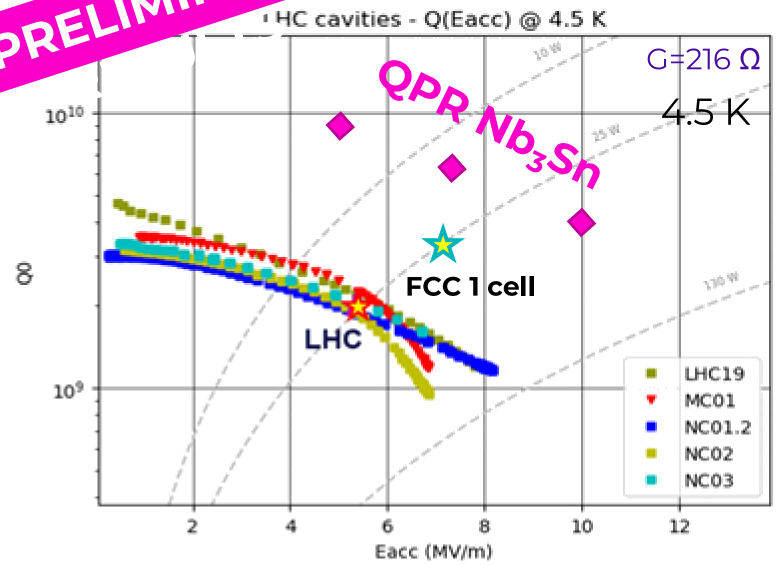
Move from Nb @2K to Nb_3Sn @4.5 K would reduce cryogenic power by a factor of 3





Nb_3Sn on Cu coating





Equivalent to a Q of $9*10^9$ @5 MV/m @4.5 K

Almost 1 order of magnitude better than LHC !

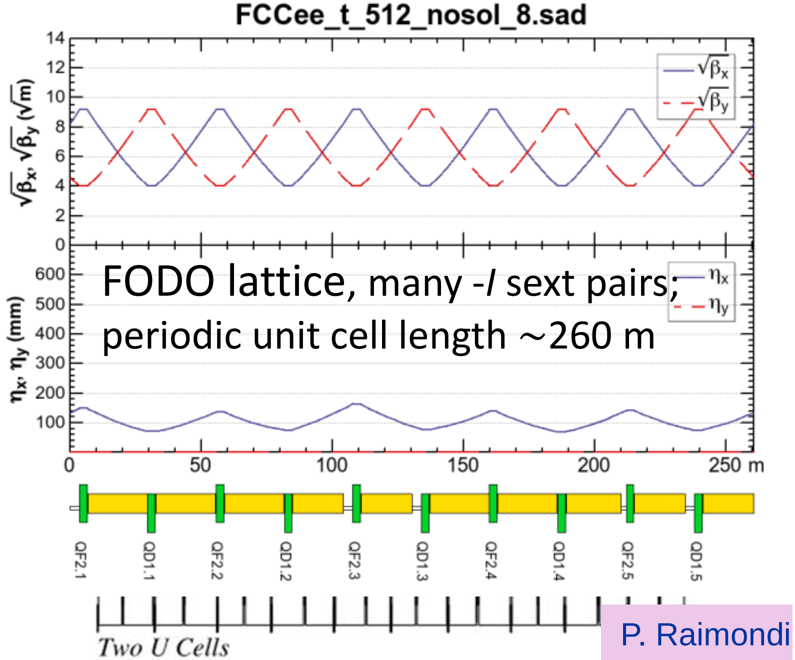
Room for improvement

FCC-ee optics baseline & further evolution(s)

regular arc

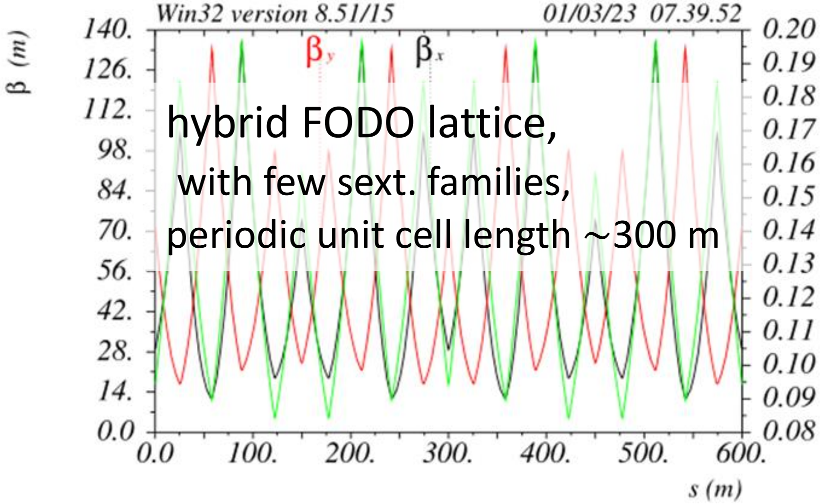
K. Oide

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



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

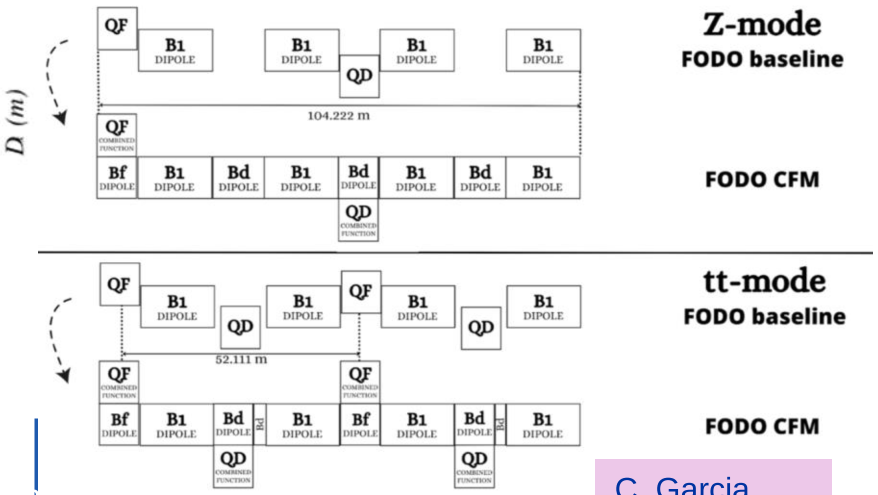
P. Raimondi



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

optimisation goals:

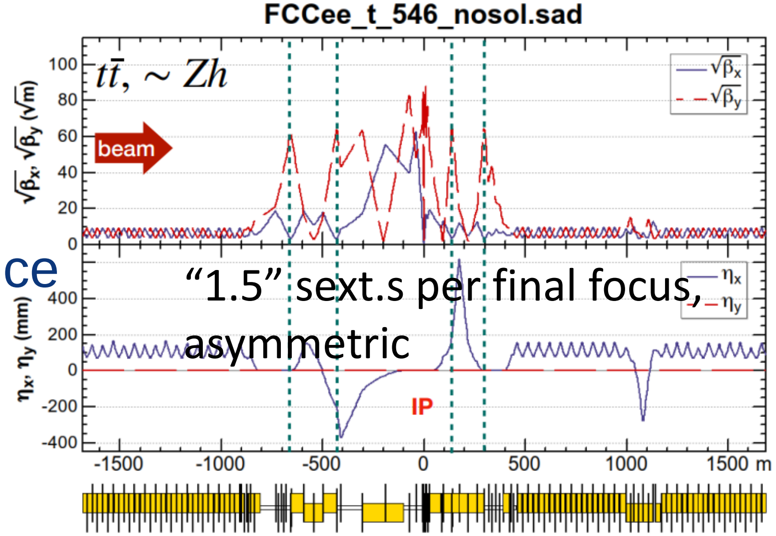
- reduced power consumption
- lower SR energy loss
- increased momentum acceptance
- relaxed tolerances
- larger dynamic aperture
- simplified powering schemes



C. Garcia, R. Tomas, et al.

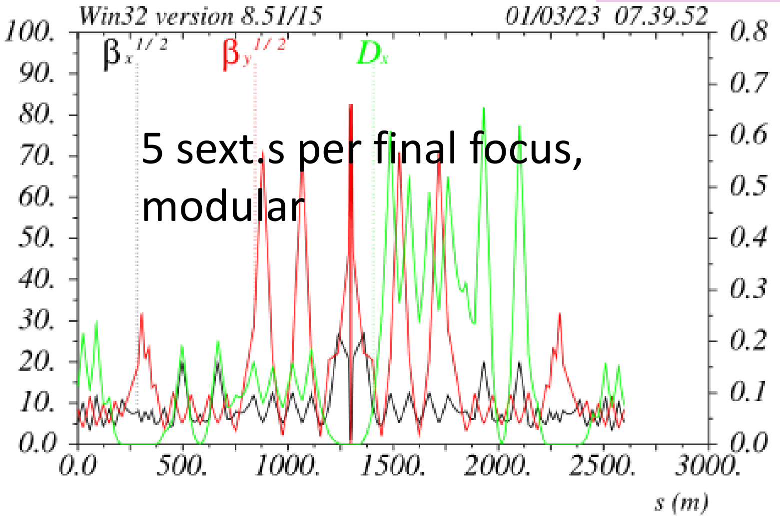
interaction region

K. Oide



"1.5" sext.s per final focus, asymmetric

P. Raimondi

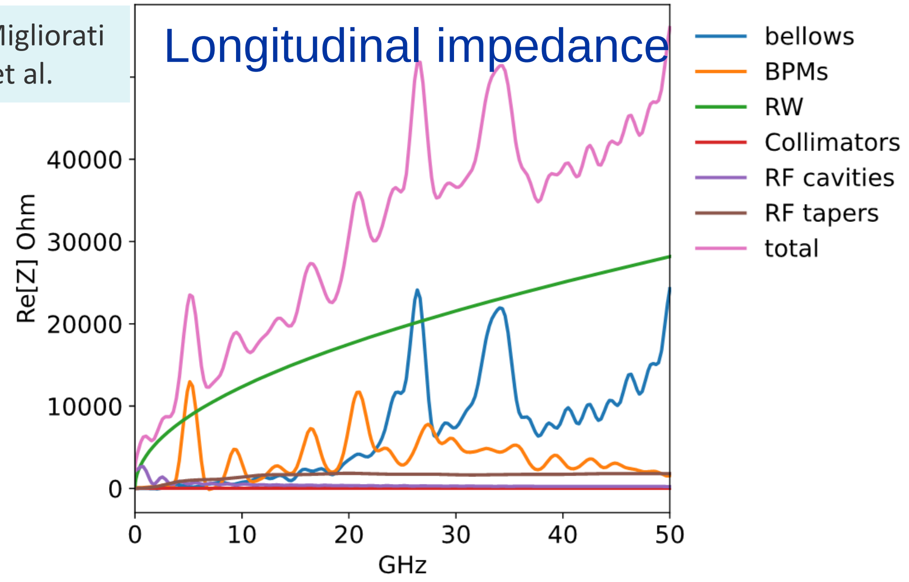


5 sext.s per final focus, modular

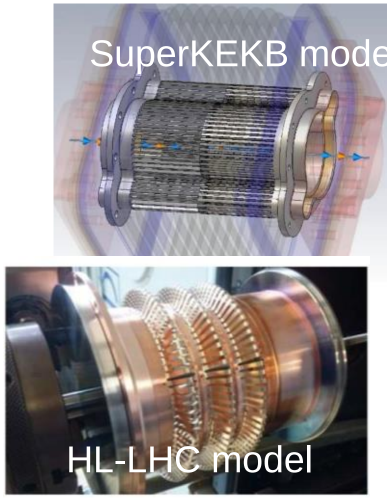
FCC-ee Beam Impedance & Collective Effects

FUTURE CIRCULAR COLLIDER

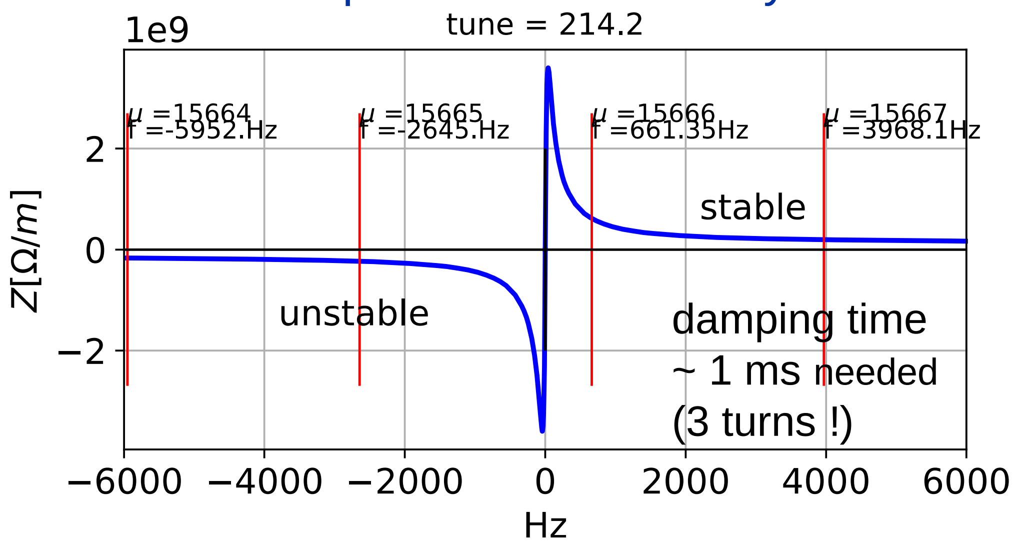
M. Migliorati et al.

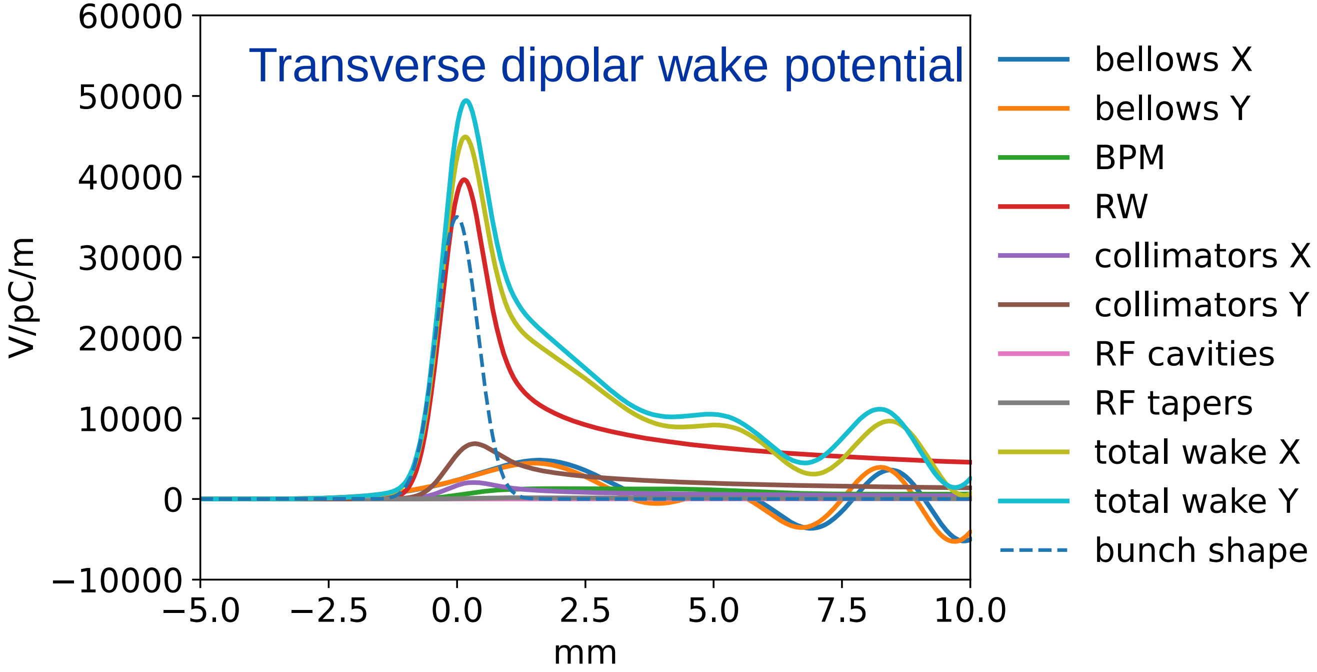


Bellows

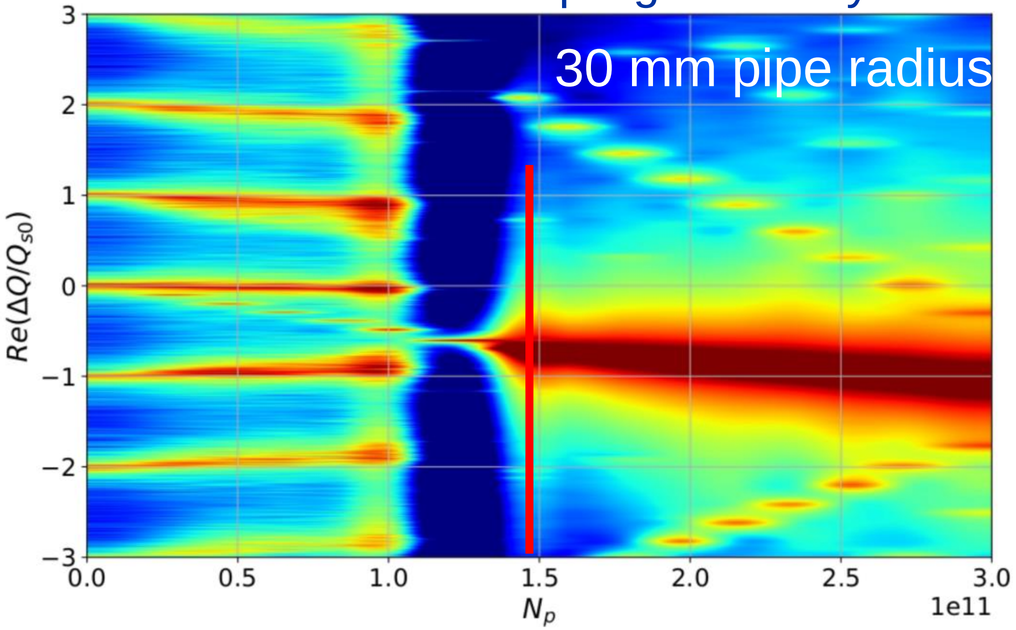


Transverse coupled bunch instability and feedba



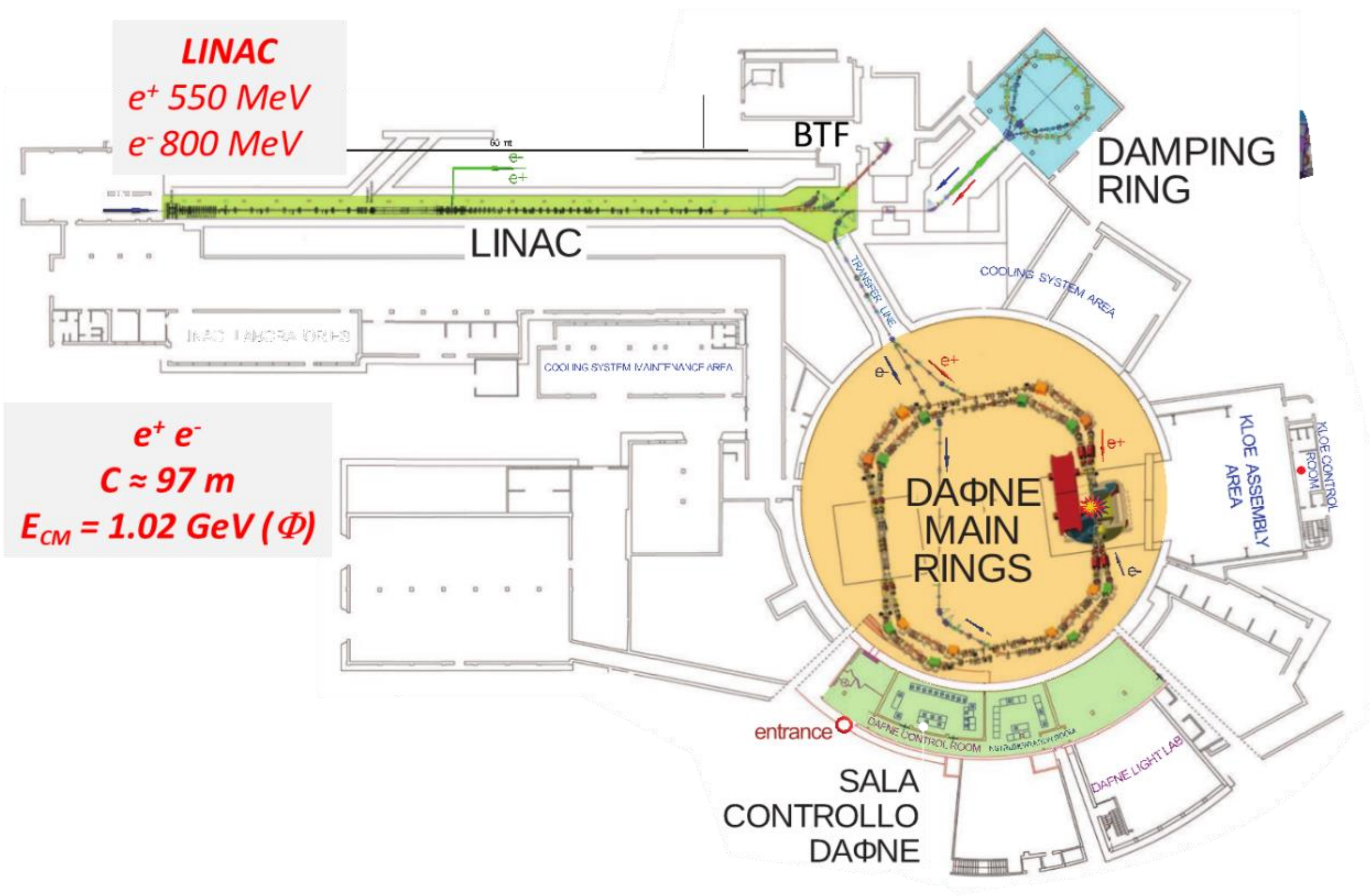


Transverse Mode Coupling instability



Proposed DAΦNE Collider Test Facility

C. Milardi



Schematic of the DAΦNE collider complex in Frascati, which could become a formidable test facility for the FCC-ee

Highlight assets:

- "**crab-waist collisions**", developed at DAΦNE, key for FCC-ee
- **monochromatised beam collisions**, concept invented at LNF, proposed for FCC-ee
- **highest electron and positron beam currents in the world**
- **only operating electron-positron collider** in Europe (& none in the United States)

Example studies:

1) Testing advanced optics measurements, beam-based alignment, and machine tuning;
2) Studying luminosity performance through tune scans in crab-waist collision - importance of synchro-betatron resonances ?;
3) Exploring the interplay of beam-beam forces and wakefields;
4) Demonstrating monochromatized collisions;
5) Test of advanced beam diagnostics, e.g. prototype BPMs and IR bellows for the FCC-ee;
6) Development and testing of advanced beam feedback systems;
7) Beam test of prototype FCC-ee collimators;
8) Code benchmarking for electron-cloud and ion effects, as well as for collimation simulation tools;
9) Beam tests of prototype FCC-ee magnets and SRF cavities.

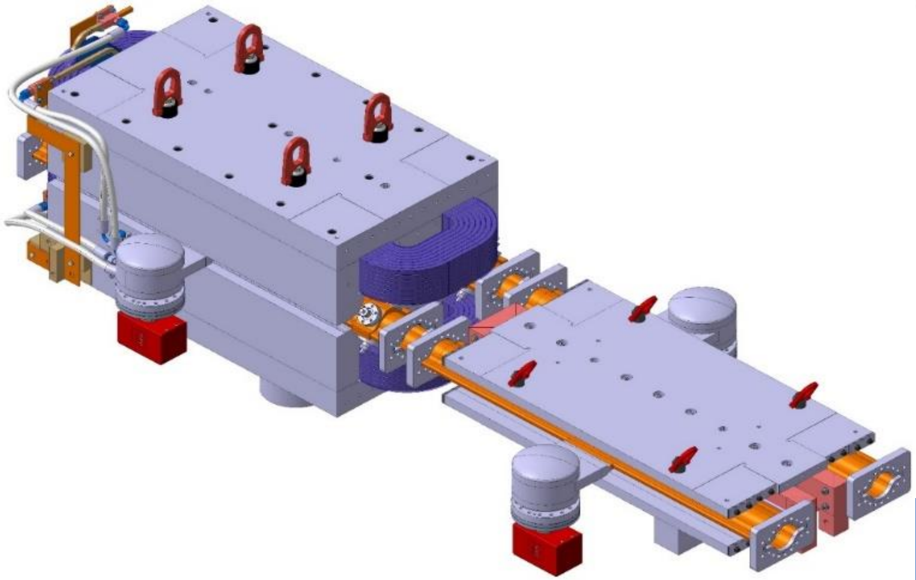
Continuing the operation of DAΦNE as a test facility is an unique opportunity not to be missed.

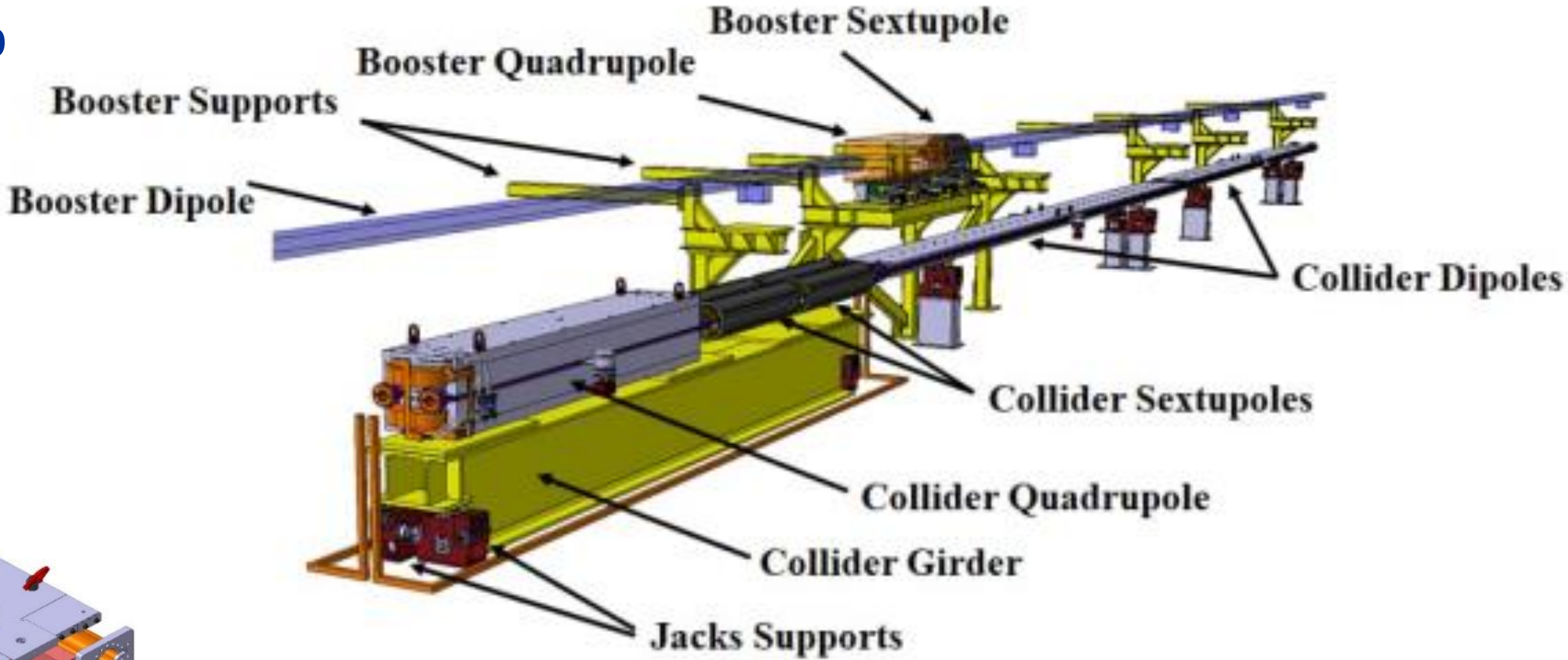
Arc layout and integration optimisation

Arc cell optimisation – 80 km total system 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,

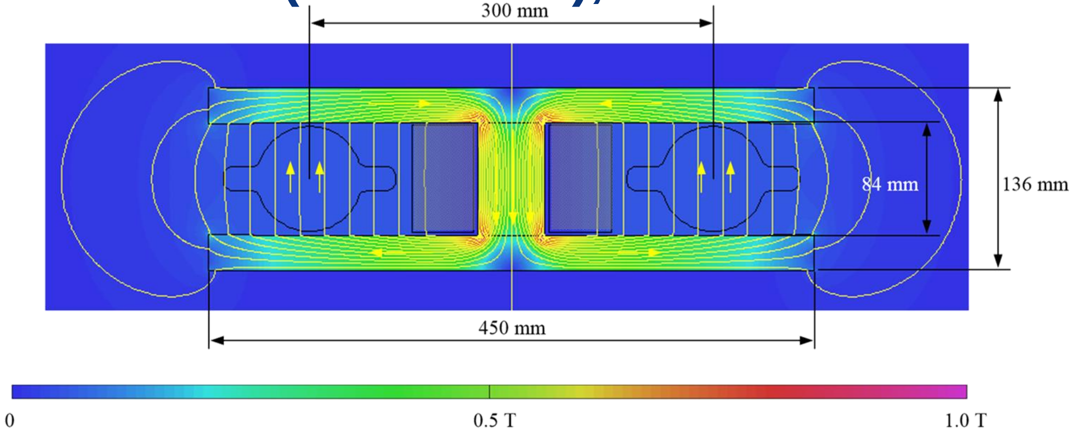
FCC-ee arc half-cell mock up

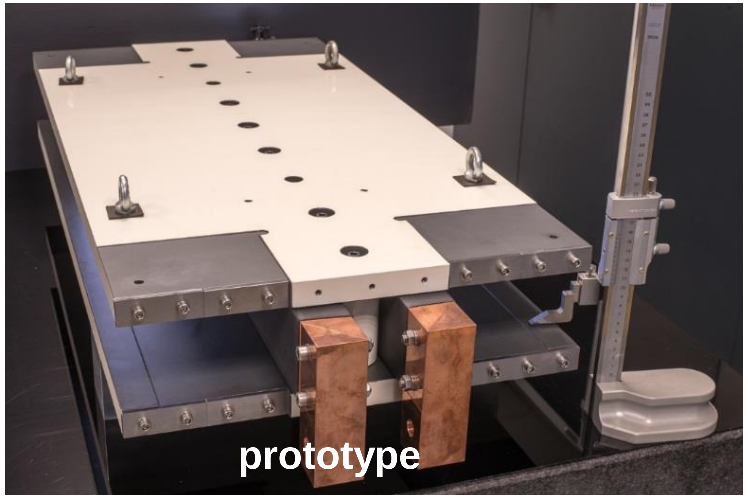




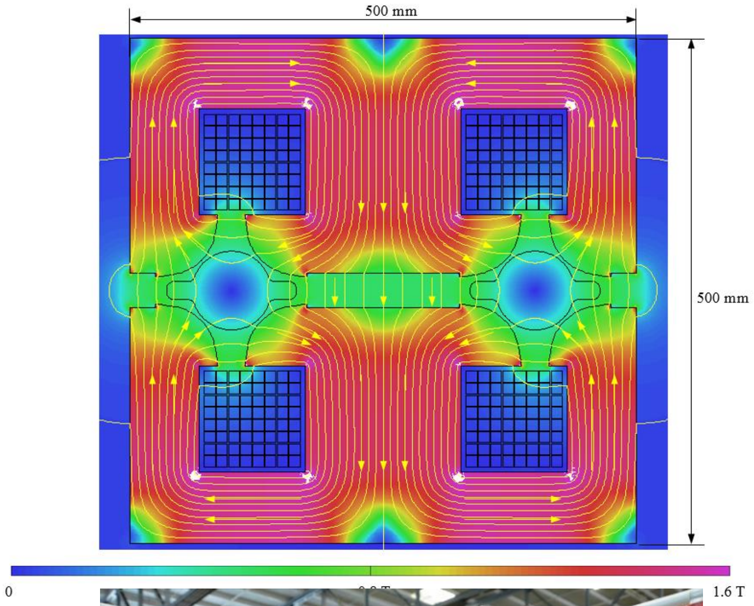
Prototypes of FCC-ee low-power magnets

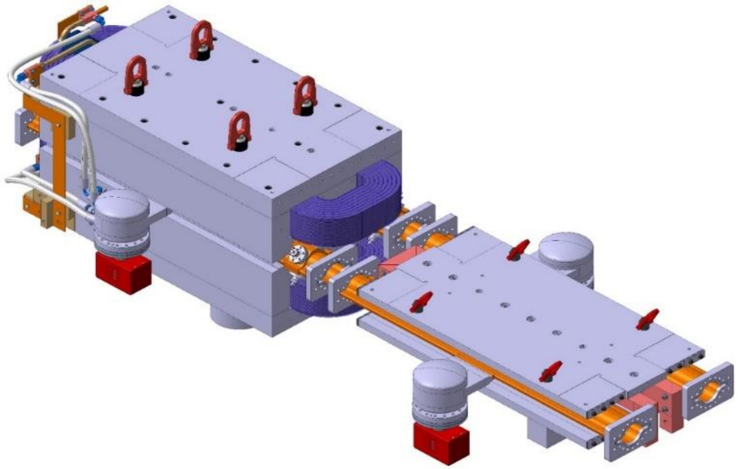
Twin-dipole design with 2× power saving 16 MW (at 175 GeV), with Al busbars

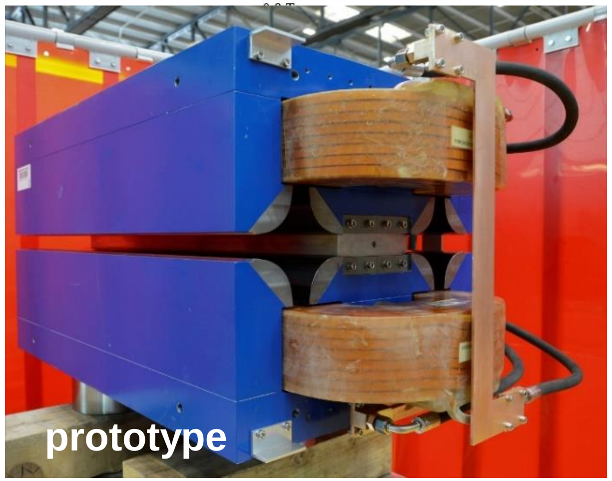




Twin F/D arc quad design with 2× power saving 25 MW (at 175 GeV), with Cu conductor







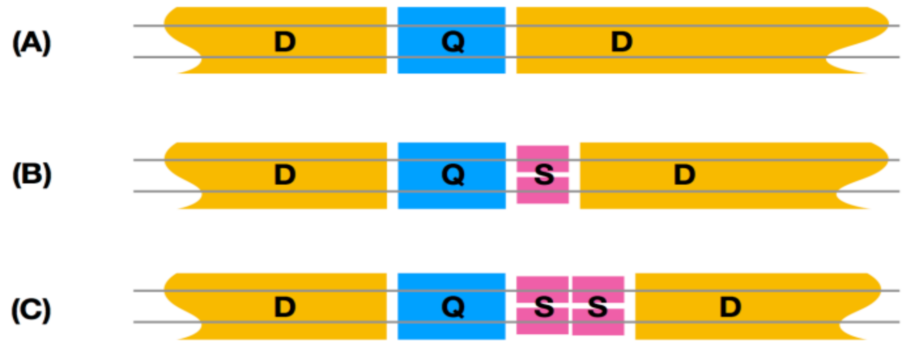
even more efficient alternative magnet designs are being explored

HTS option for FCC-ee arc quads and sextupoles

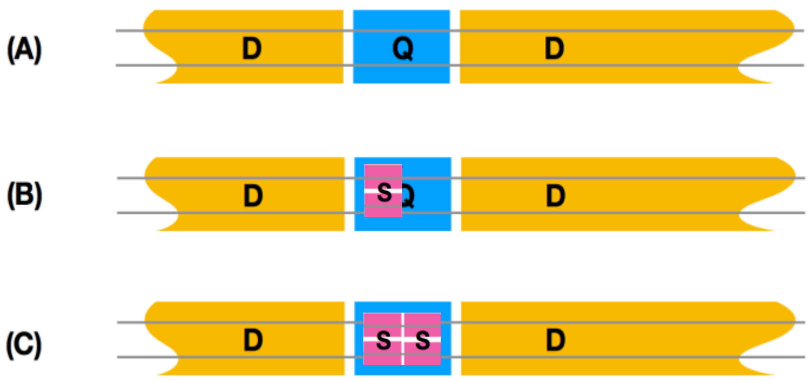
CDR: 2900 quads & 4700 sextupoles

- Normal conducting, ~50 MW @ ttbar
- 3 different types of short straight sections

CDR arc lattice



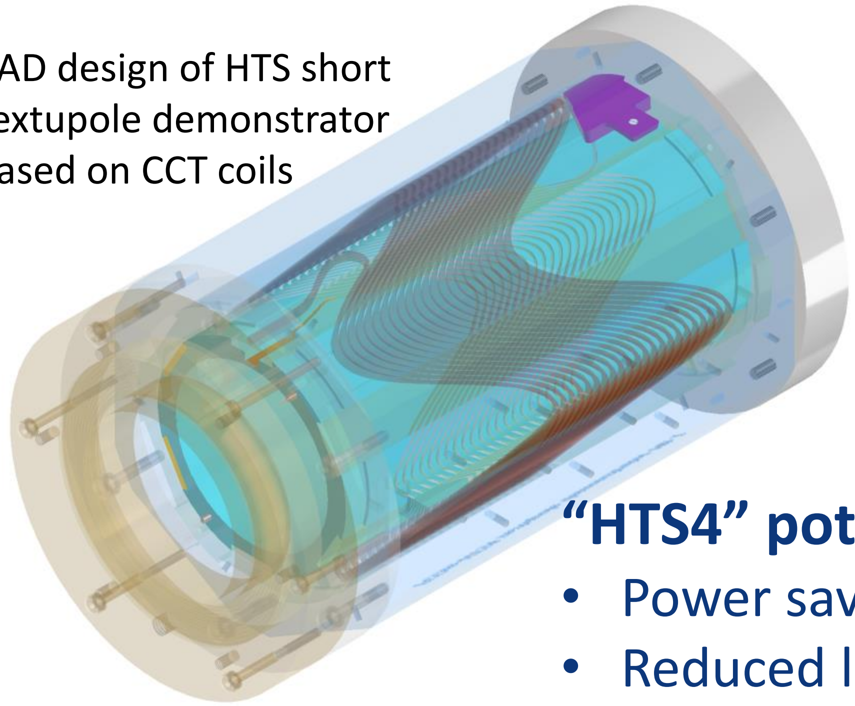
HTS option

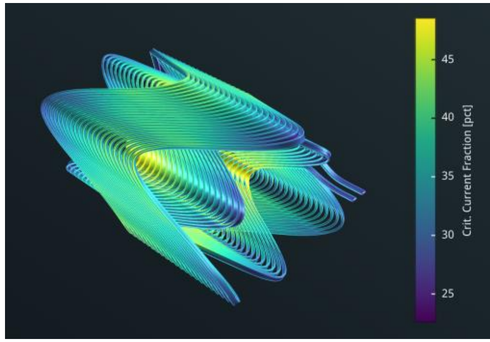


"HTS4" project within CHART collaboration

- Nested SC sextupole and quadrupole.
- HTS conductors operating at around 40K.
- Cryo-cooler supplied cryostat
- Produce a ~1m prototype by 2026

CAD design of HTS short sextupole demonstrator based on CCT coils





"HTS4" potential

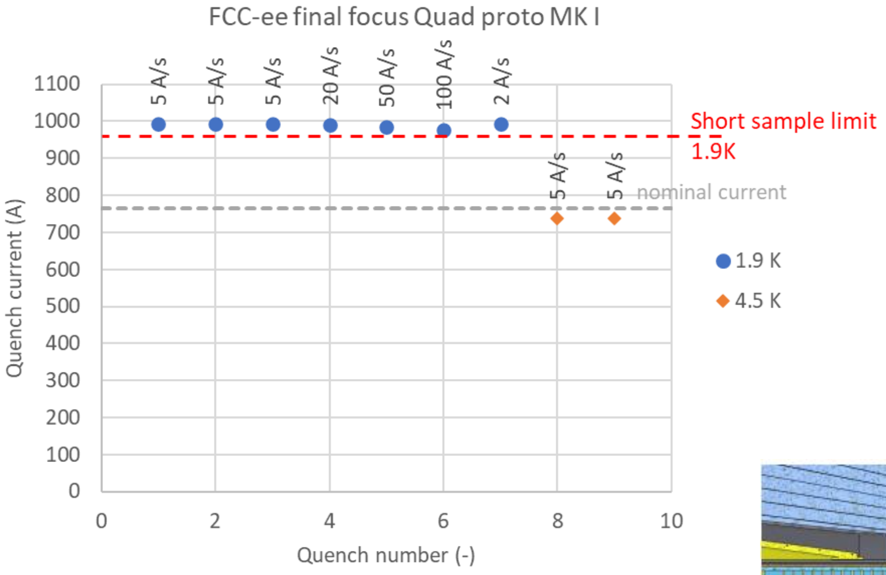
- Power saving
- Reduced length and increased dipole filling factor
- Optics flexibility

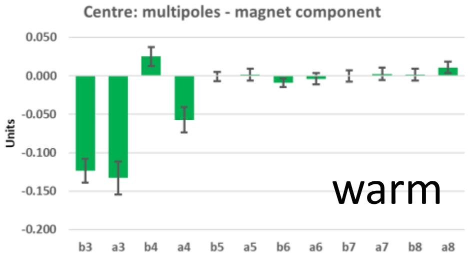
M. Koratzinos, B. Auchmann

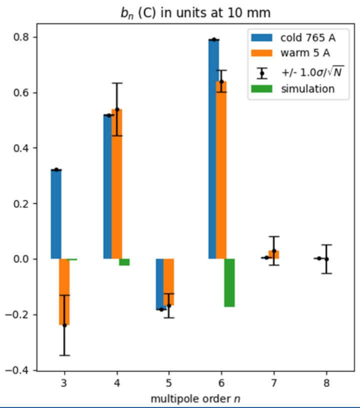
Prototype Q1 (left) & Interaction Region Mock-Up (right)

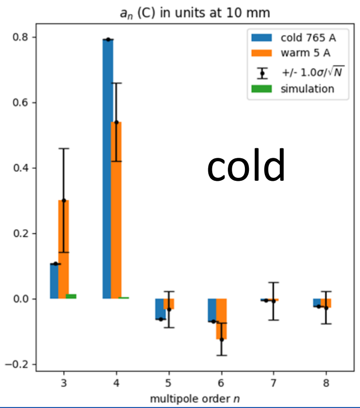
FUTURE CIRCULAR COLLIDER

Testing at cold in SM18 (CERN), 27-31 October 2023





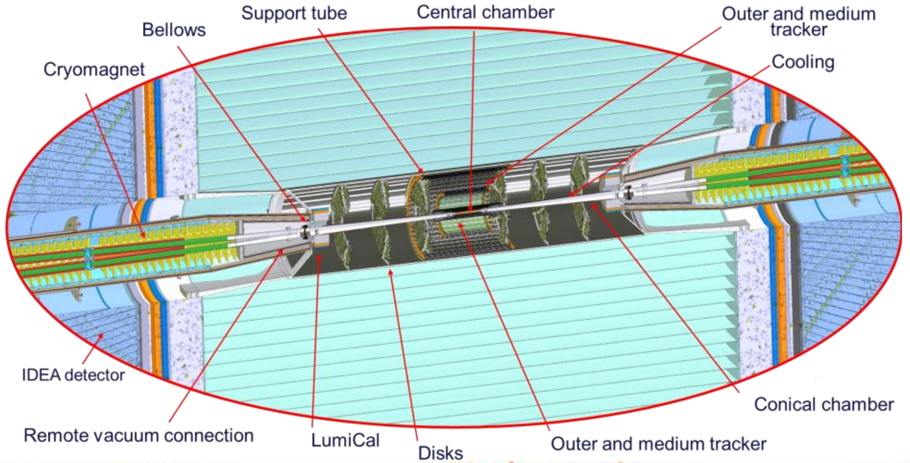




field quality:
all multipole errors <1 unit !

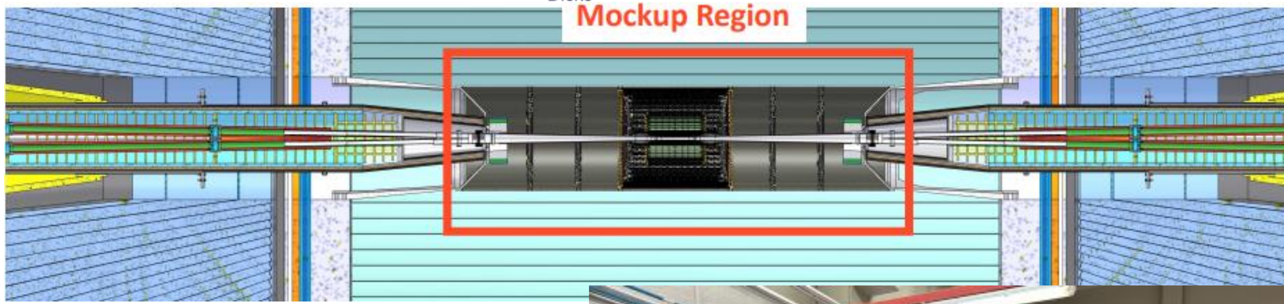
CERN-PSI collaboration

PAUL SCHERRER INSTITUT PSI



INFN-LNF, CERN and INFN-Pisa collaboration

INFN PISA Istituto Nazionale di Fisica Nucleare Sezione di Pisa

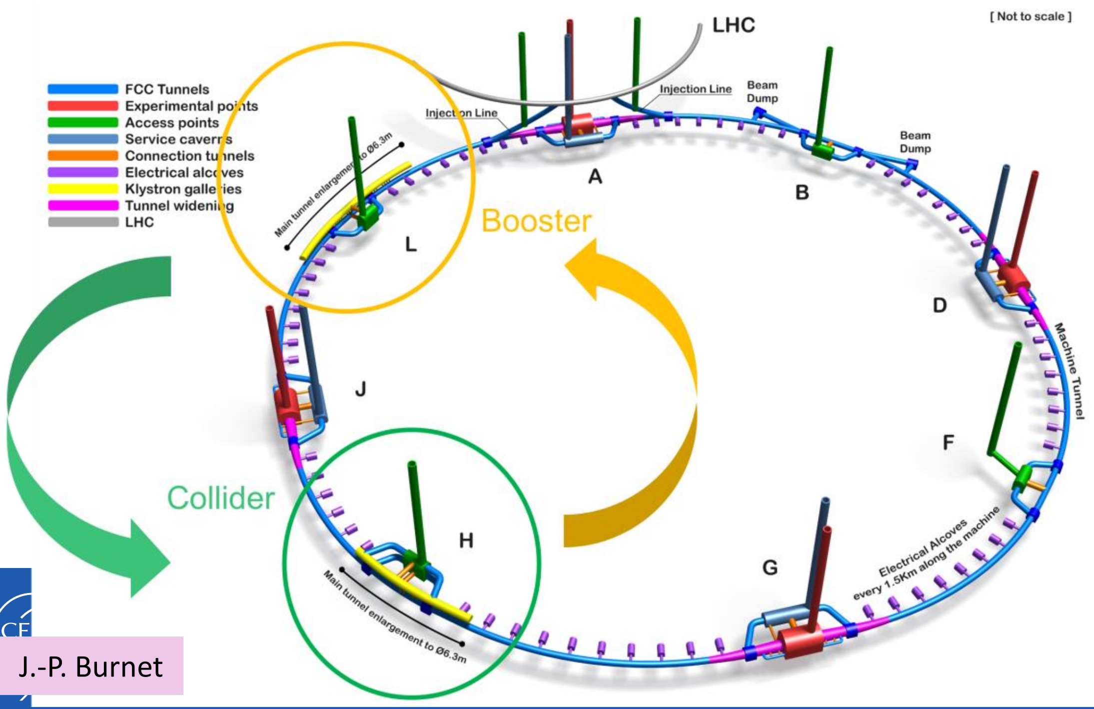


INFN LNF Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

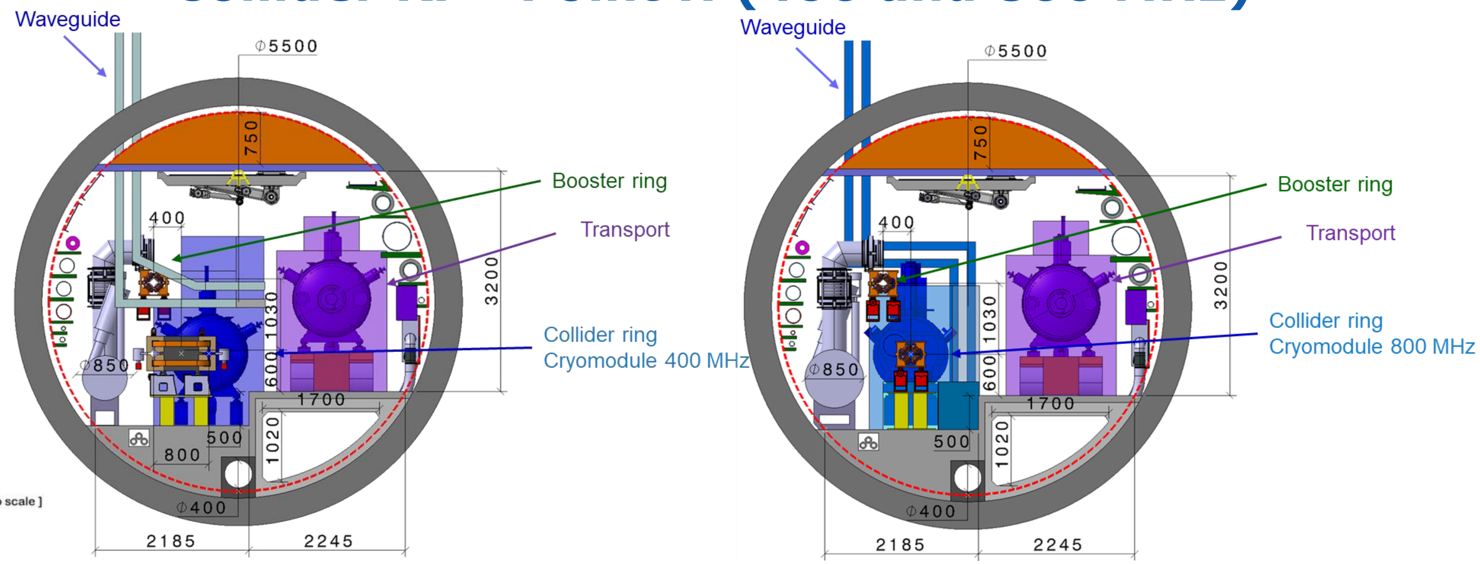
FCC-ee IR mock-up assembly & test lab at INFN Frascati

FCC-ee RF layout

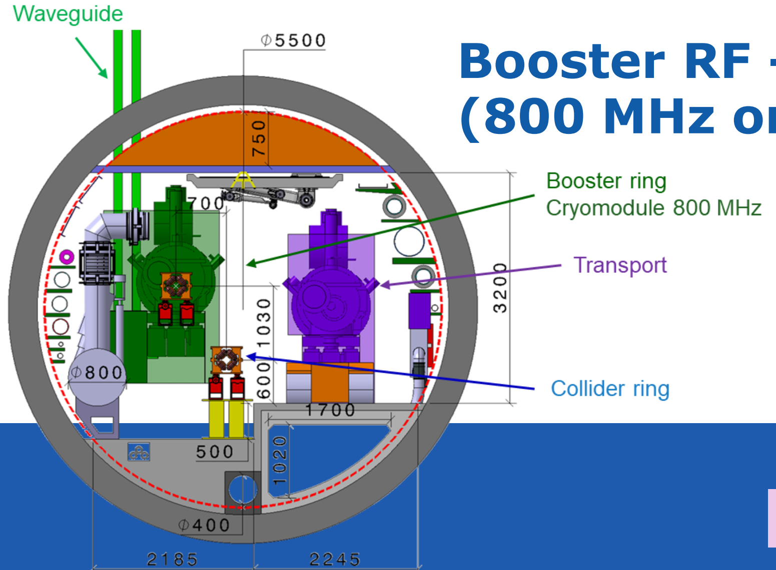
- RF for collider and booster in separate straight sections H and L.
- fully separated technical infrastructure systems (cryogenics)
- collider RF (highest power demand) in point H with optimum connection to existing 400 kV grid line and better suited surface site



Collider RF - Point H (400 and 800 MHz)



Booster RF - Point L (800 MHz only)



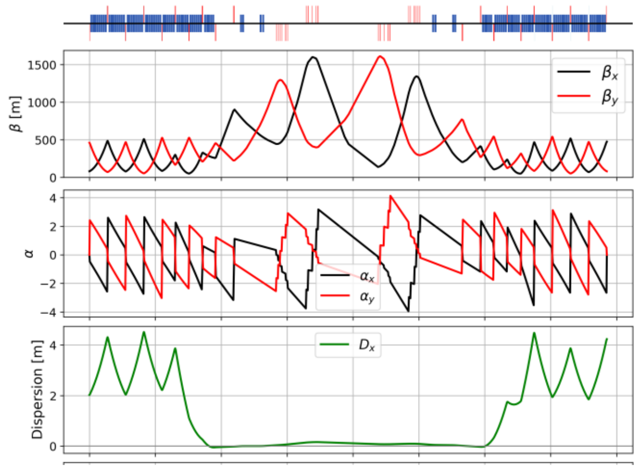
J.-P. Burnet

F. Valchova, F. Peauger

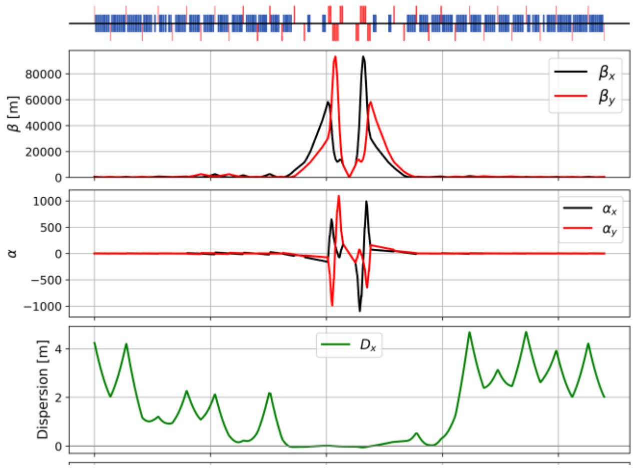
Key activities on FCC-hh: cryo magnet system, optics design

Optics design activities:

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



betatron collimation straight



experimental straight

High-field cryo-magnet system activities

- Conceptual study of cryogenics concept and temperature layout for LTS and HTS based magnets, in view of electrical consumption.
- HFM R&D (LTS and HTS) on technology and magnet design, aiming also at bridging the TRL gap between HTS and Nb_3Sn.
- Integration studies for HFM designs (LTS and HTS) to ensure compatibility with tunnel.