Future Circular Colliders

HEP research infrastructure for the 21st century

Michael Benedikt, CERN

on behalf of the FCC collaboration

http://cern.ch/fcc

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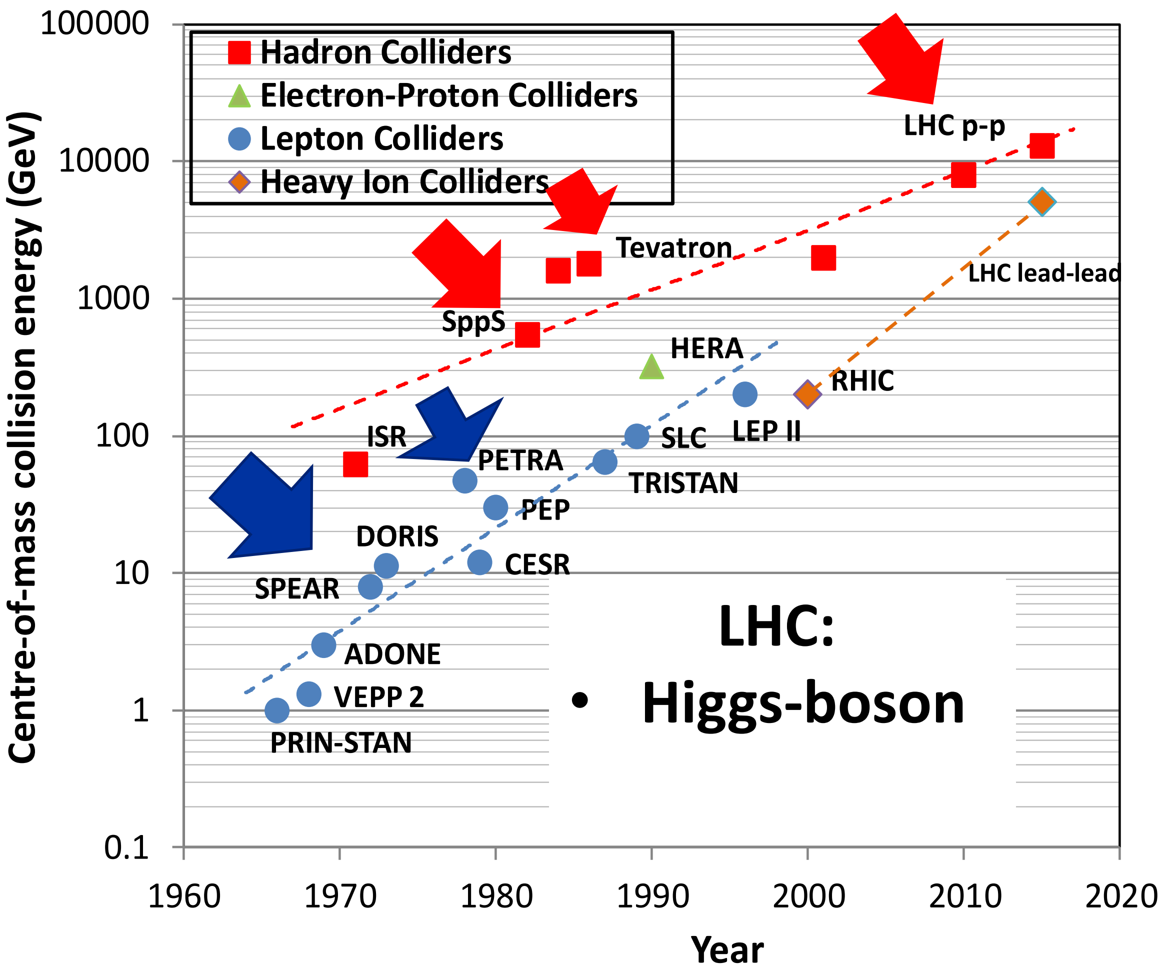
European Commission | Horizon 2020 European Union funding for Research & Innovation

photo: J. Wenninger

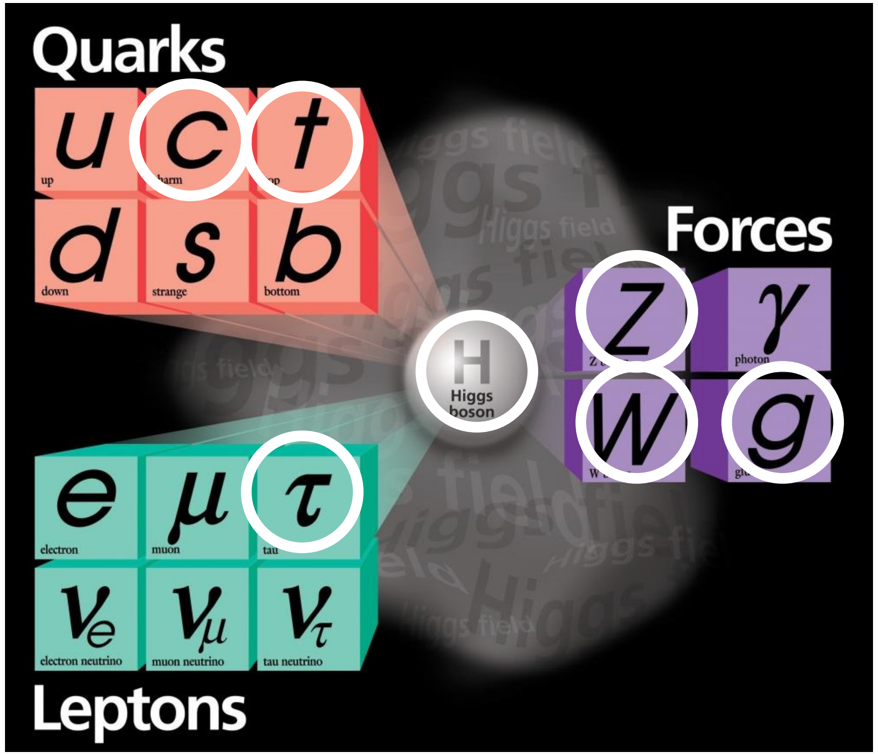
Discoveries with colliders



LHC:

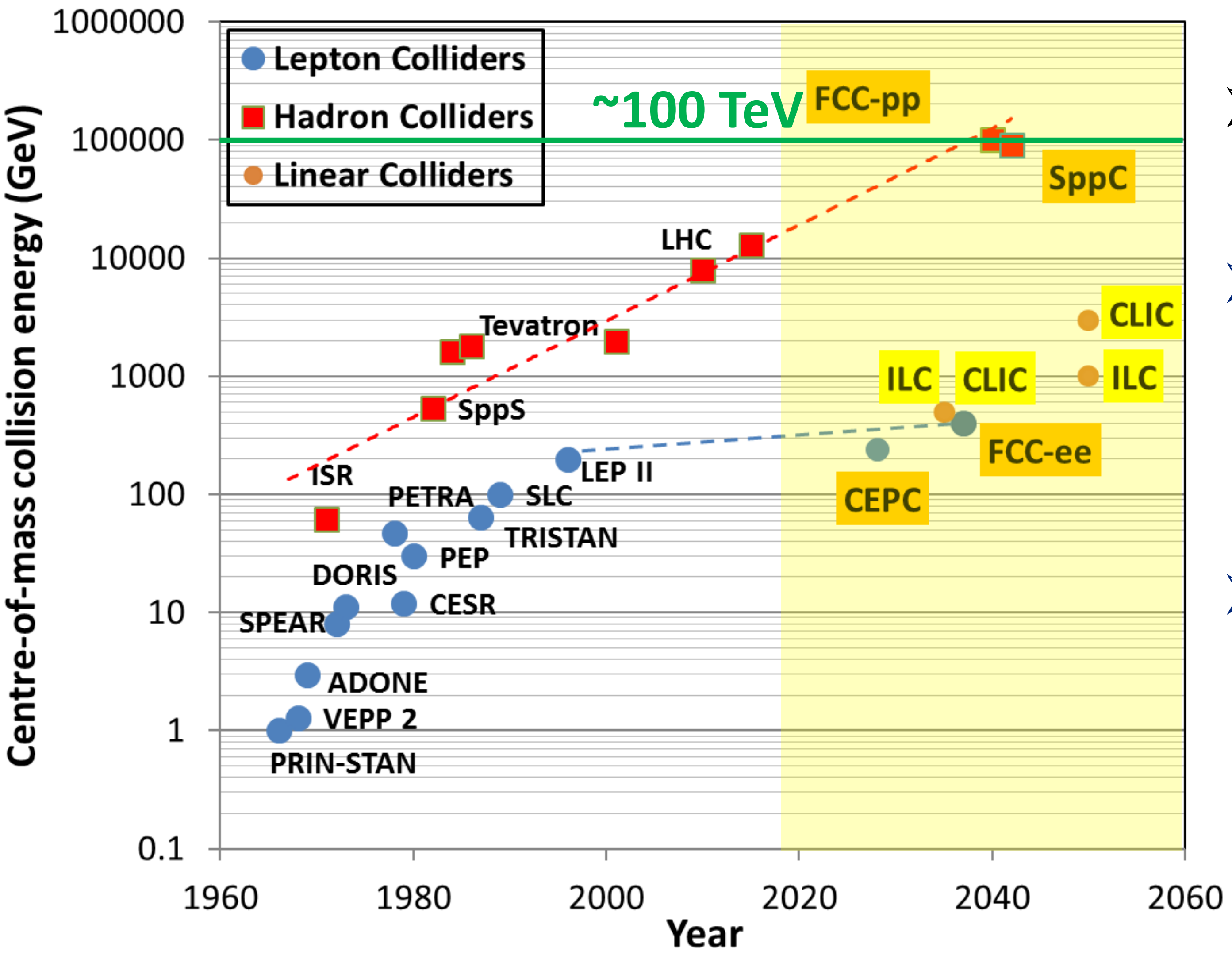
- Higgs-boson

Standard Model
Particles and forces



Colliders are powerful instruments in HEP for particle discoveries and precision measurements

High energy colliders under study



- **Linear e^+e^- colliders** (CLIC, ILC)
  E_{CM} up to ~ **3 TeV**
- **Circular e^+e^- colliders** (CepC, FCC-ee)
  E_{CM} up to ~ **400 GeV**
  limited by $e^\pm$ synchrotron radiation
  → **precision measurements**
- **Circular p-p colliders** (SppC, FCC-hh)
  E_{CM} up to ~ **100 TeV**
  energy (momentum) limited by **p = Bρ**
  → **direct discoveries at energy frontier**

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OPEN QUESTIONS

Despite of impressive progress and discoveries in the past decades several fundamental question remain open:

Today 80 % of the mass of the universe is unknown.
What is the universe made of?

Is there only a single type of Higgs boson and does it behave exactly as predicted?

Why is the universe composed only of matter? Where has the anti-matter gone that was produced simultaneously in the big bang?

Why is the gravitation so much smaller than the other forces?
How to reconcile gravitation with quantum mechanics?

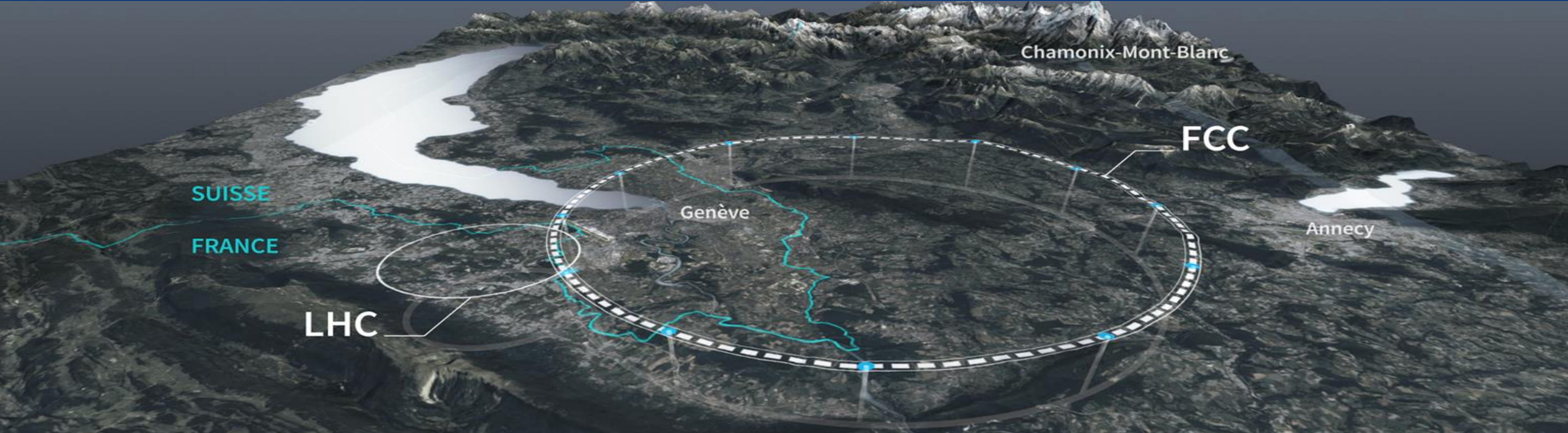
European Strategy for Particle Physics

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 – a research infrastructure for the 21st century



A new 91km tunnel to host multiple colliders
100 – 300 m under ground
8 surface sites

<u>FCC-ee: electron-positron</u> @ 91, 160, 240, 365 GeV
<u>FCC-hh: proton-proton</u> @ 100 TeV, and heavy-ions (Pb) @39 TeV
<u>FCC-eh: electron-positron</u>@ 3.5 TeV

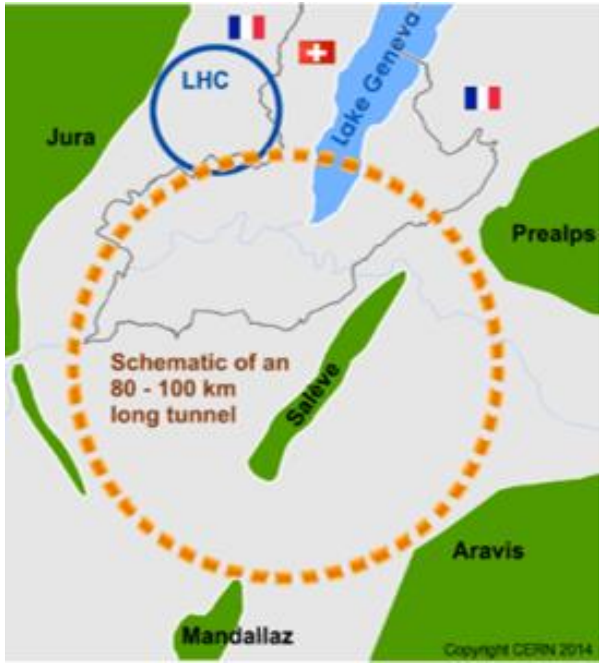
The FCC integrated program inspired by successful LEP – LHC programs at CERN

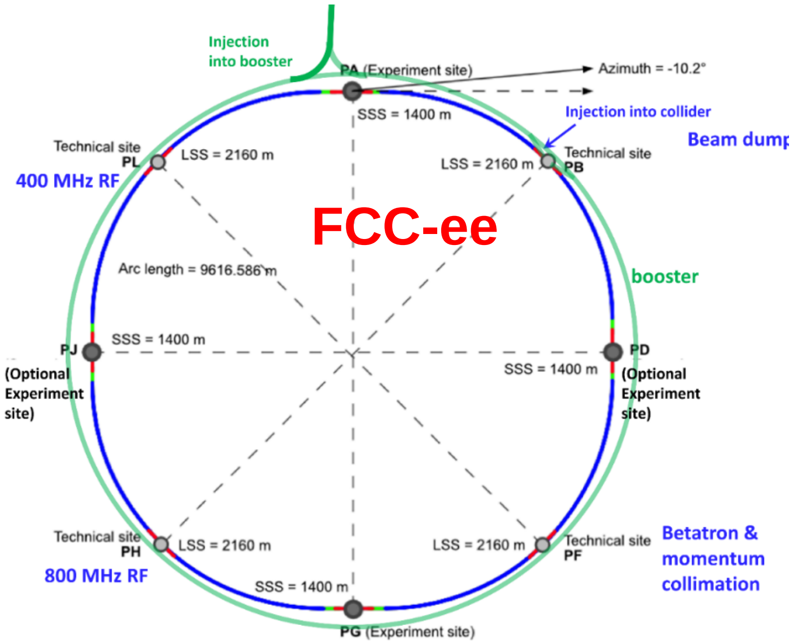
comprehensive long-term program maximizing physics opportunities

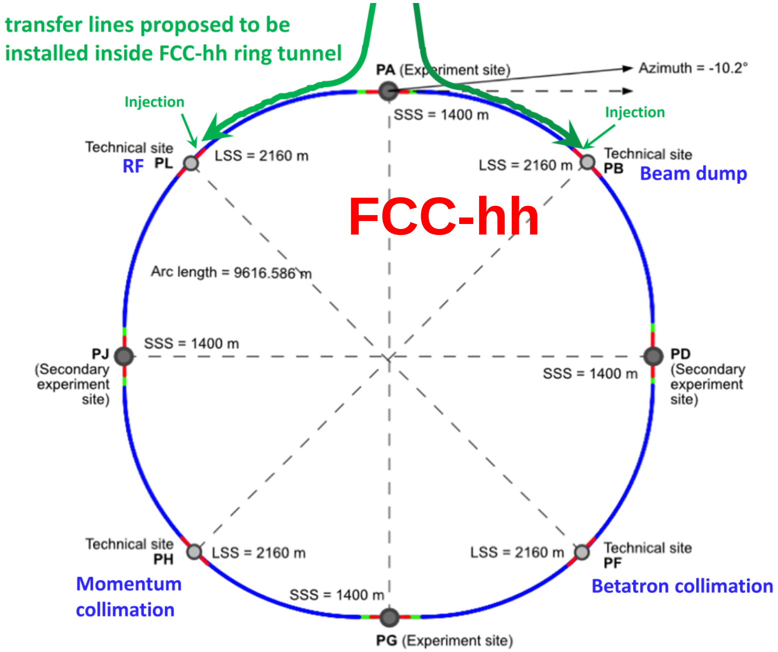
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure

stage 1: FCC-ee: high-intensity electron-positron collider for detailed study of the Higgs boson (10^6), top-quark (10^6), W (10^8), Z (10^{12}) → indirect sensitivity to new physics up to ~ 70 TeV (> 10 times LHC)

stage 2: FCC-hh: proton-proton collider with collision energy of at least 100 TeV
→ direct discovery potential for new physics up to ~ 40 TeV (~ 10 times the LHC)

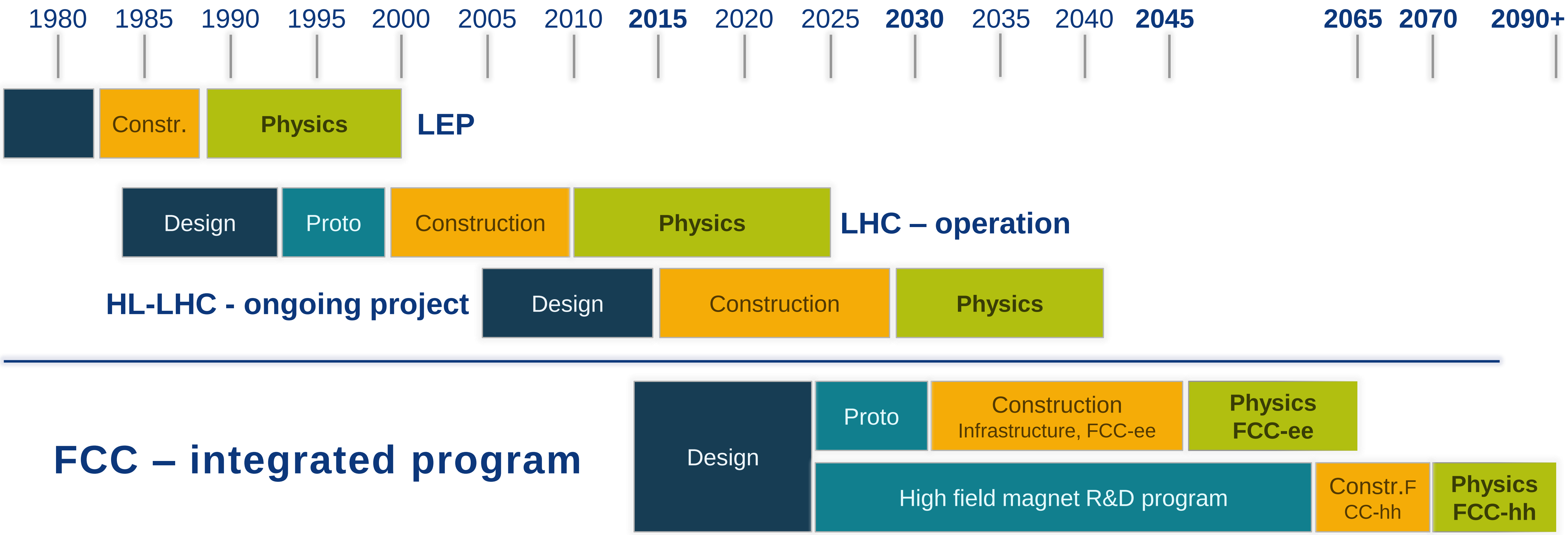






2020 - 2040 | **2045 - 2063** | **2070 - 2090++**

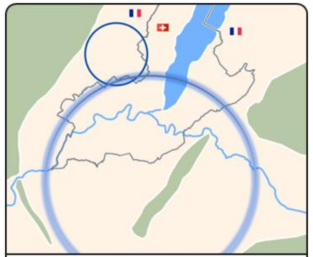
CERN Circular Colliders & FCC

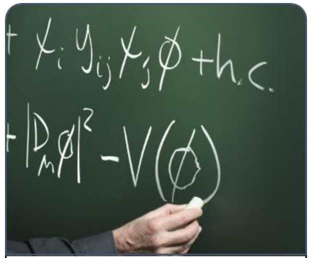


FCC integrated programme allows seamless continuation of collider-based HEP after completion of the HL-LHC program, until end of century

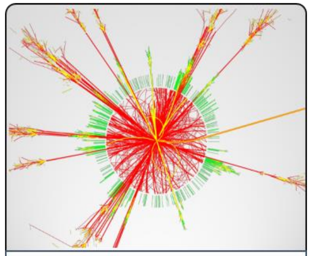
High-level goals of the FCC Study

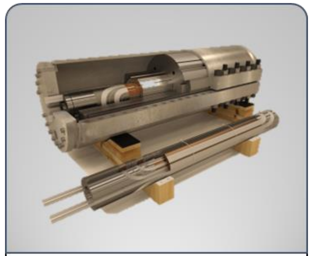
- together with the Host States, **optimisation of placement and layout of the ring,** and demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas;
- **consolidation of the physics case** and detector concepts, optimisation of the **design of the colliders and their injector chains**, supported by targeted **R&D to develop the needed key technologies**;
- development of the technical infrastructure concepts and integration with territorial constraints and identification of opportunities for co-construction;
- elaboration of a **sustainable operational model for the colliders** and experiments in terms of human and financial resource needs, **environmental aspects and energy efficiency**;
- **identification of substantial resources** from outside CERN's budget for the implementation of the first stage of a possible future project;
- Final deliverable is a **Feasibility Study Report by end 2025.**


Infrastructures


Physics Cases

Collider Designs


Experiments


R&D Programs

Cost Estimates

FCC roadmap towards first e^+e^- collisions

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Highest priority goals:

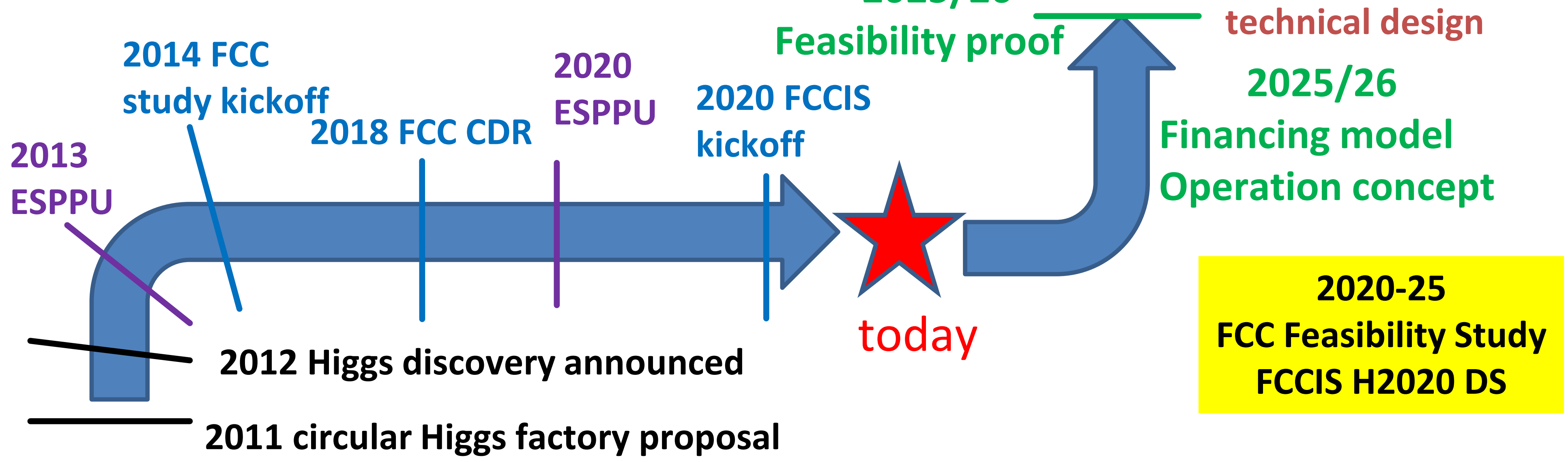
Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

Financial feasibility

Technical and administrative feasibility of tunnel:
no show-stopper for ~100 km tunnel

Technologies of machine and experiments: magnets; minimised environmental impact; energy efficiency & recovery

Gathering scientific, political, societal and other support



FCC stage 1: infrastructure and FCC-ee project cost estimate and spending profile

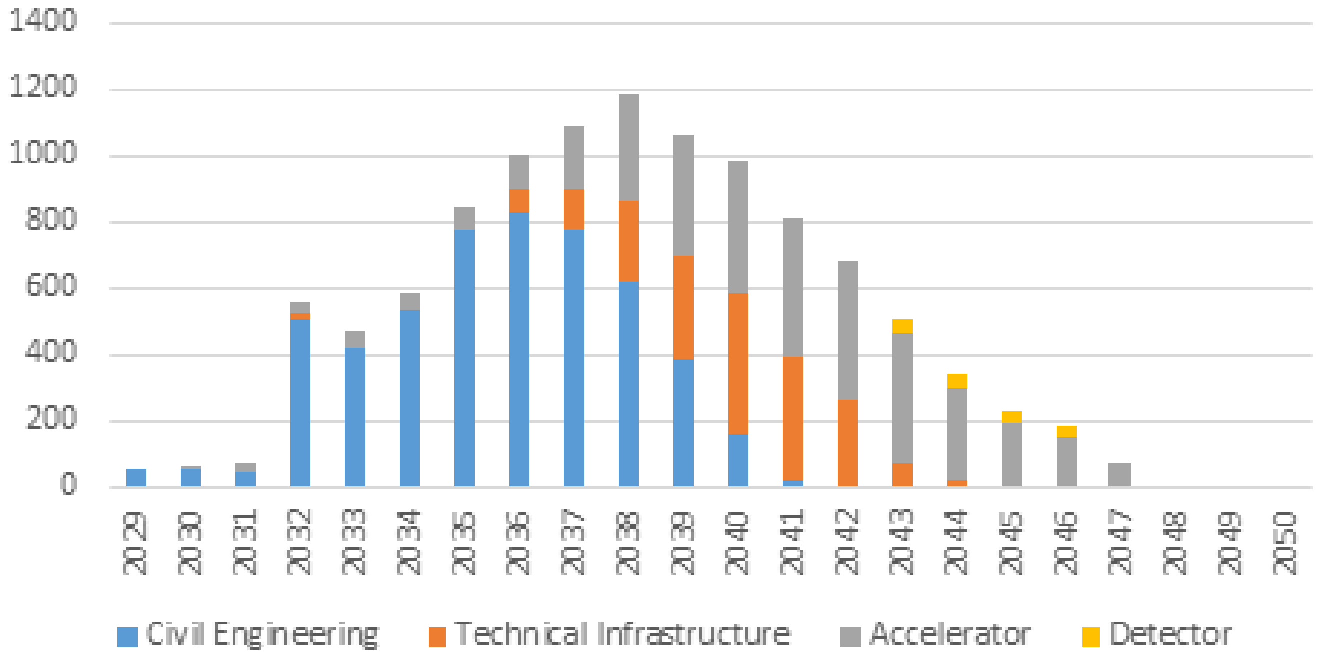
Construction cost estimate for FCC-ee

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

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

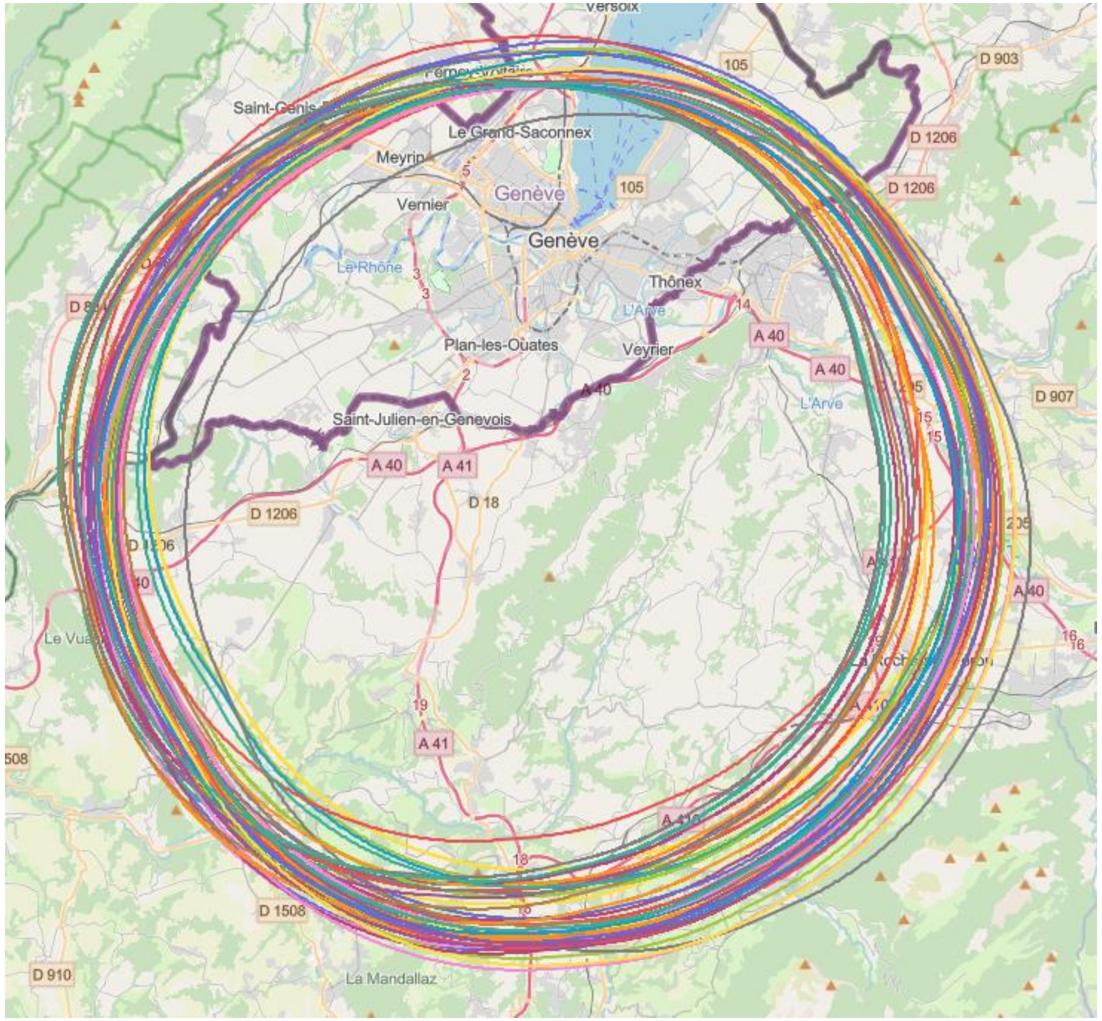
Spending profile for FCC-ee

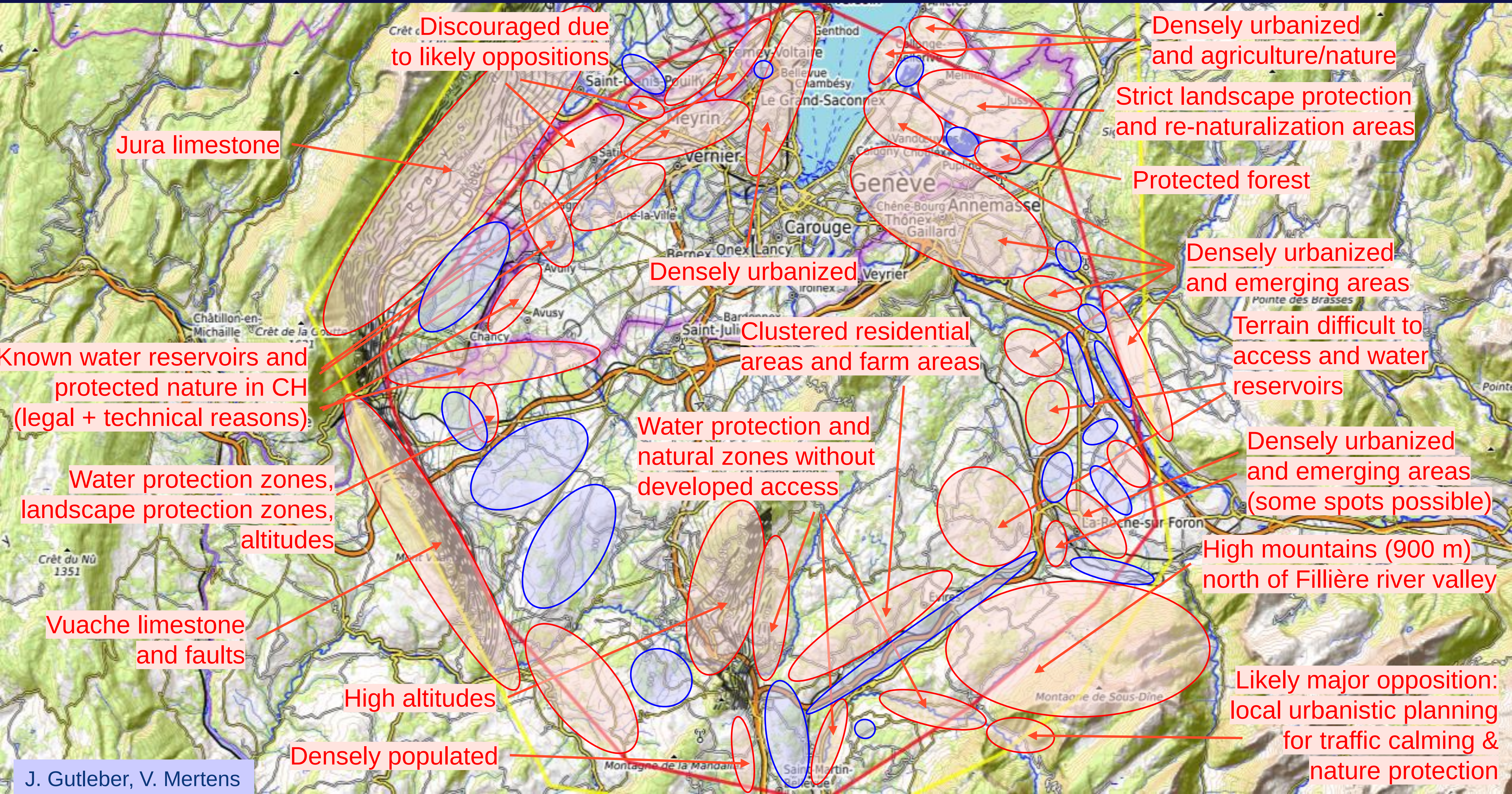
- CE construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.



Implementation optimization with host states

- layout & placement optimisation across both host states, Switzerland and France;
- following ***"avoid-reduce-compensate"*** directive of European & French regulatory frameworks;
- diverse requirements and constraints:
  - **technical feasibility of civil engineering** and subsurface geological constraints
  - **territorial constraints on surface** and subsurface
  - **nature, accessibility**, technical infrastructure, resource needs & constraints
  - **optimum machine performance and efficiency**
  - economic factors including benefits for, and synergies, with the **regional developments**
  - …
- **collaborative effort: FCC technical experts, government-notified bodies, consulting companies**

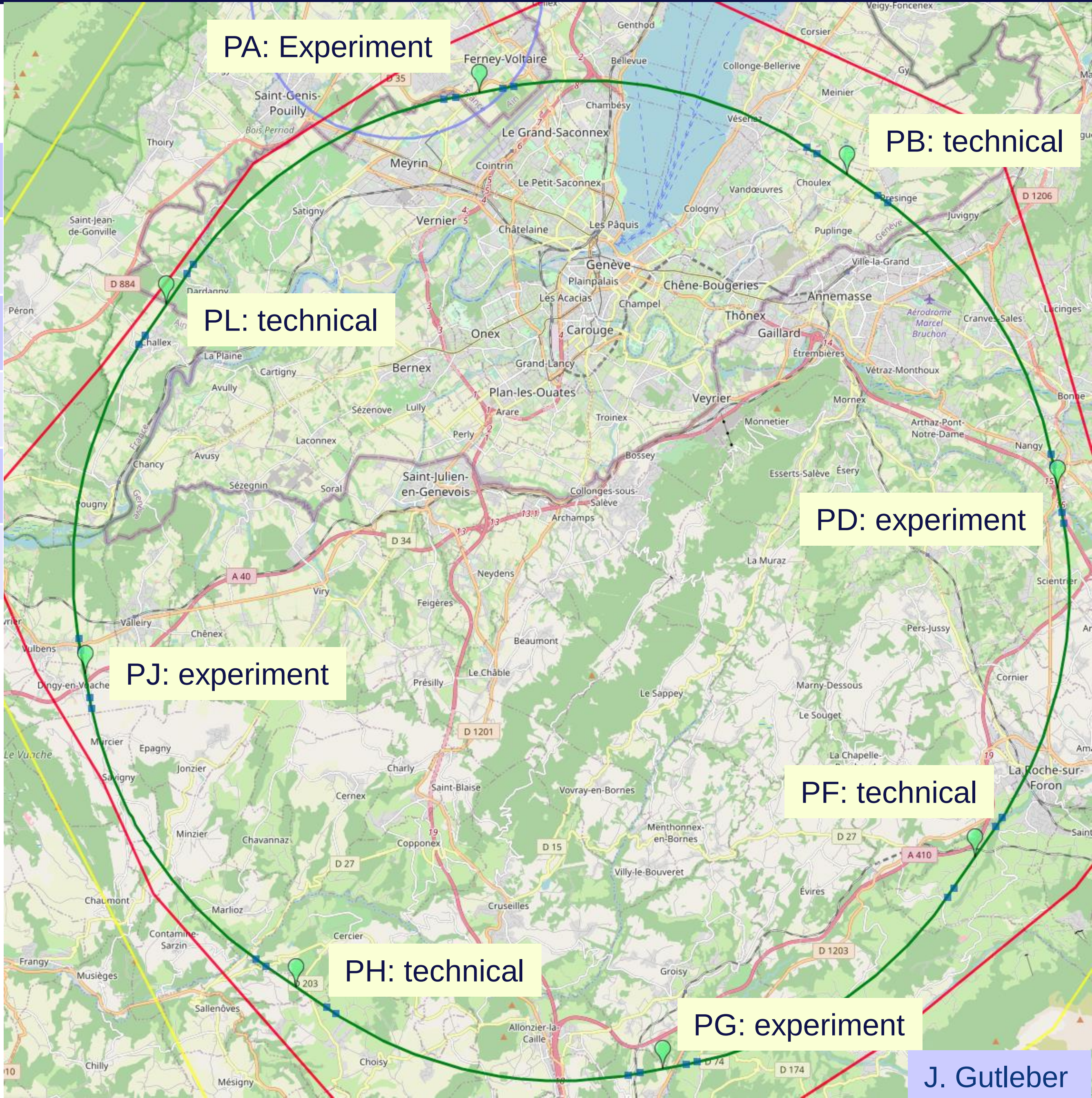



Discouraged due
to likely oppositions
Densely urbanized
and agriculture/nature
Strict landscape protection
and re-naturalization areas
Jura limestone
Protected forest
Densely urbanized
Densely urbanized
and emerging areas
Clustered residential
areas and farm areas
Terrain difficult to
access and water
reservoirs
Known water reservoirs and
protected nature in CH
(legal + technical reasons)
Water protection and
natural zones without
developed access
Densely urbanized
and emerging areas
(some spots possible)
Water protection zones,
landscape protection zones,
altitudes
High mountains (900 m)
north of Fillière river valley
Vuache limestone
and faults
High altitudes
Likely major opposition:
local urbanistic planning
for traffic calming &
nature protection
Densely populated

8-site baseline ”PA31”

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

- **8 surface sites <40 ha total land use**
- **Possibility for 4 experiment sites**
- **All sites close to road infrastructures (< 5 km of new road constructions required)**
- **Vicinity of several sites to 400 kV grid lines**



J. Gutleber

Regional interactions

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 technique et experimental

PF – Roche sur Foron/Etaux (FR) – site technique

PG – Charvonnex/Groisy (FR) – site experimental

PH – Cercier (FR) – site technique

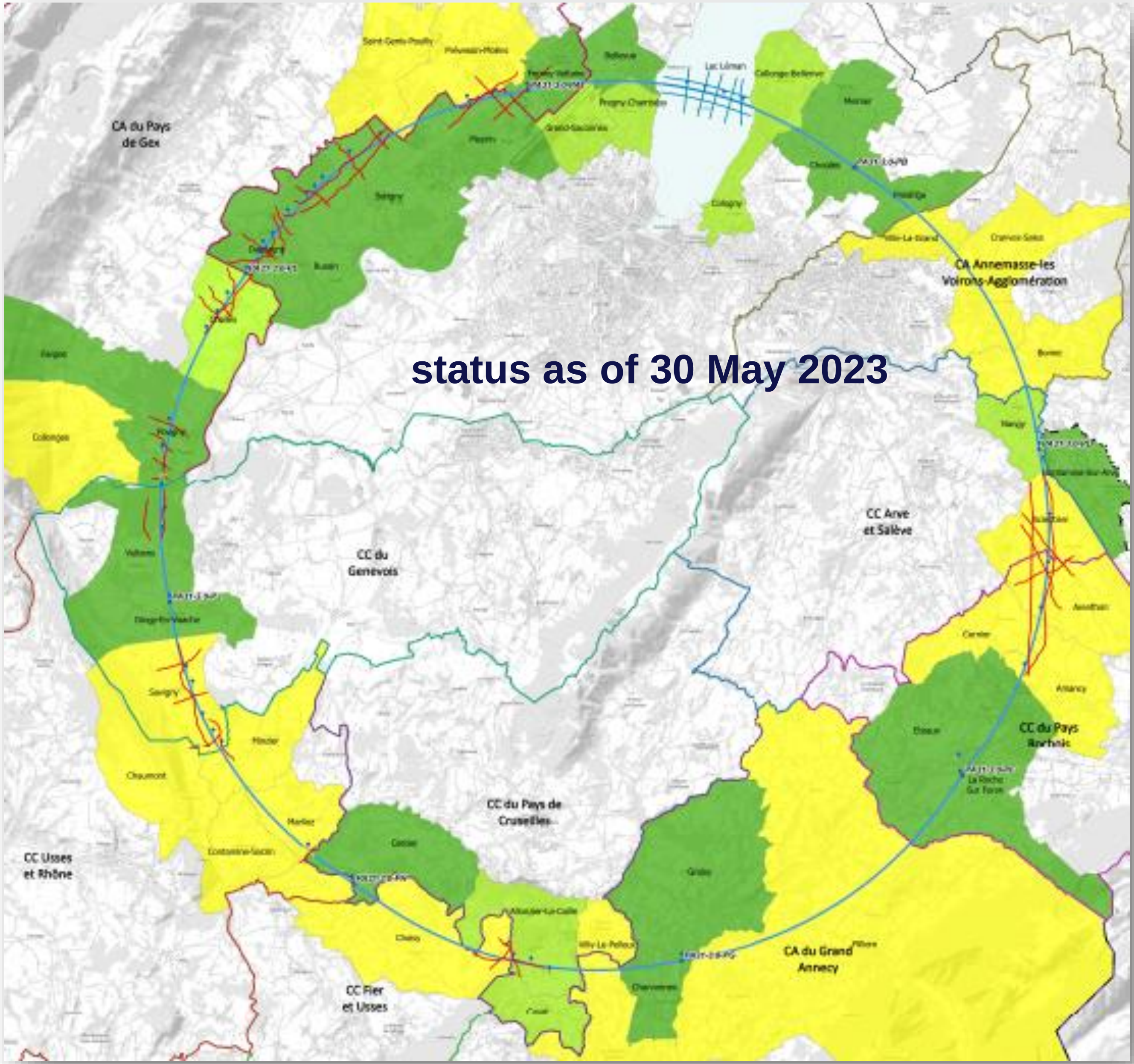
PJ – Vulbens/Dingy en Vuache (FR) site technique et experimental

PL – Challex (FR) – site technique

Rencontrée individuellement

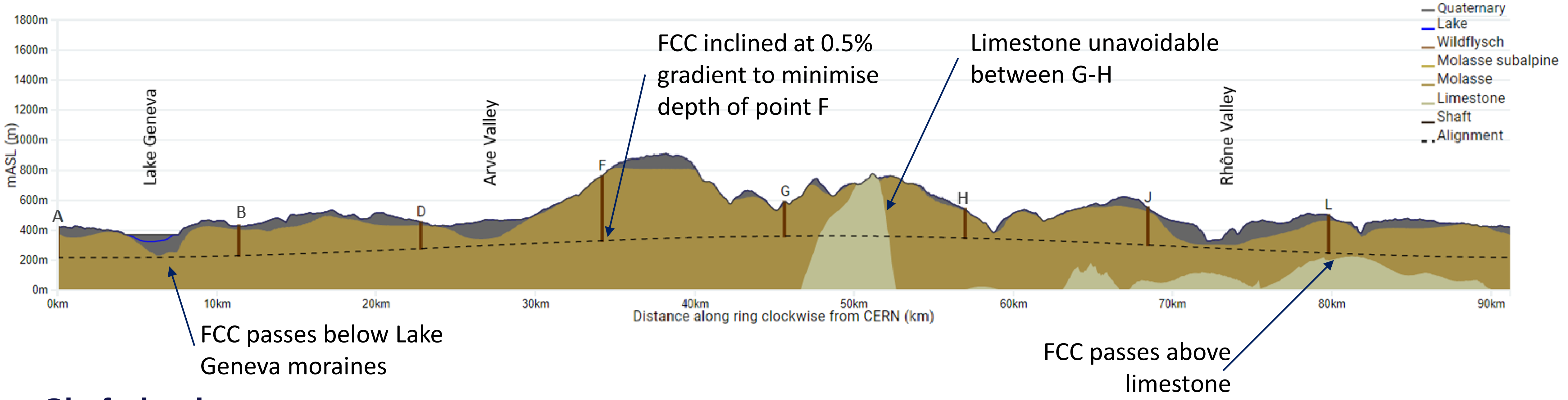
Rendez-vous proposé / programmé

Rencontre collective



Environmental studies and preparation of geological investigations (drillings and seismics) ongoing since February 2023

FCC tunnel longitudinal section - geology



Shaft depth:

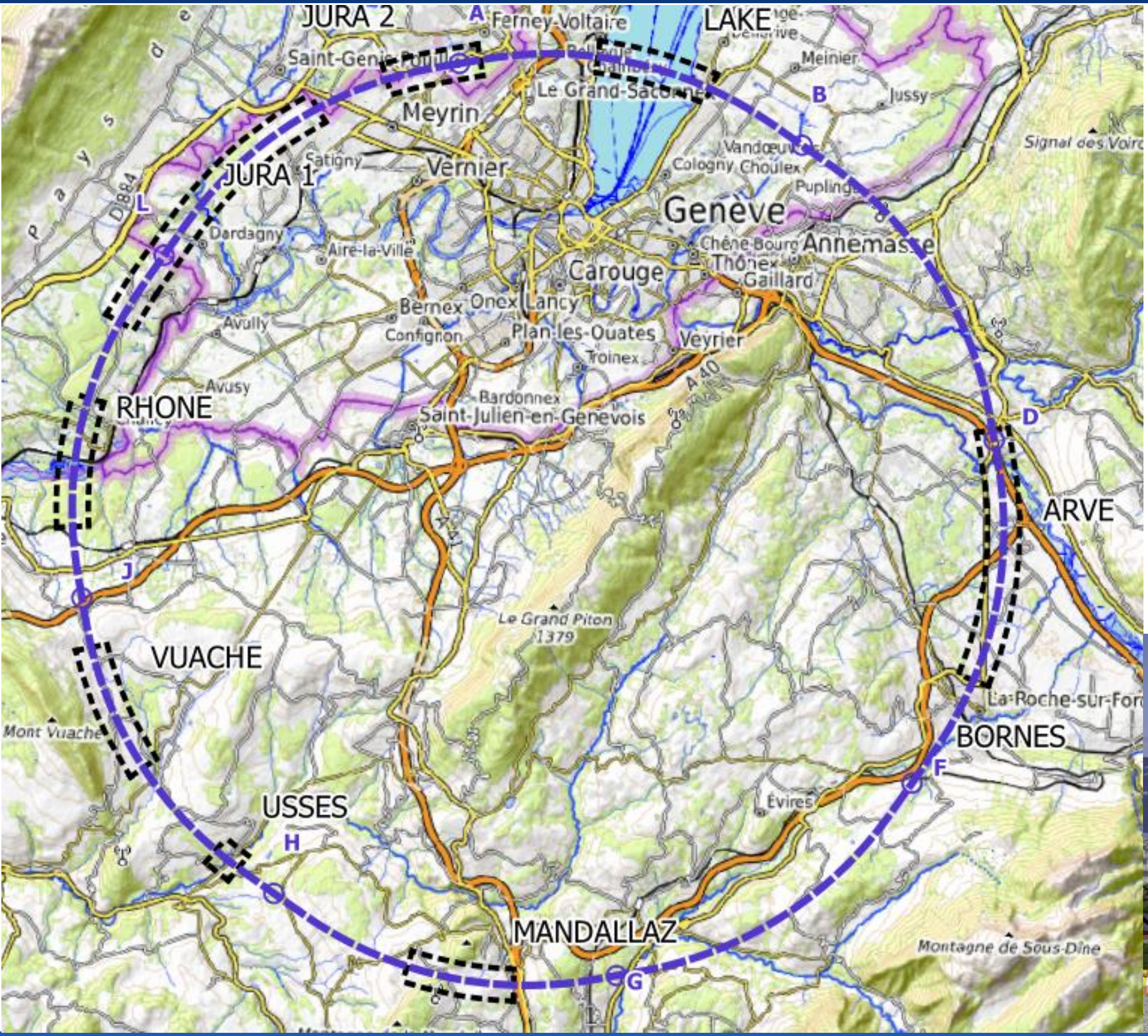
A: 202 m B: 200 m D: 177 m F: 399 m G: 228 m H: 139 m J: 251 m L: 253 m

Tunneling mainly in moraine layer (soft rock), well suited for fast, low-risk TBM construction.

Around 8 million m³ excavation material

John Osborne

Geological investigations



Site investigations planned for 2024 – 2025:
~45 drillings, 100 km of seismic lines

Top of limestone
Karstification and filling-in at the tunnel depth
Water pressure at tunnel level

Top of the molasse
Quaternary soft grounds, water bearing layers

High overburden molasse properties

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Innovation Study

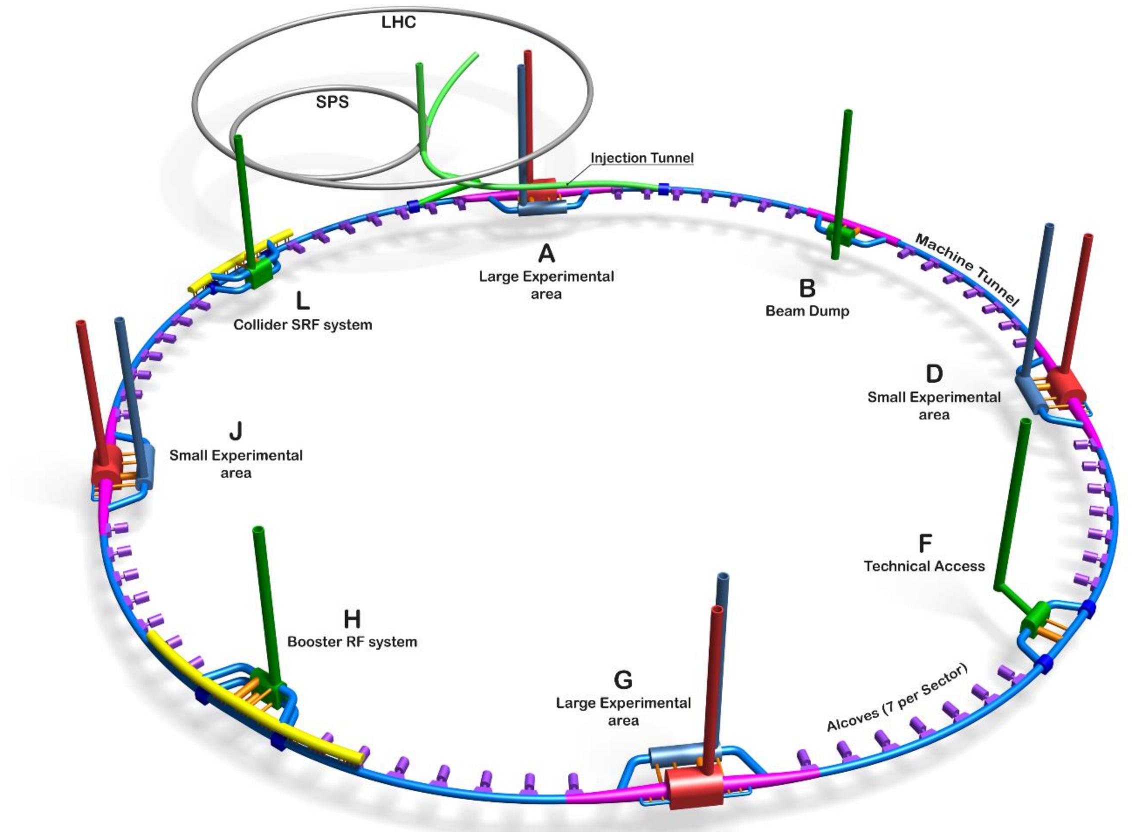
Mining the future – excavation material reuse

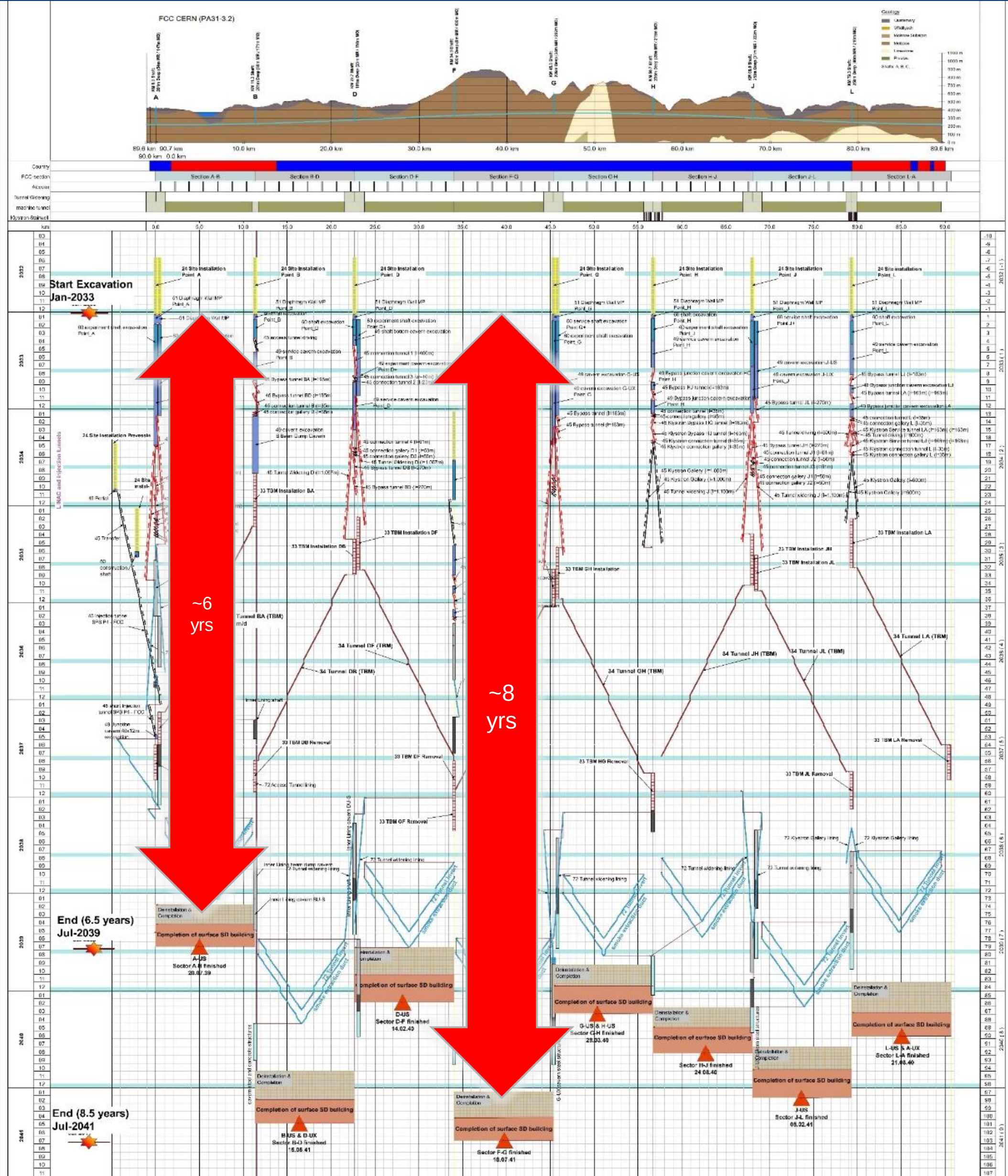
EU co-financed, led by MUL Leoben

- **AMBERG Konsortium: In-situ characterisation** (crossbelt elemental analyzer) and preparation for use as construction material on site, **production of construction elements withouth cement/concrete**.
- **BG Konsortium: Online-analysis** and preparation of Molasse for **construction elements from sandstone, filing material for concrete, low-carbon concrete, etc.**
- **ARCADIS Konsortium:** Molasse combined with some stabilisation material for **production of construction bricks via high mechanical pressure. Replacing high-carbon construction materials.** Mobile production plants directly on site.
- **EDAPHOS Konsortium:** Combining mineral (Molasse) material and organic material to **produce fertile soil with on-site production plants by using mikrobiology** to accelerate humus creation. **Fertile soil as top layer for agricultural use, recultivation.**

Pilot plant from TRL 4 to TRL 8 in 2024-2027

Civil engineering studies





- **Total construction duration 8 years**
- **First sectors ready after 6 years for start of technical infrastructure installation**

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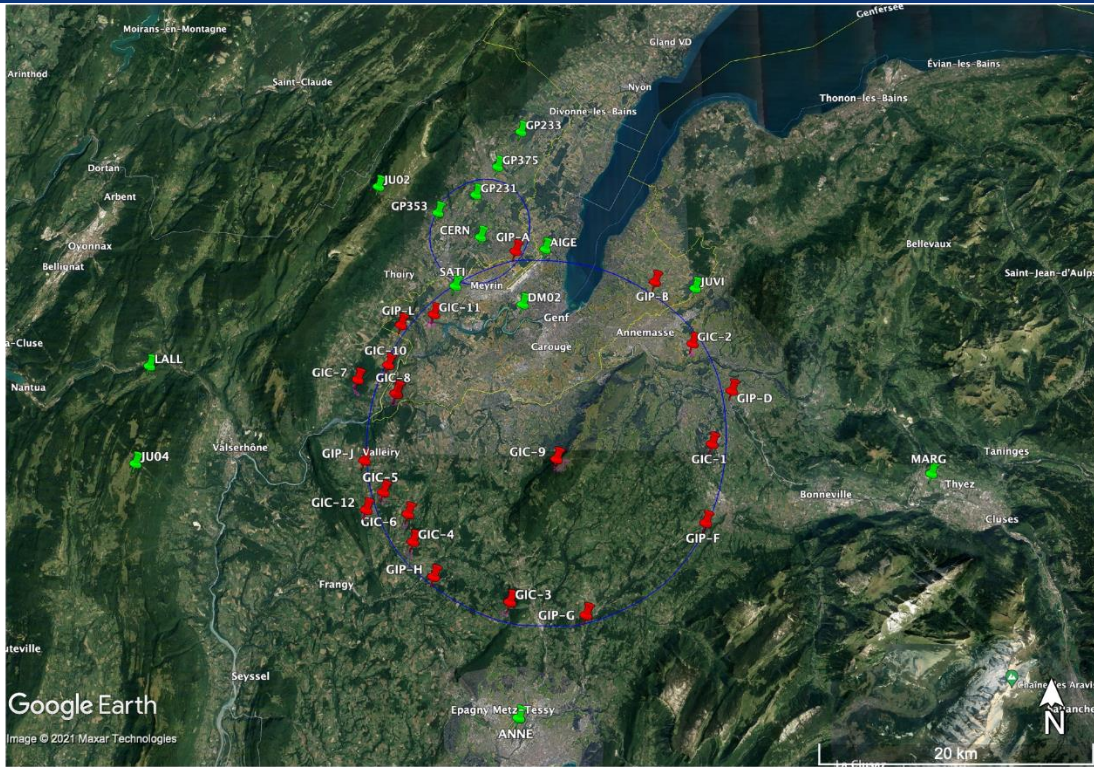
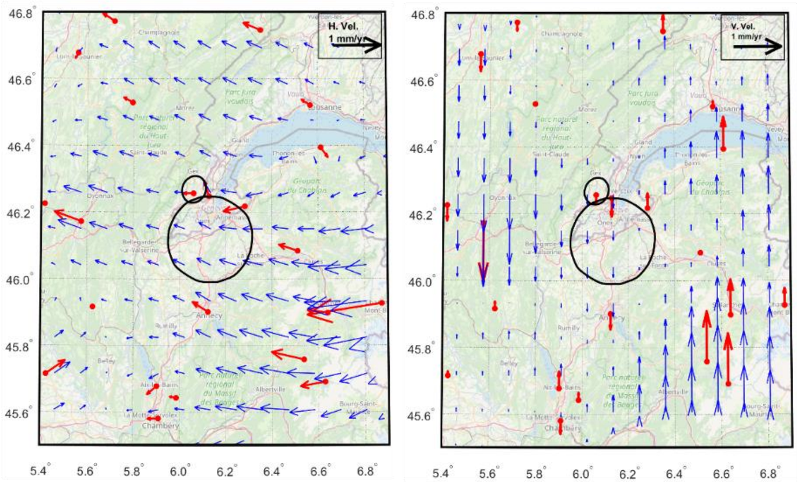
Building Geodesy Surface Reference Network



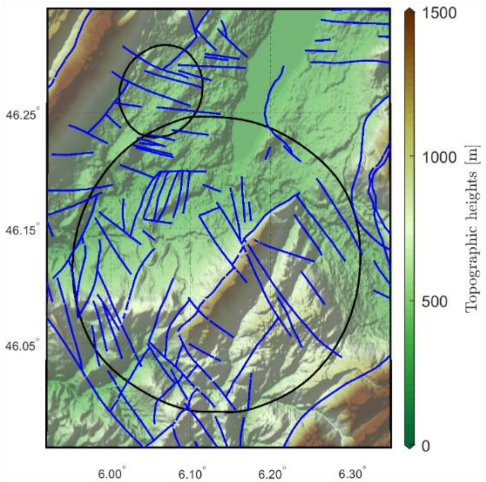
Surface geodetic network needs to be spatially extended

- Realization of a coordinate reference frame (CTRF) for georeferencing of site investigation data and as basis for all geospatial works using global navigation satellite system (GNSS) and surveying instruments
- GNSS-based monitoring of the geokinematic surface deformations (assure stable main geodetic points, quantify differential displacements which may affect later alignment)

EUREF surface velocity field
(differential displacements)



Faults
(potential discontinuities of displacements)



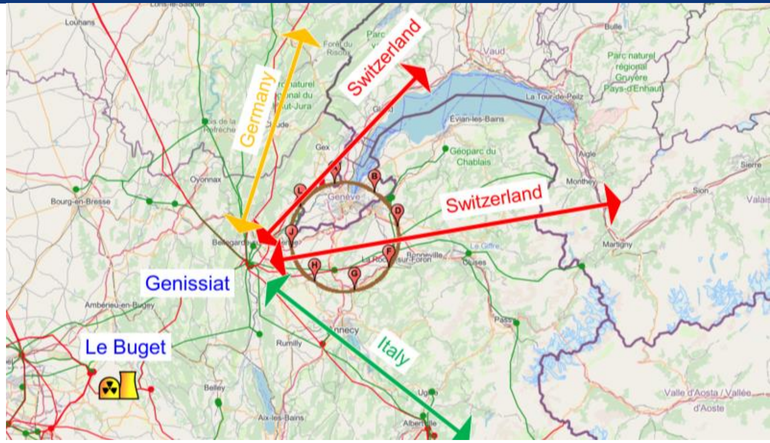
Collaboration with IGN (France),

SWISSTOPO (Switzerland),

ETH Zuerich

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**

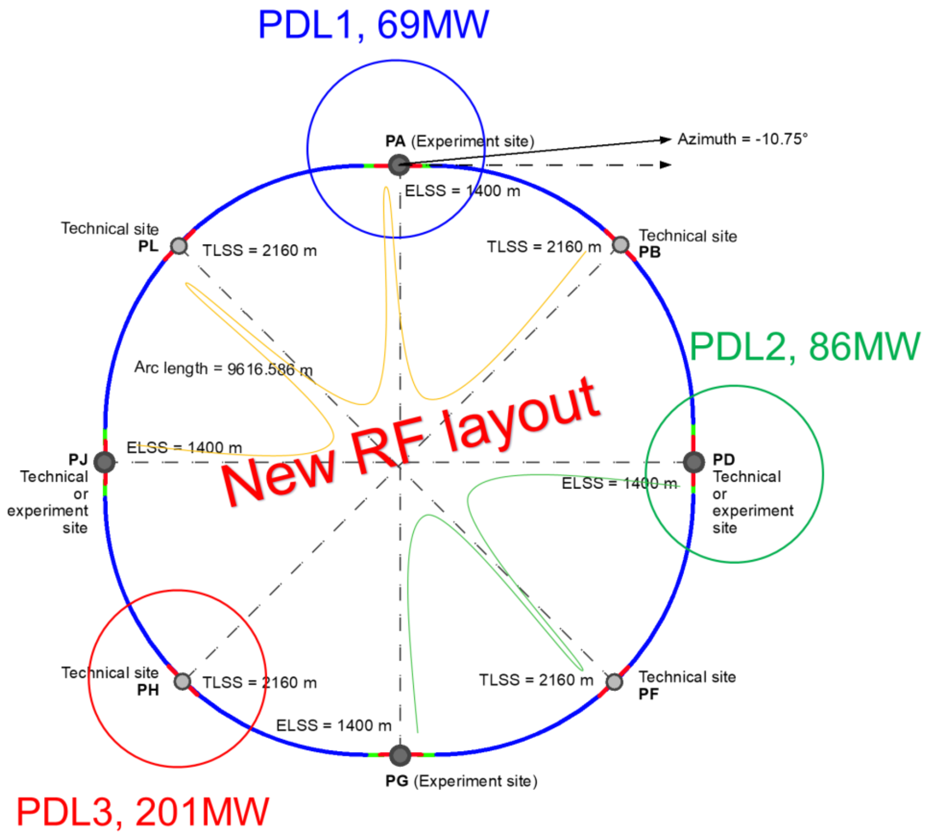


Powering concept and max power load by sub-stations:

The loads could be charged on the three sub-stations (optimum connections 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 L, with a sub-station covering PJ – PL – PA
- → Alternative to new sub-station at Point L is **reusing the existing CERN Prevession station to PA**

- **All options pursued with RTE**
- **Powering concept and max. power rating of the three sub-stations compatible FCC-hh.**



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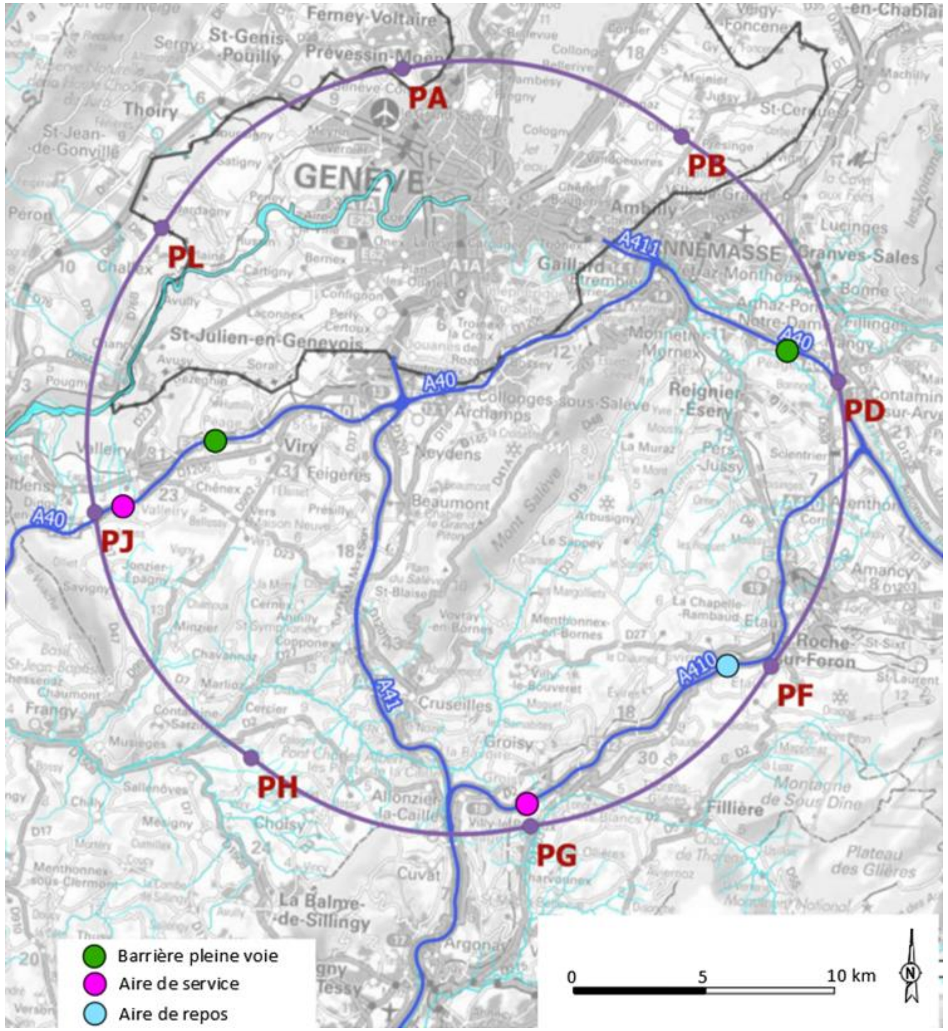
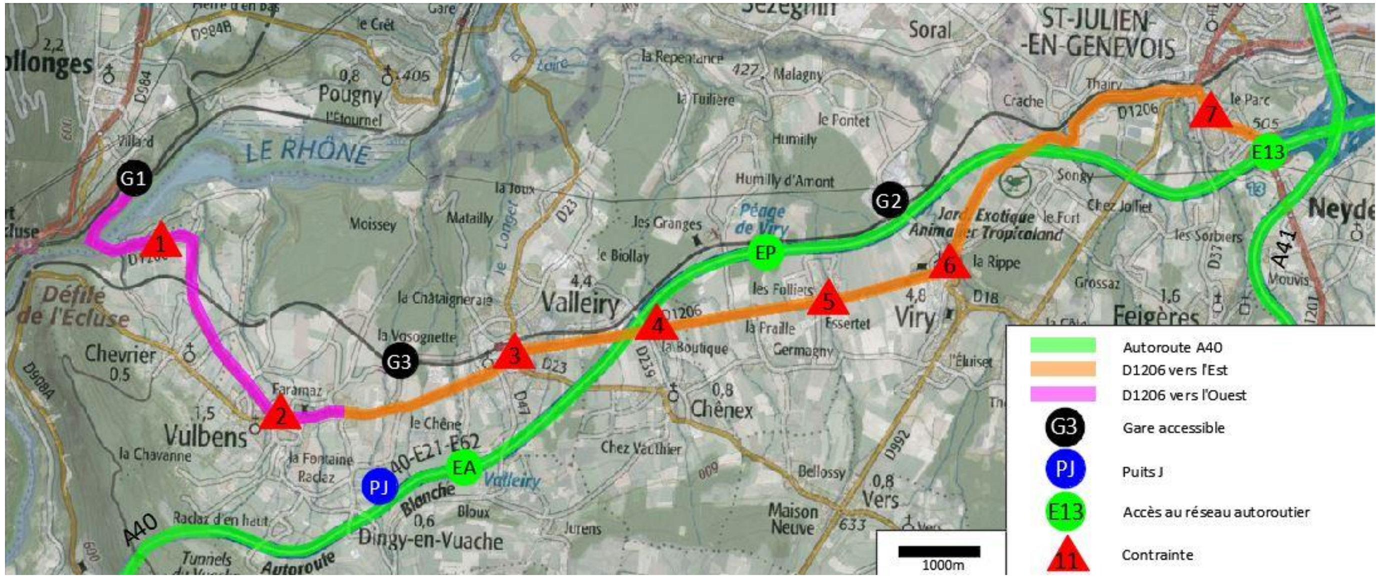
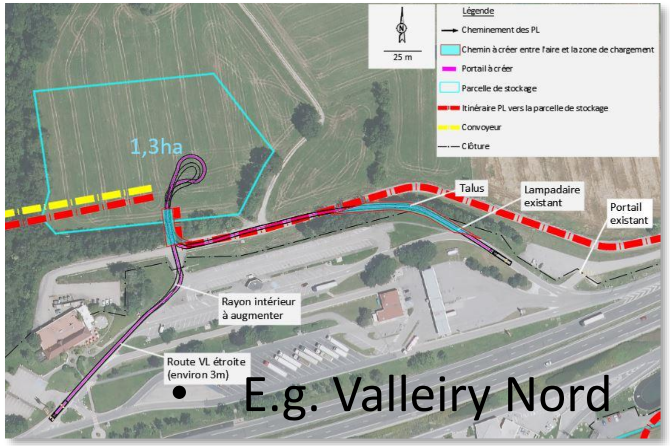
Connections to transport infrastructure

- 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)







- E.g. Valleiry Nord

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

FCC-ee basic design choices

Double ring e+ e- collider

Common footprint with FCC-hh, except around IPs

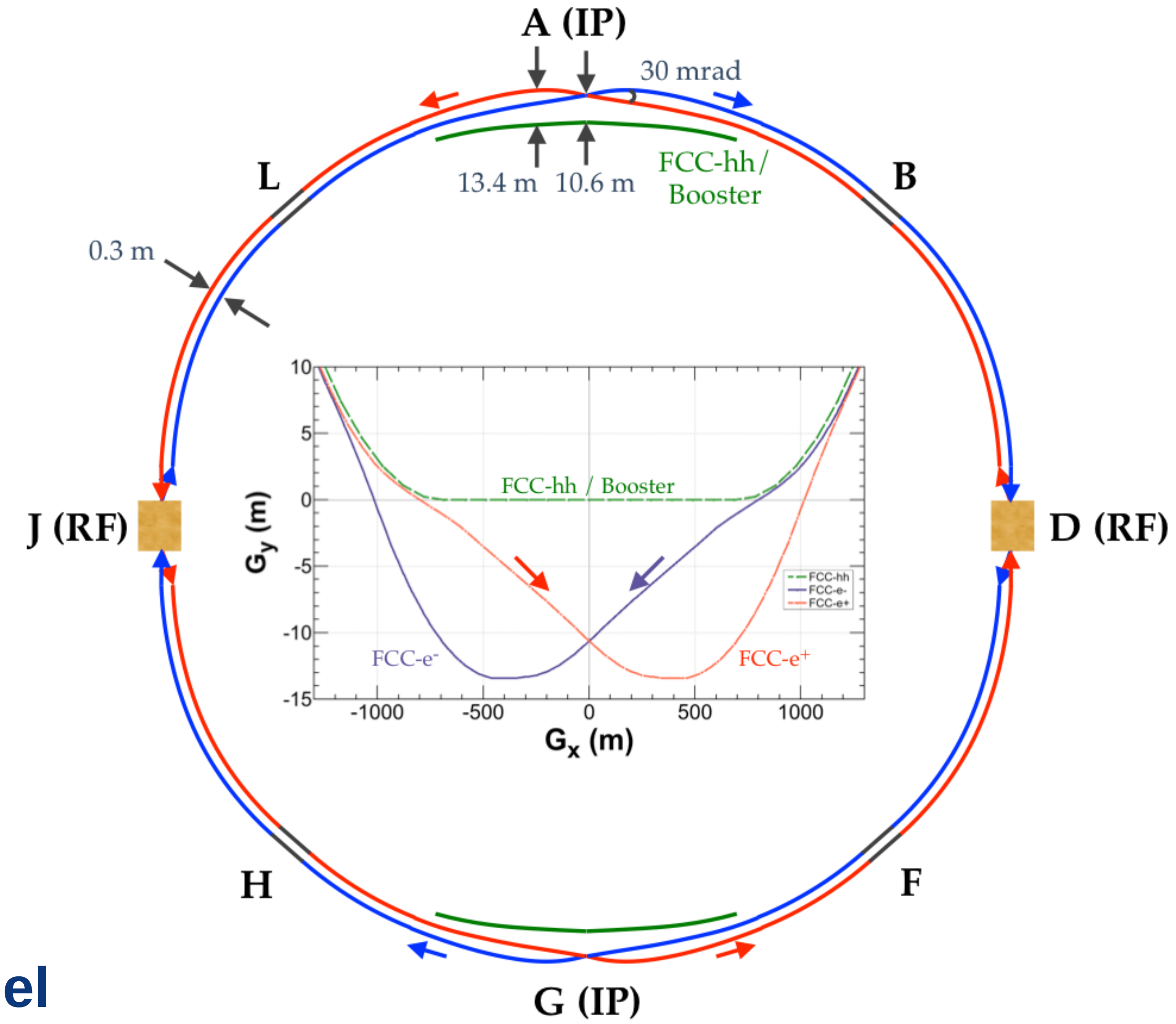
Asymmetric IR layout and optics to limit synchrotron radiation towards the detector

Perfect 4-fold superperiodicity allowing 2 or 4 IPs; large horizontal crossing angle **30 mrad, crab-waist collision optics**

Synchrotron radiation power 50 MW/beam at all beam energies. Energy loss ΔE per turn:

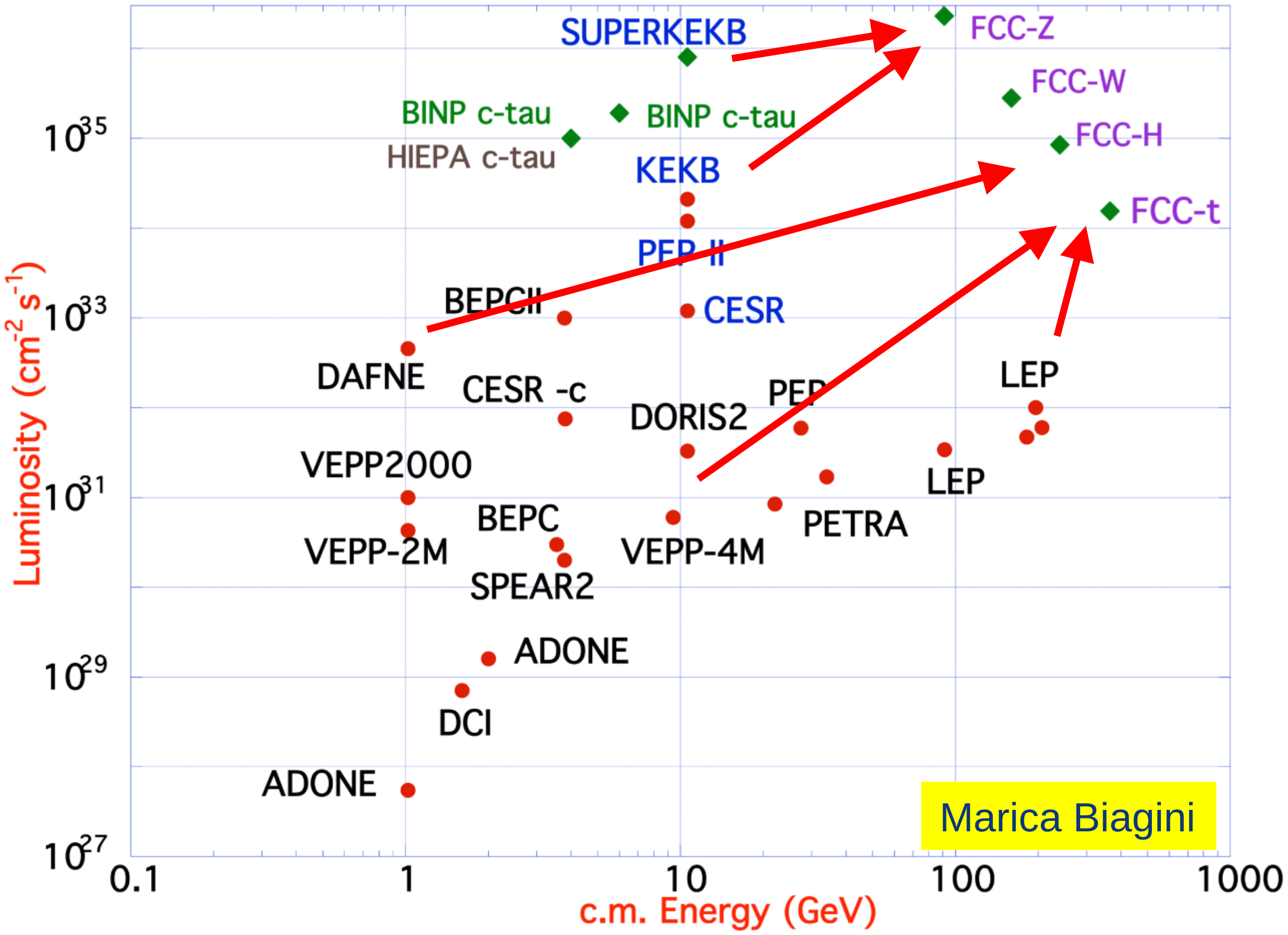
$$\Delta E \sim \gamma^4/r = (E/m_0)^4/r$$

Top-up injection scheme for high luminosity
Requires **booster synchrotron in collider tunnel**



FCC-ee design concept

based on lessons and techniques from past colliders (last 40 years)



B-factories: KEKB & PEP-II:
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

S-KEKB: low β_y*, crab waist

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

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FCC-ee: main machine parameters

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
- 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

FCC-ee: efficient Higgs/electroweak factory

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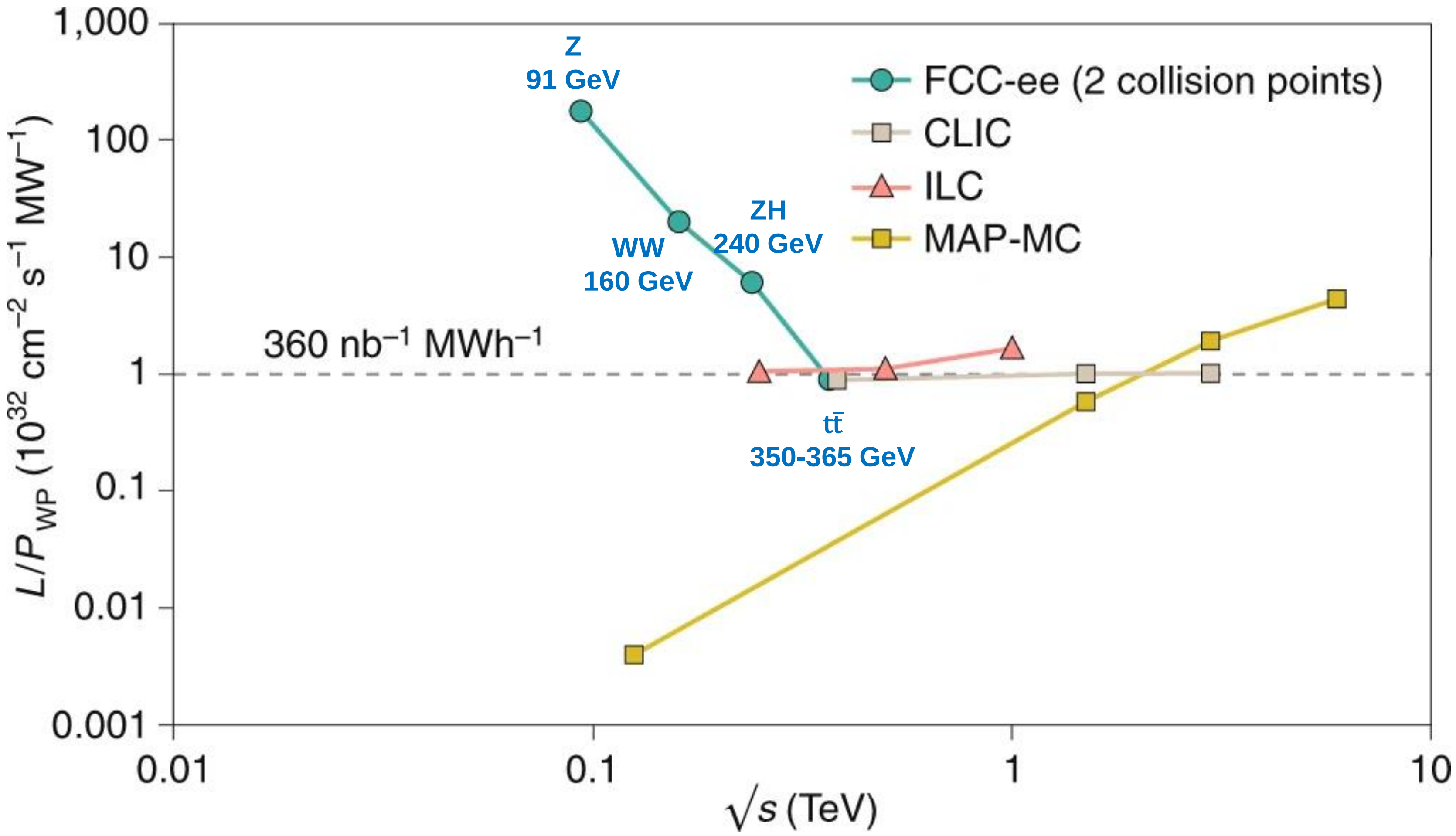


luminosity L per supplied electrical wall-plug power P_{WP} shown as a function of centre-of-mass energy for several proposed future lepton colliders.

enormous performance increase wrt LEP:

- **collects LEP data statistics in few minutes**
- **highest lumi/power of all *Higgs* factory proposals**

M. Benedikt, A. Blondel, P. Janot, et al., **Nat. Phys. 16**, 402-407 (2020), and **European Strategy** for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

FCC-ee RF staging scenario

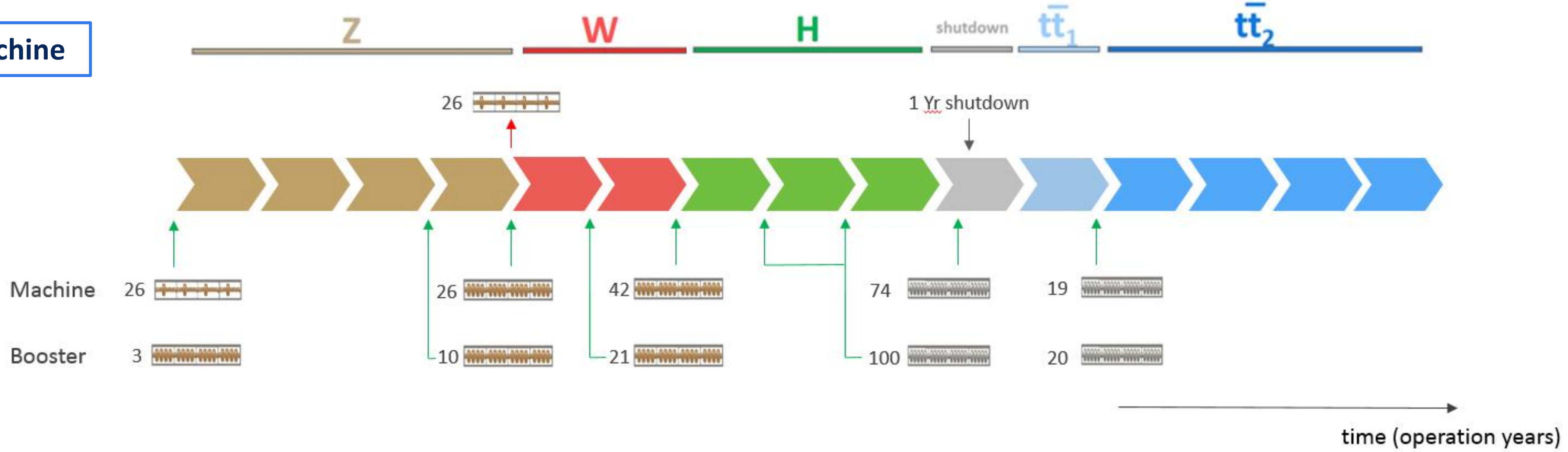
“Ampere-class” machine

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

“high-gradient” machine

three sets of RF cavities to cover all options for FCC-ee & booster:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**

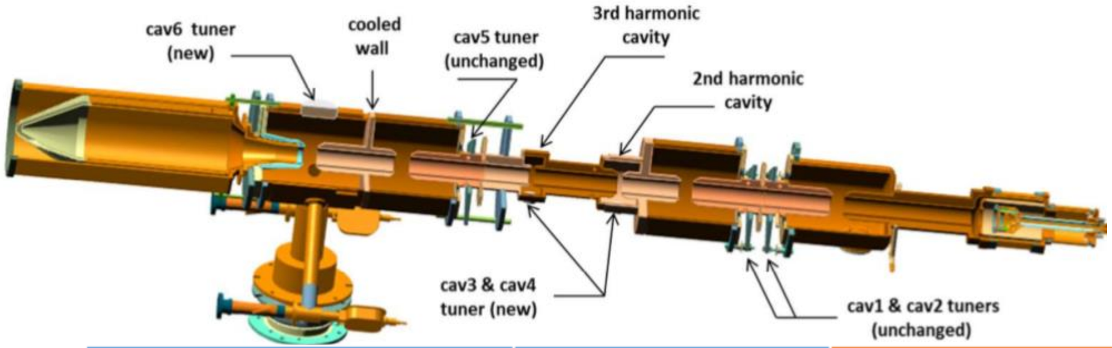


Efforts towards energy efficiency and sustainablity

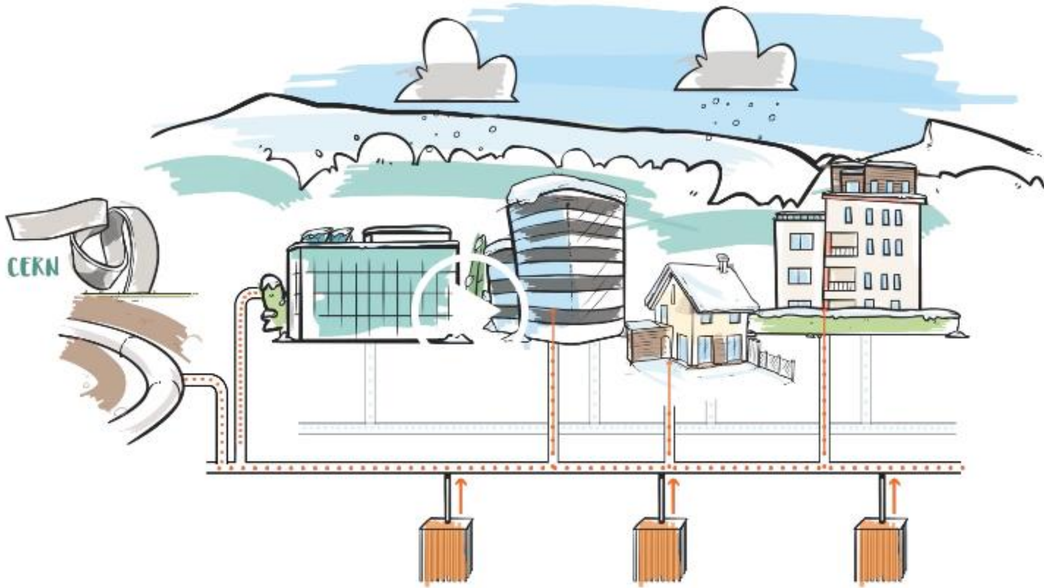
- **Technology R&D with industry**
  - Radio-frequency power production efficiency
  - Efficiency of cryogenics plants, new coolants e.g. Nelium, etc.

- **Optimisation of collider operation modes**
  - Adapt operation mode and energy consumption to the availability of electrical energy on the regional grid.

- **Waste heat reuse (few 100 GWh/y potential)**
  - Identification of opportunities in the region,
  - Co-construction with local communes and regional industry. (LHC P8, 40 GWh/year).

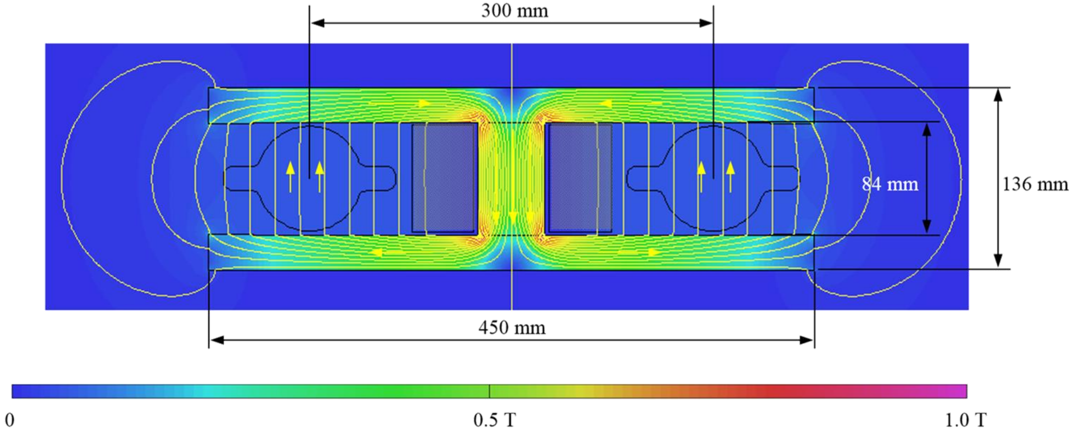


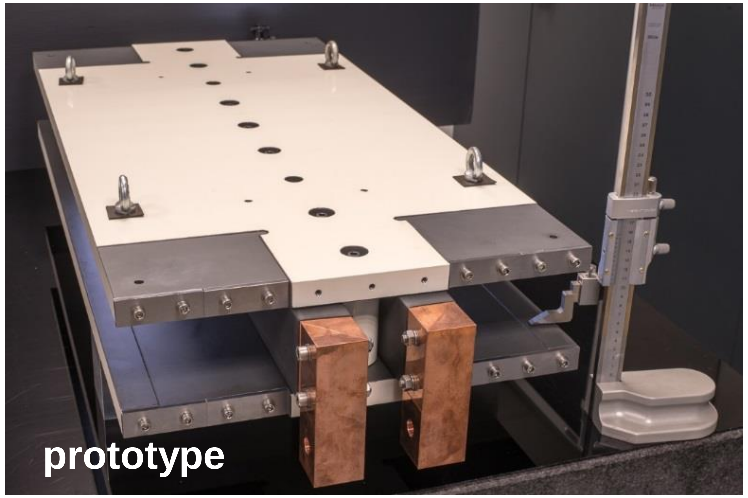
Parameter	present TH2167	CSM upgrade
Frequency [MHz]	400	
Beam voltage [kV]	54	
Saturated RF power [kW]	**300**	**350**
Efficiency [%]	**60**	**70**

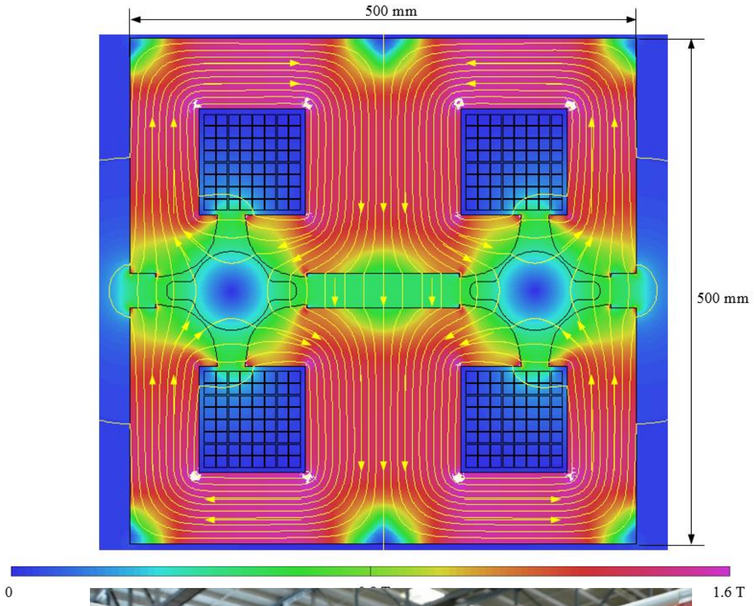


Prototypes of FCC-ee low-power magnets

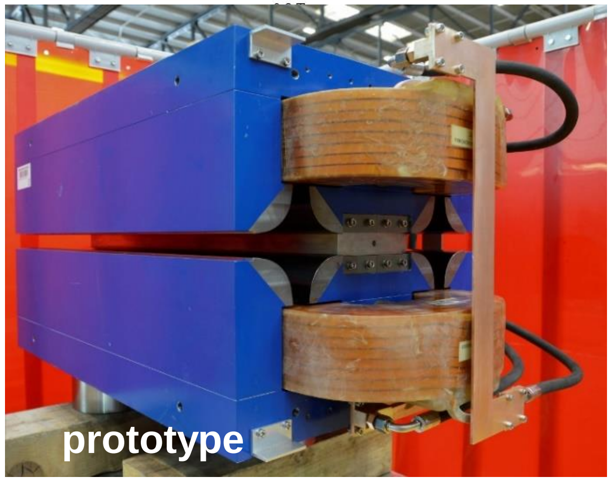
Twin-dipole design with 2× power saving
16 MW (at 175 GeV), with Al busbars



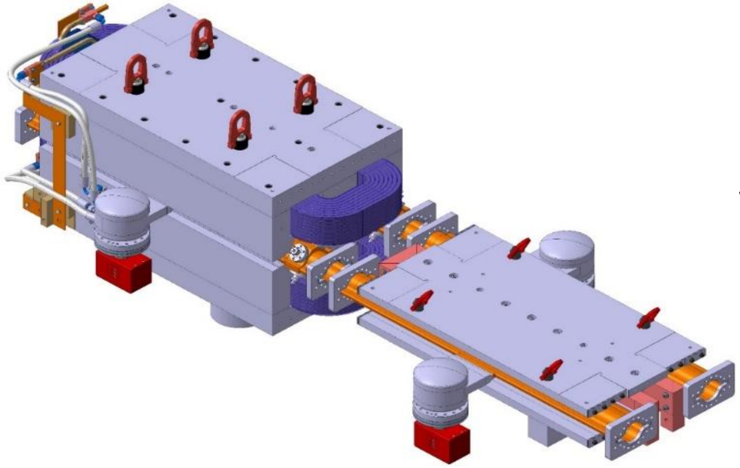




Twin F/D arc quad design with 2× power saving 25 MW (at 175 GeV), with Cu conductor



FCC key deliverables: prototypes by 2025



FCC-ee arc half-cell mock up

including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.

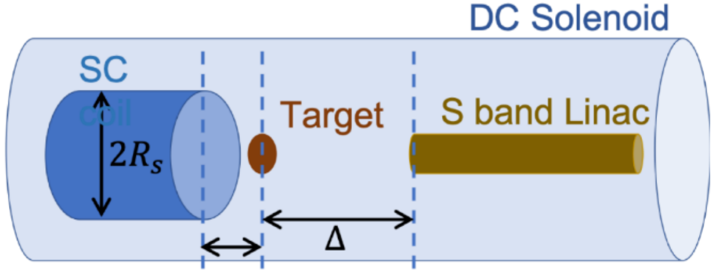
400 MHz SRF cryomodule,

with prototypes of multi-cell cavities

High-efficiency RF power sources

high-yield positron source

target with DC SC solenoid or flux concentrator

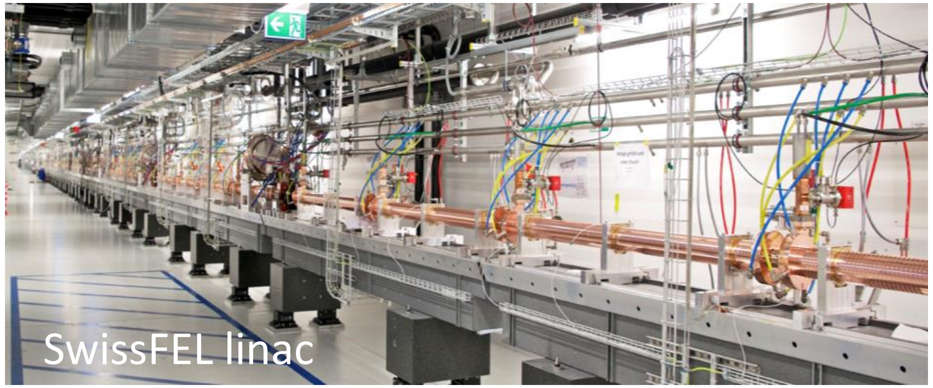


positron capture linac

large aperture S-band linac

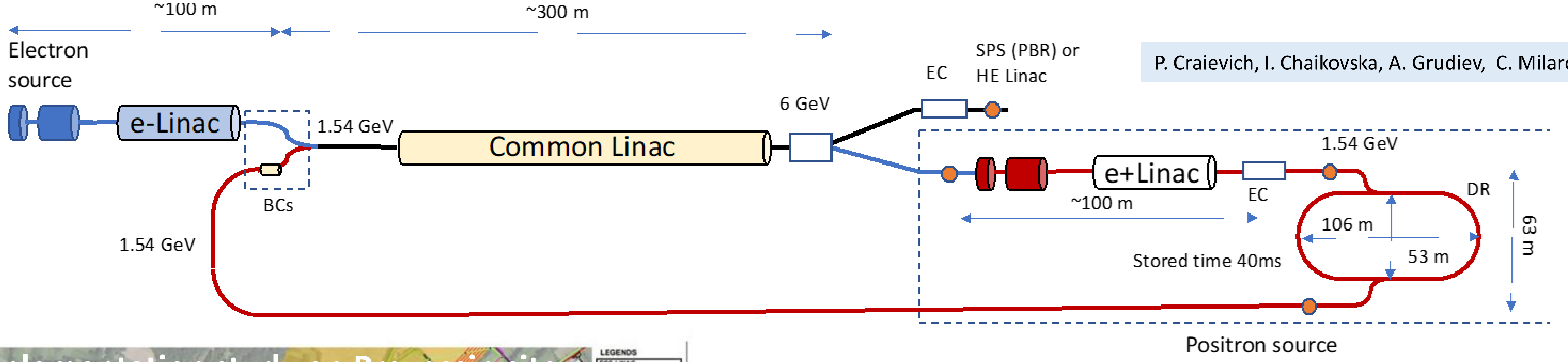
- Freq : 2.856 GHz
- 90 cells per structure
- Length: 3.254 m
- Distance between two TWs: 45 cm
- Gradient: 20 MV/m
- Aperture: 30 mm

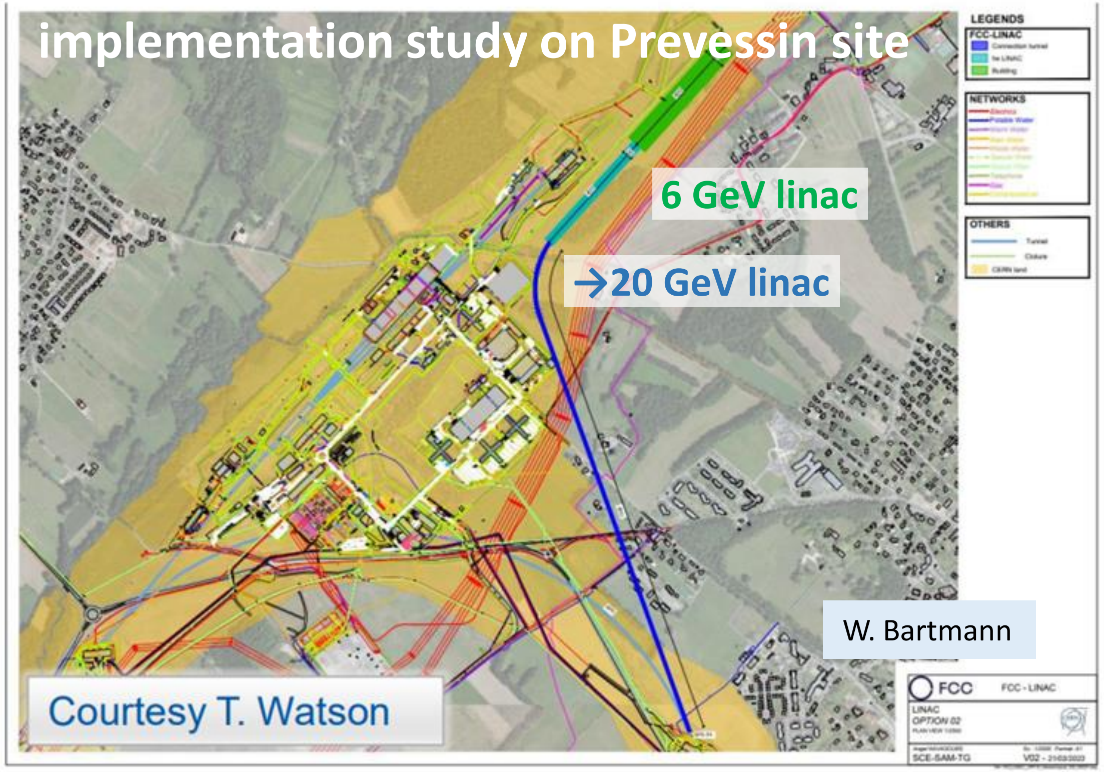
beam test of e^+ source & capture linac at SwissFEL – yield measurement



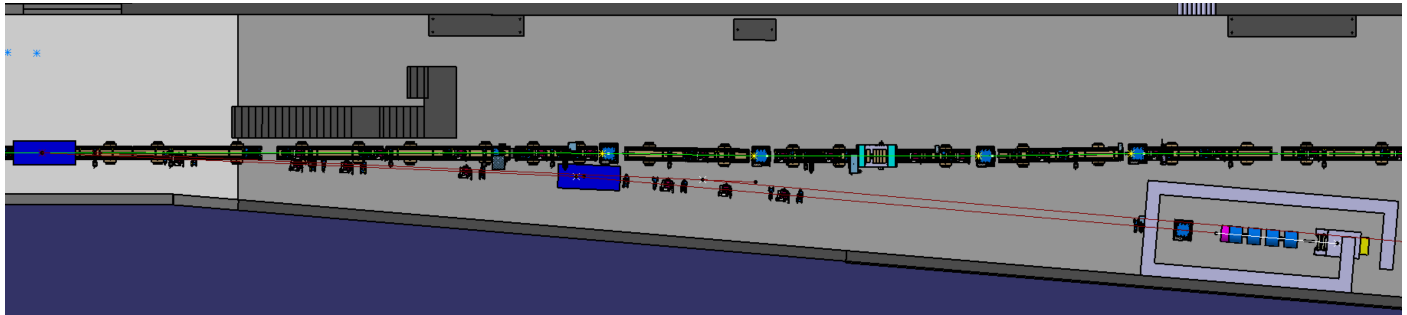
FCC-ee injector layout & implementation

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

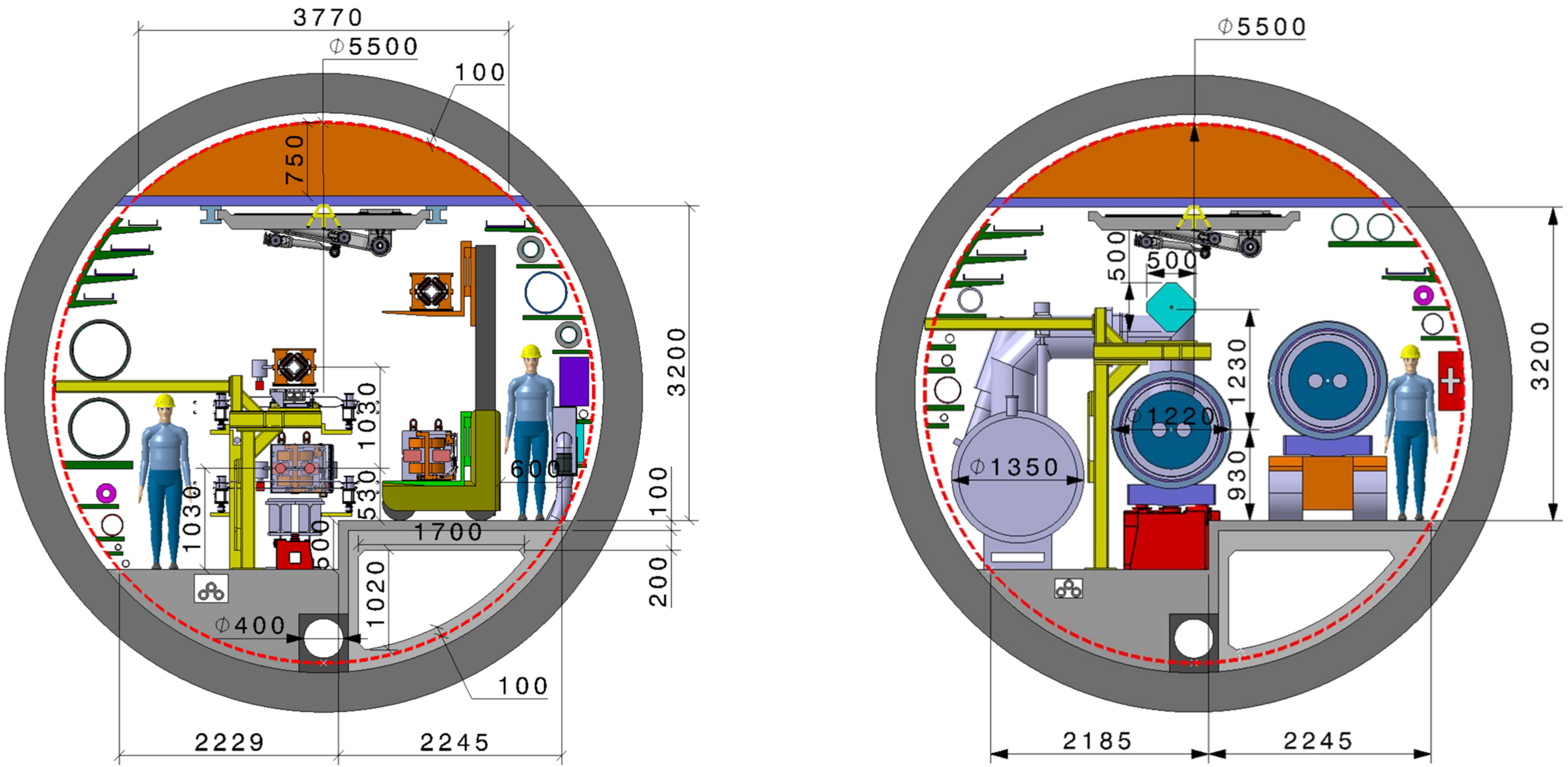




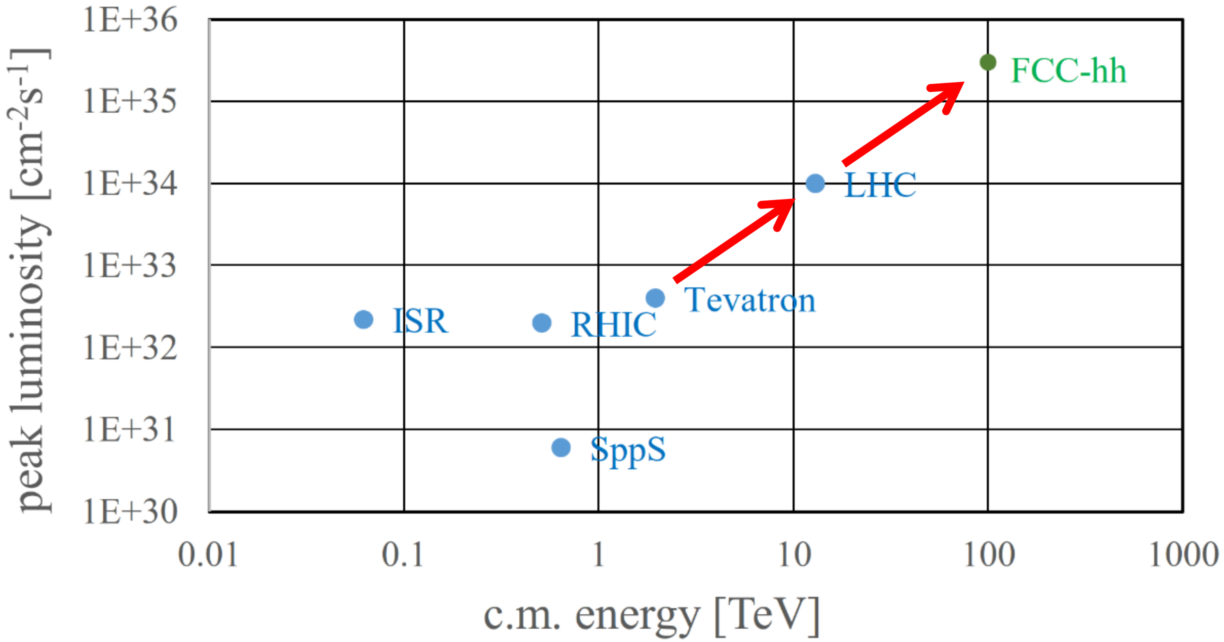
"Positron production experiment" at PSI's SwissFEL, beam tests from 2025/26 (6 GeV C-band linac)



Tunnel integration for FCC ee and FCC hh



FCC-hh: highest collision energies



order of magnitude performance increase in both energy & luminosity

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

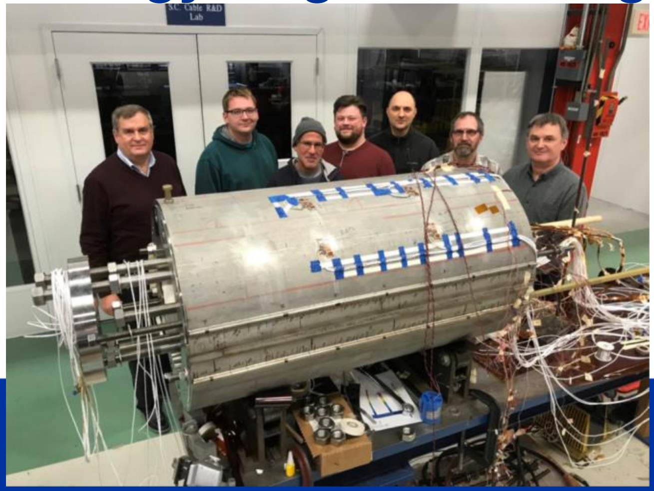
20 ab-1 per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

similar performance increase as from Tevatron to LHC

key technology: high-field magnets

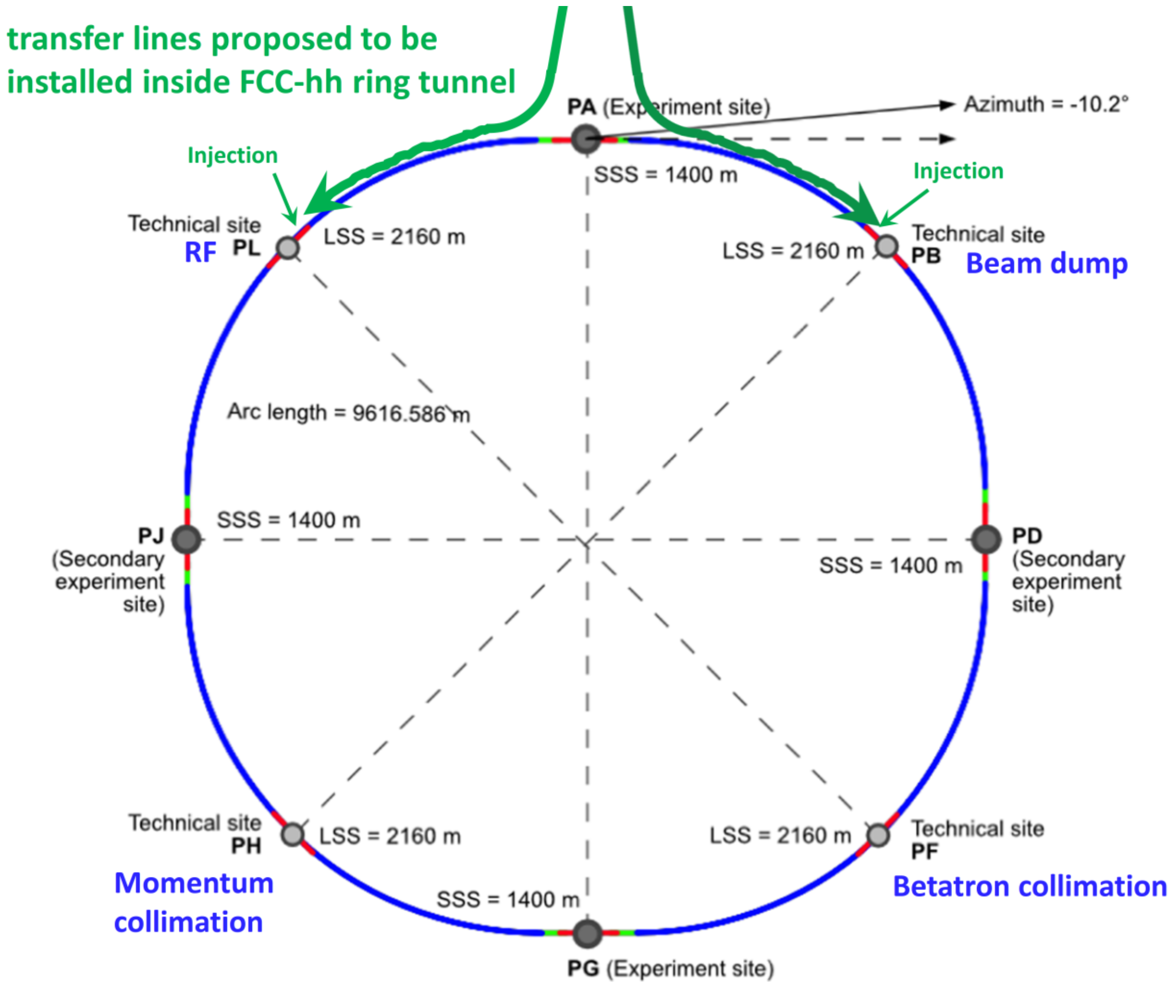
from
LHC technology
8.3 T NbTi dipole

via
HL-LHC technology
12 T Nb_3Sn quadrupole



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

FCC hh basic design choices



- **dual aperture superconducting magnets**
- **two high-luminosity experiments (A & G)**
- **two other experiments (L & B)** combined with **injection upstream** of experiments
- two collimation insertions
  - betatron cleaning (J)
  - momentum cleaning (F)
- extraction/dump insertion (D)
- RF insertion (H)
- **Injection from LHC (~3 TeV) or scSPS (~1.2 TeV)**

Stage 2: FCC-hh main machine parameters

FUTURE CIRCULAR COLLIDER

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]	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	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]	6.1-8.9		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300

If 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:

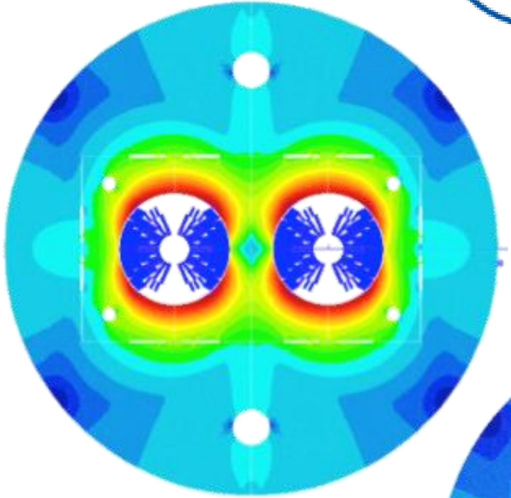
- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ❑ Final word about WIMP dark matter

F. Gianotti

16 T dipole design activities and options

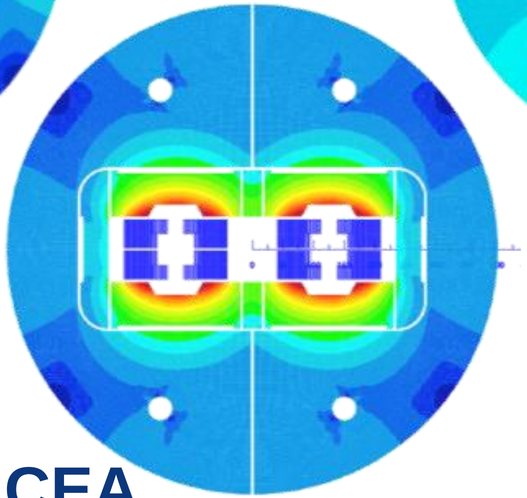
H2020

Cos-theta



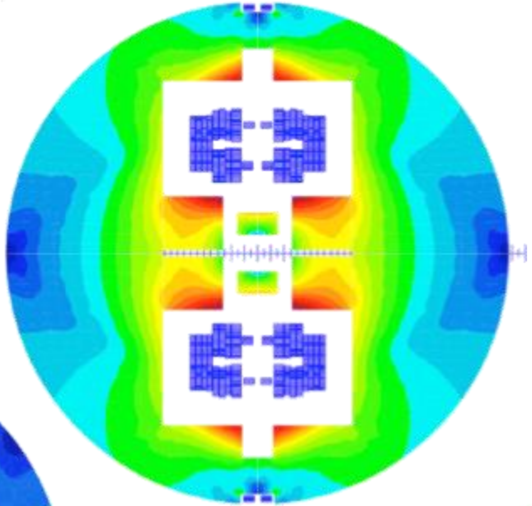
INFN

Blocks



CEA

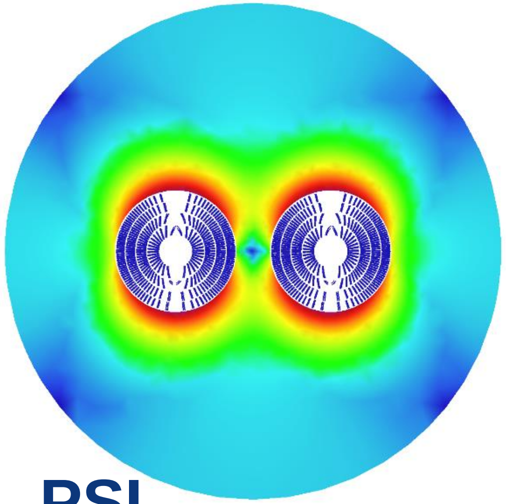
Common coils



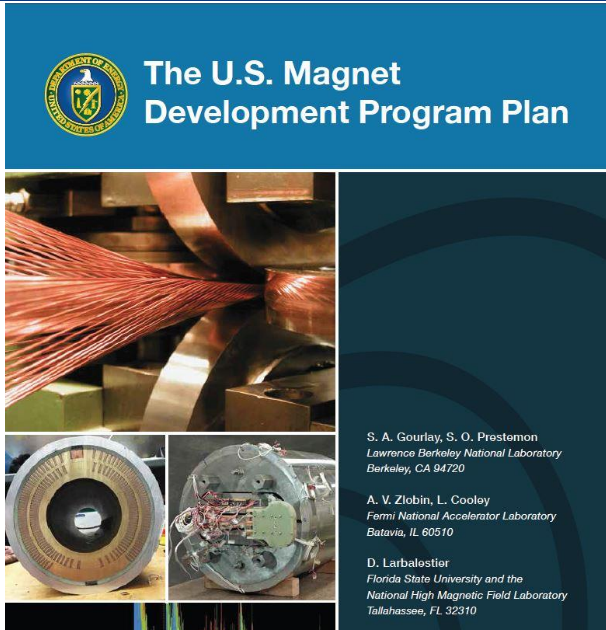
CIEMAT

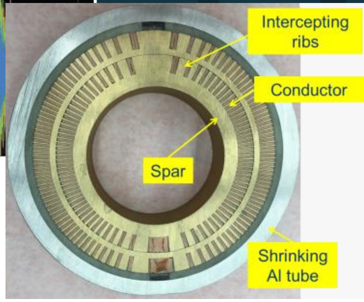
Swiss contribution

Canted Cos-theta



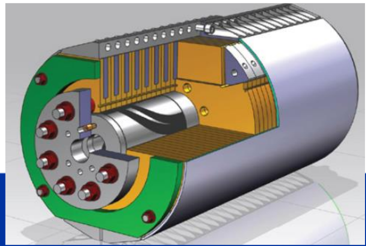
PSI





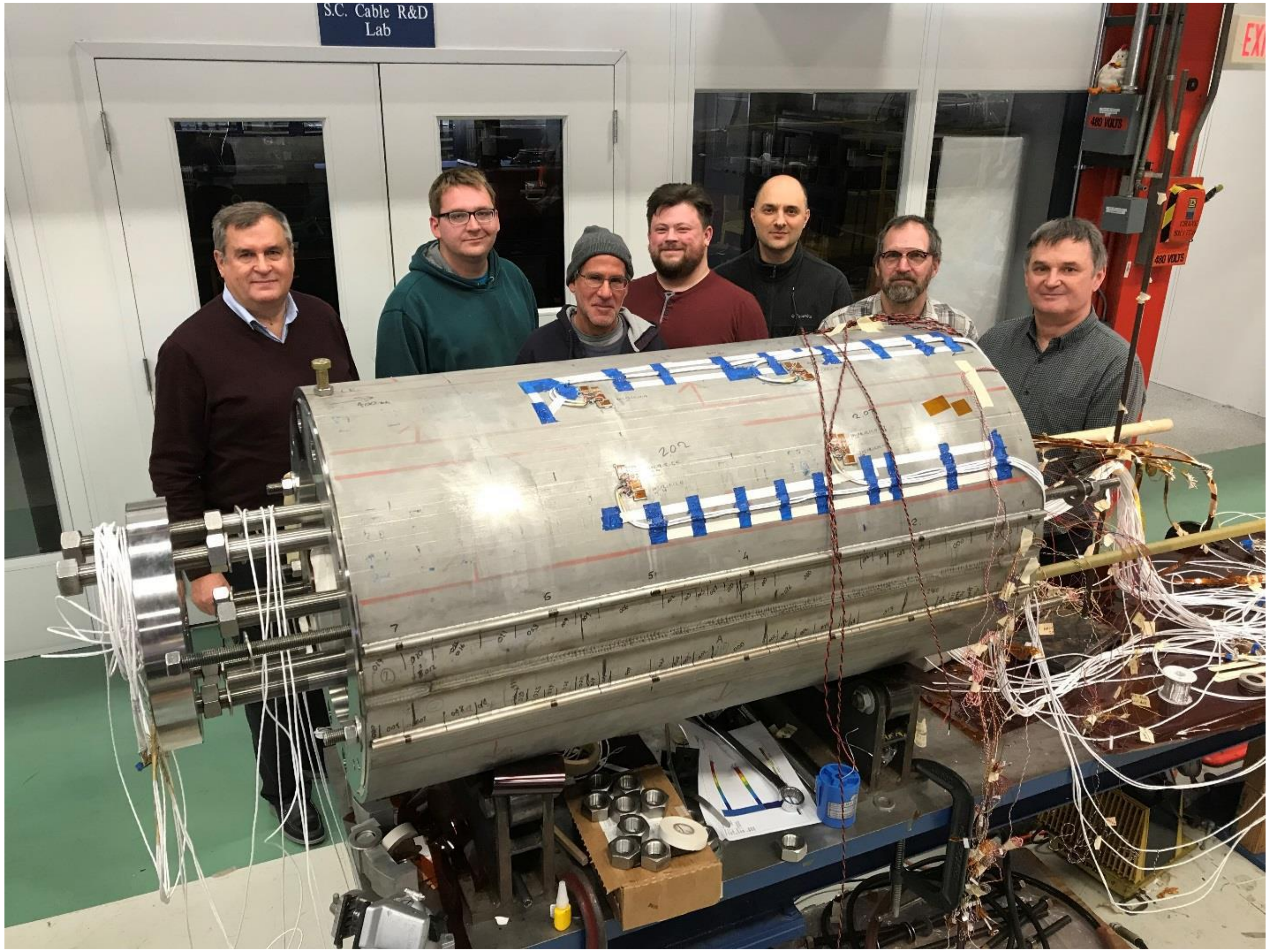
LBNL

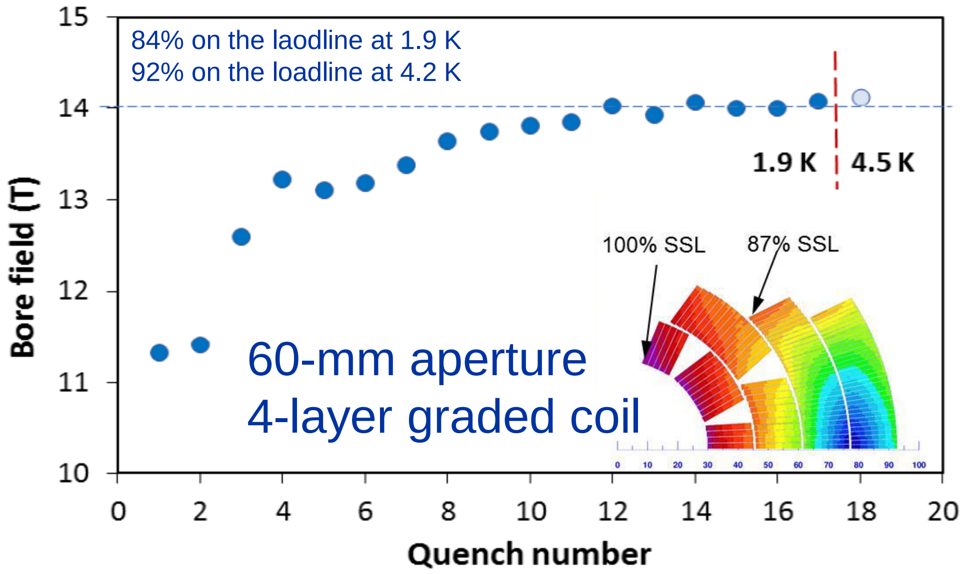
FNAL



Various programs on short model magnets ongoing

US – MDP: 14.5 T magnet tested at FNAL

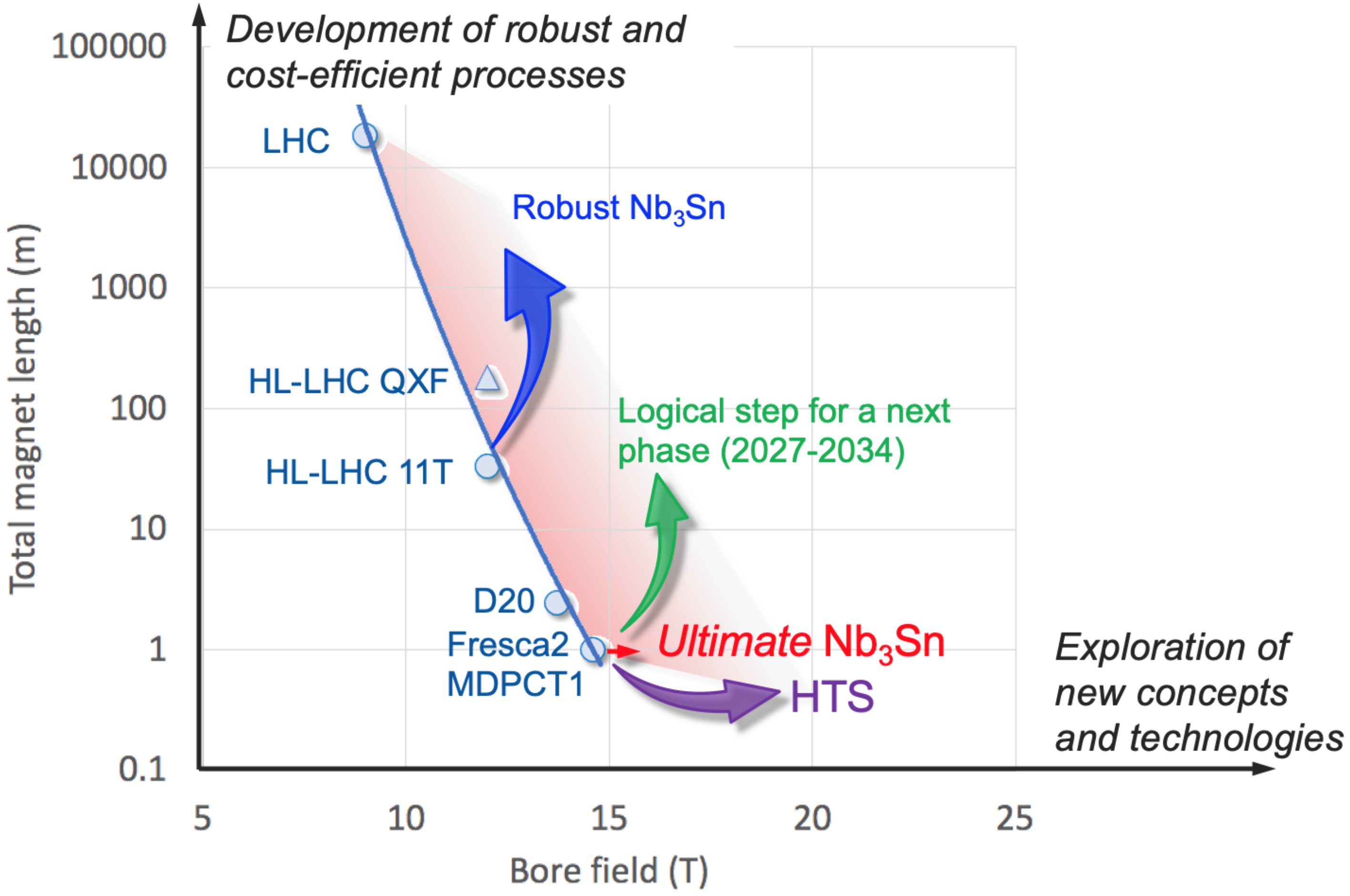




- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 20209 with additional pre-stress reached 14.5 T

High-field magnets R&D: 1st steps towards FCC-hh

In parallel to FCC Study, HFM development program as long-term separate R&D project

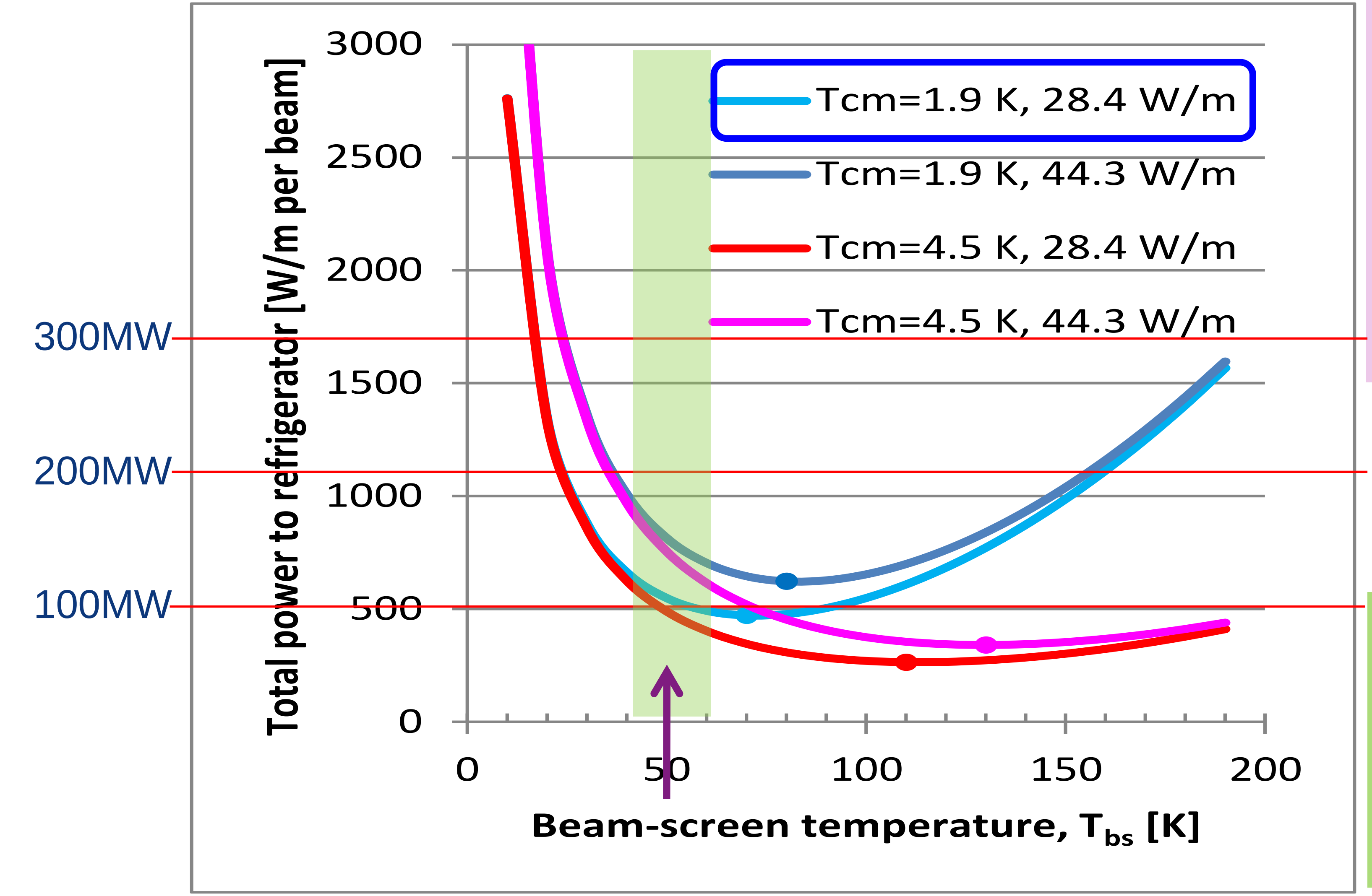


Main R&D activities:

- ❑ 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

Global collaborations already established during FCC CDR phase.

FCC-hh cryoplants – energy efficiency



BS temperature choice is overall optimisation of:

- **Cryoplant power consumption**
- **Vacuum system performance**
- **Impedance and beam stability**

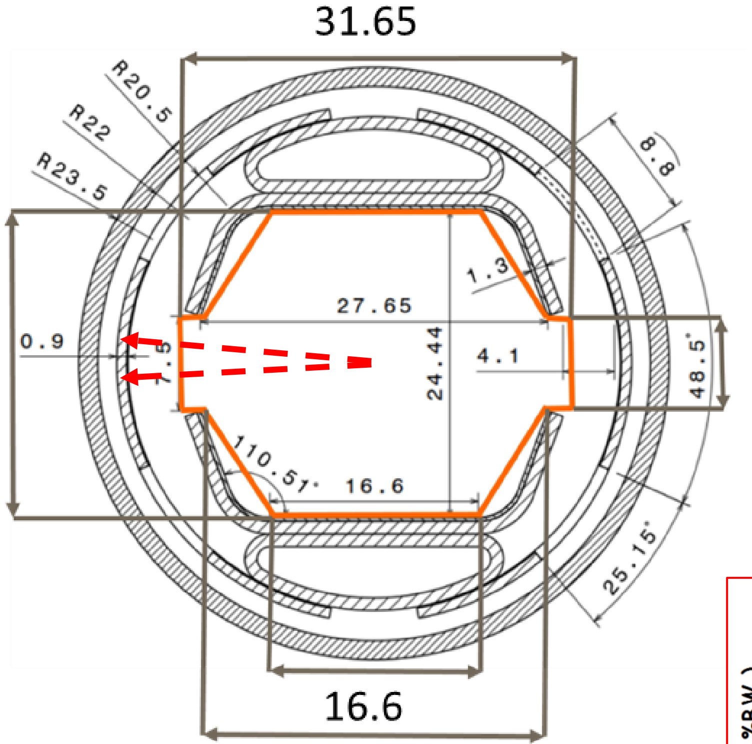
Ideal Carnot process:
$\Delta W = \Delta Q \cdot (T - T_{lowT}) / T_{lowT} =$
$= \Delta Q \cdot (300 - 1.9) / 1.9 \sim 155 \cdot \Delta Q$

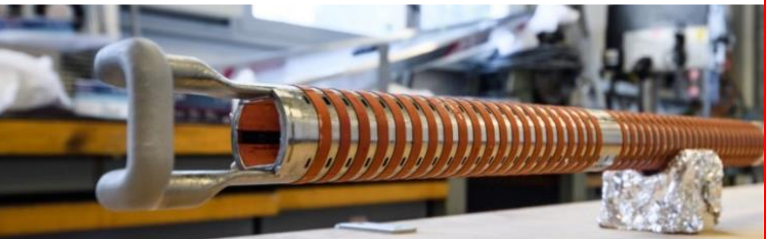
- **Optimum beam screen operation temperature 40 - 60 K**
- **Electrical power for beam screen cooling ~100 MW .**

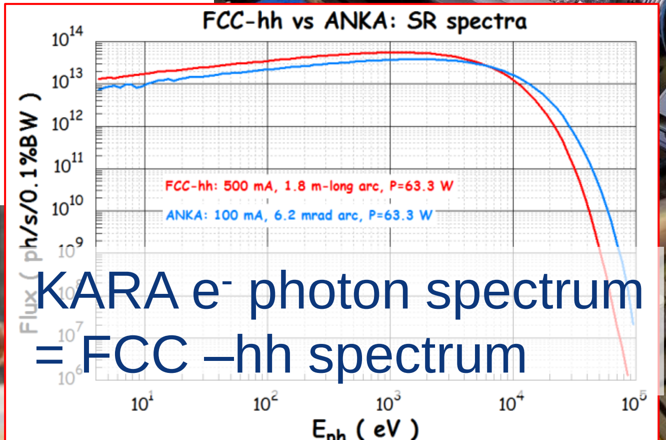
Succesful test of FCC-hh beam screen

synchrotron radiation (~ 30 W/m/beam (@16 T field) (cf. LHC <0.2W/m) **~ 5 MW total load in arcs**

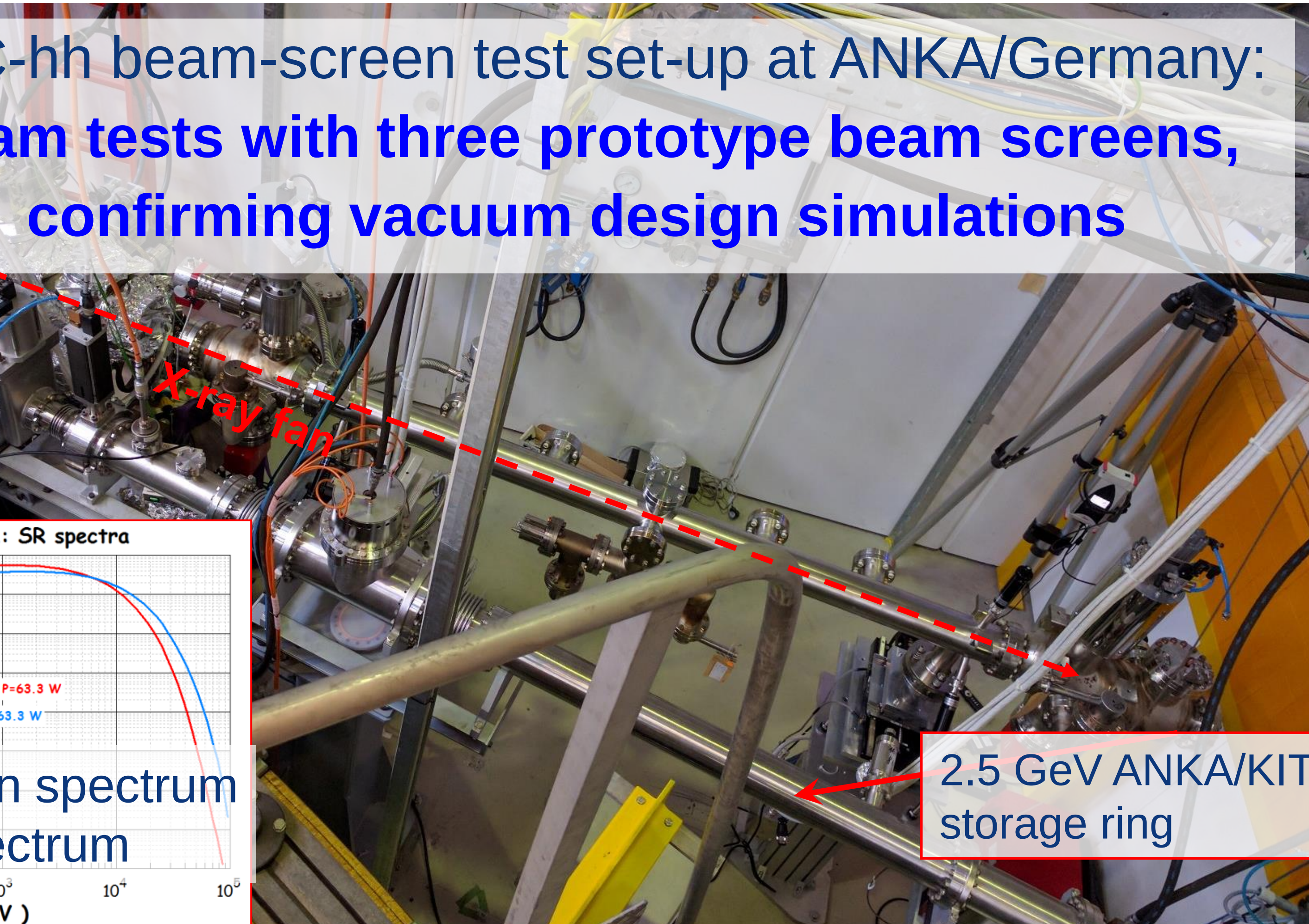
- **absorption of synchrotron radiation at higher temperature (> 1.8 K)** for cryogenic efficiency
- provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.







KARA e^- photon spectrum = FCC –hh spectrum



FCC-hh beam-screen test set-up at ANKA/Germany:

beam tests with three prototype beam screens, confirming vacuum design simulations

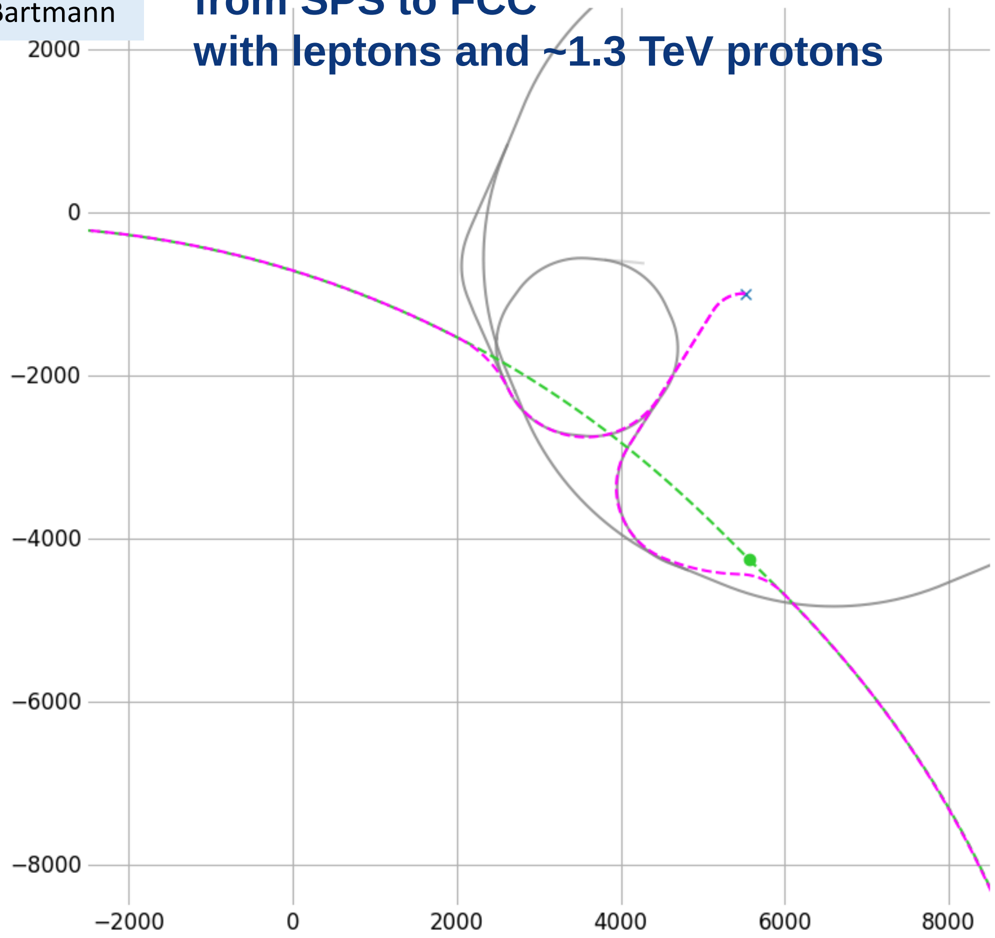
2.5 GeV ANKA/KIT storage ring

FUTURE CIRCULAR COLLIDER

transfer lines for ee & hh

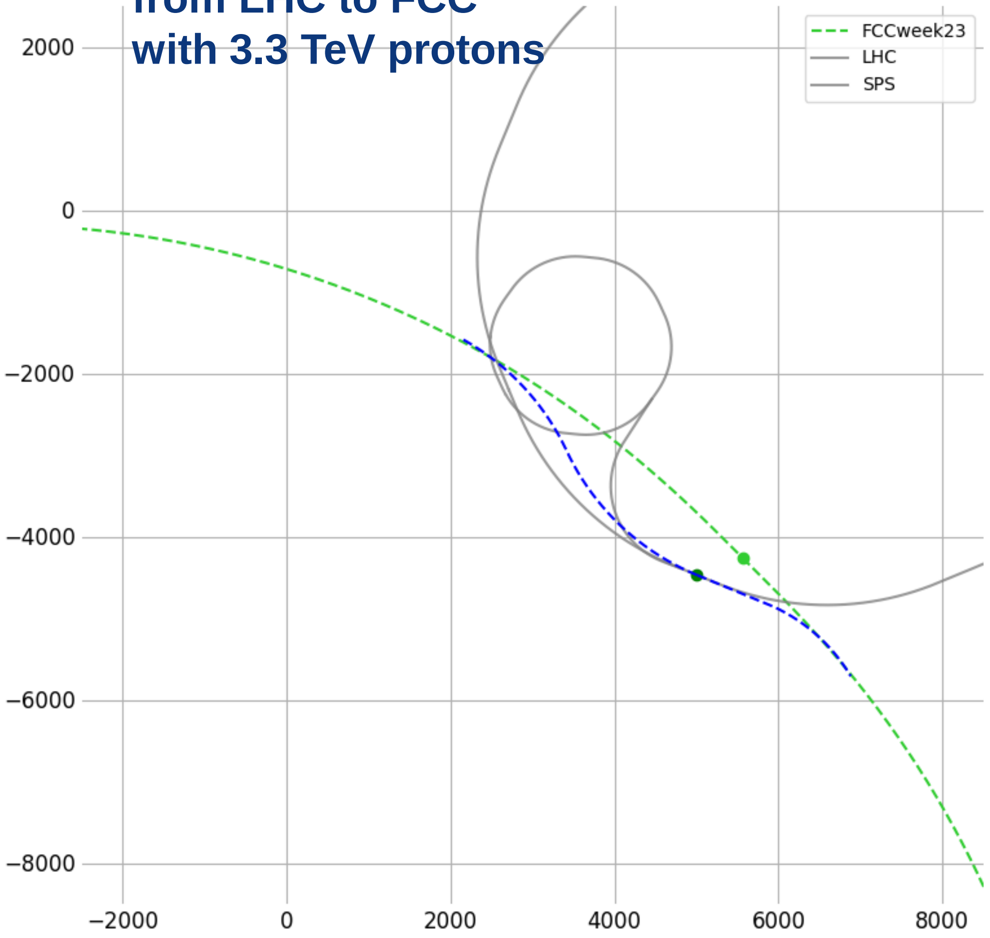
W. Bartmann

from SPS to FCC
with leptons and ~1.3 TeV protons



From 6 or 20 GeV Linac on Prevessin site, 1.7 km tunnel down to SPS LSS4, both particle species; then beam separation: (1) one beam into TI 8 tunnel and at LHC level a new tunnel of 1.8 km to connect to the FCC collider, (2) other beam fed through the SPS tunnel, extracting at LSS6 followed by short 800 m tunnel to connect to FCC; all lines from SPS level onwards compatible with 1.3 TeV protons; options also compatible with SPS as lepton pre-booster if 6 GeV linac.

from LHC to FCC
with 3.3 TeV protons



blue lines are compatible with 3.3 TeV hadrons and would need new tunnels; leptons could be fed down as for the SPS option via TI8 and then one beam just continue in the same direction, the other beam would need a small u-turn around LHC P8 to use the same line as hadrons, or a u-turn to the collider tunnel or come directly via the SPS and a small connection tunnel as in the SPS option

FUTURE CIRCULAR COLLIDER

Status of Global FCC Collaboration

Increasing international collaboration as a prerequisite for success

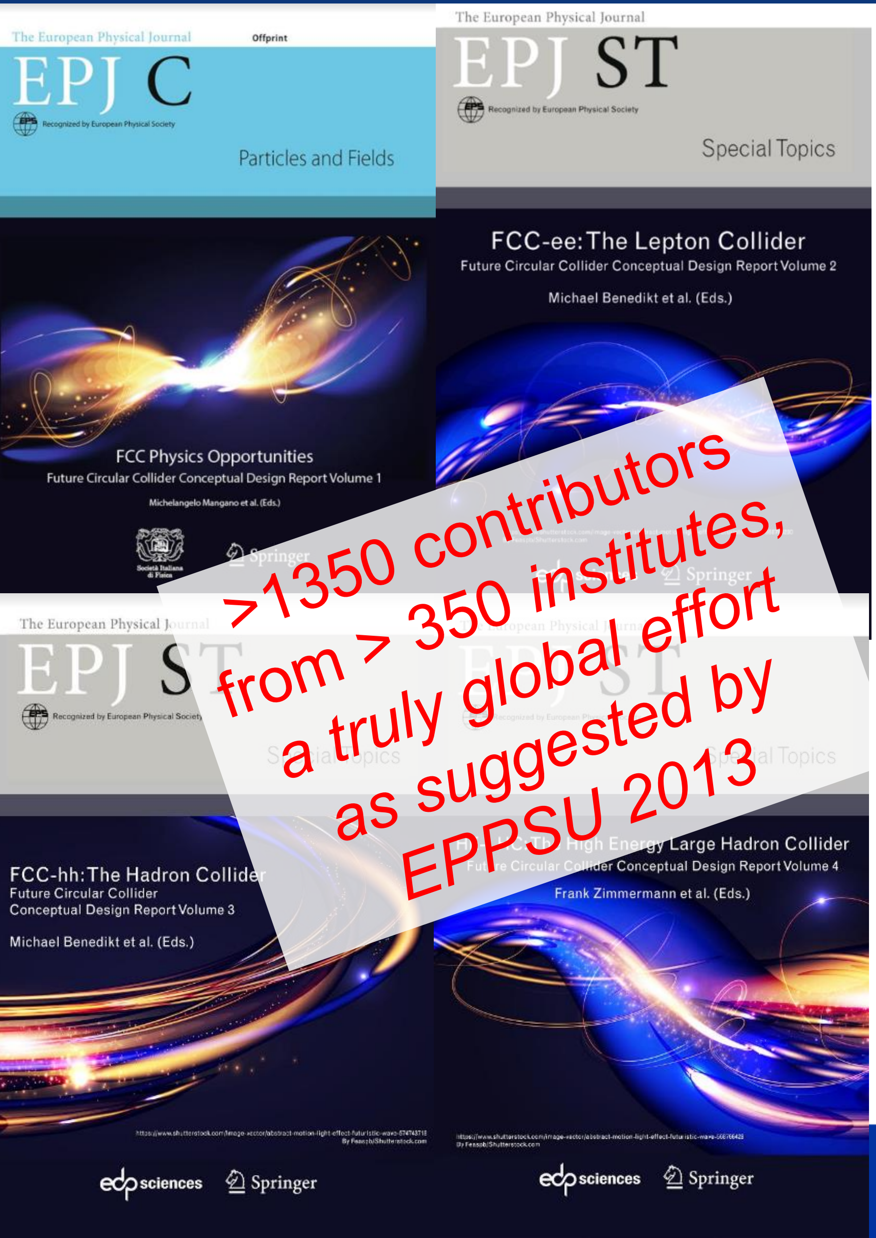
147 Institutes

30 Companies

34 Countries

EC H2020

FCC CDR & Study Documentation



- **FCC-Conceptual Design Reports:**
  - **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) [Springer]**

    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

EPJ is a merger and continuation of *Acta Physica Hungarica, Anales de Fisica, Czechoslovak Journal of Physics, Fizika A, Il Nuovo Cimento, Journal de Physique, Portugaliae Physica* and *Zeitschrift für Physik*. 25 European Physical Societies are represented in EPJ, including the DPG.

- **Summary documents provided to EPPSU 2019/20**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

Conclusions

- The European Particle Physics Strategy Update 2020 issued the request for a feasibility study of the FCC integrated programme to be delivered for the next Strategy Update.

- The FCC Feasibility Study should inform about technical, territorial and financial feasibility of the FCC project and bring all elements needed to decide about a potential project.

- Strenghtening links with science, research & development, high-tech industry and society at large will be essential to further advance and prepare the implementation of FCC as a long-term sustainable world-leading HEP research infrastructure for the 21st century to push the particle-physics precision and energy frontiers far beyond present limits.

Thank you for your attention.