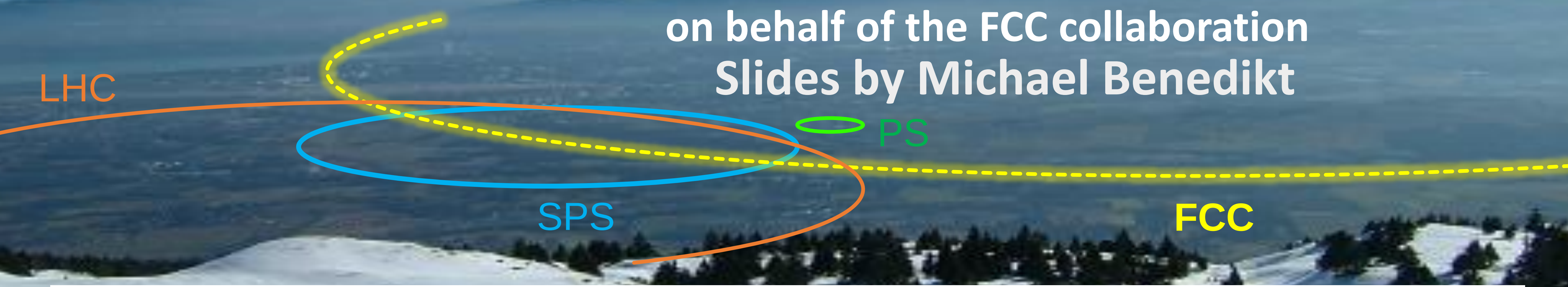
Future Circular Colliders

CERN Accelerator School, 13 May 2022

Xavier Buffat, CERN
on behalf of the FCC collaboration
Slides by Michael Benedikt



FCC hh ee he | EuroCirCol A key to New Physics | EASITrain | ARIES | FUTURE CIRCULAR COLLIDER Innovation Study | E-JADE | http://cern.ch/fcc | CERN

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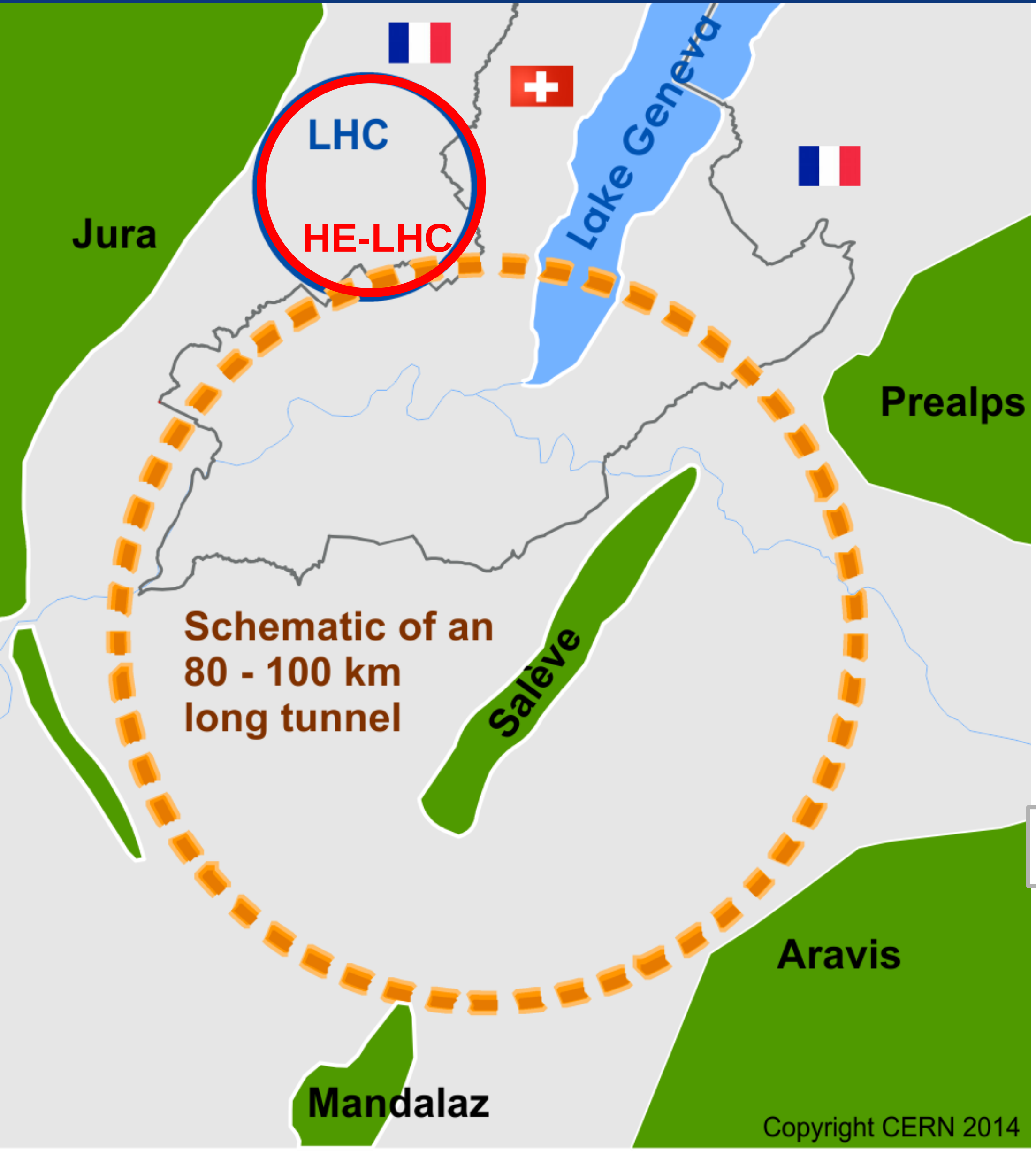
CERN Future Circular Collider Study

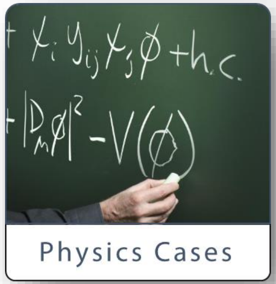


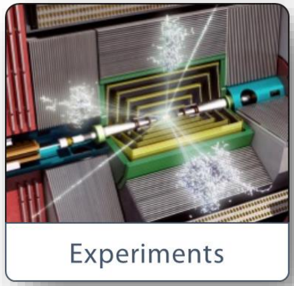
International FCC collaboration (CERN as host lab) to study:

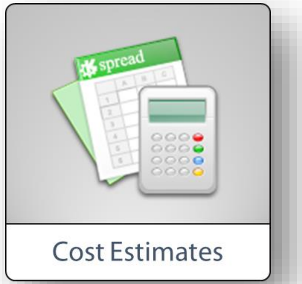
- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- ***e*⁺*e*⁻ collider (*FCC-ee*),** as potential first step
- ***pp*-collider (*FCC-hh*)** → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **lepton-hadron collisions** as options to FCC-hh







FCC study: physics and performance targets

FCC-ee:

- **Exploration of 10 to 100 TeV energy scale via couplings with precision measurements**
- **~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)**
  ($m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings)

➢ **Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points**

FCC-hh:

- **Highest center of mass energy for direct production up to 20 - 30 TeV**
- **Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks**

➢ **Machine design for ~100 TeV c.m. energy & integrated luminosity $\sim$ 20ab^{-1} within 25 years**

FCC-ee basic design choices

double ring e^+e^- collider ~100 km

follows footprint of FCC-hh, except around IPs

asymmetric IR layout & optics to limit synchrotron radiation towards the detector

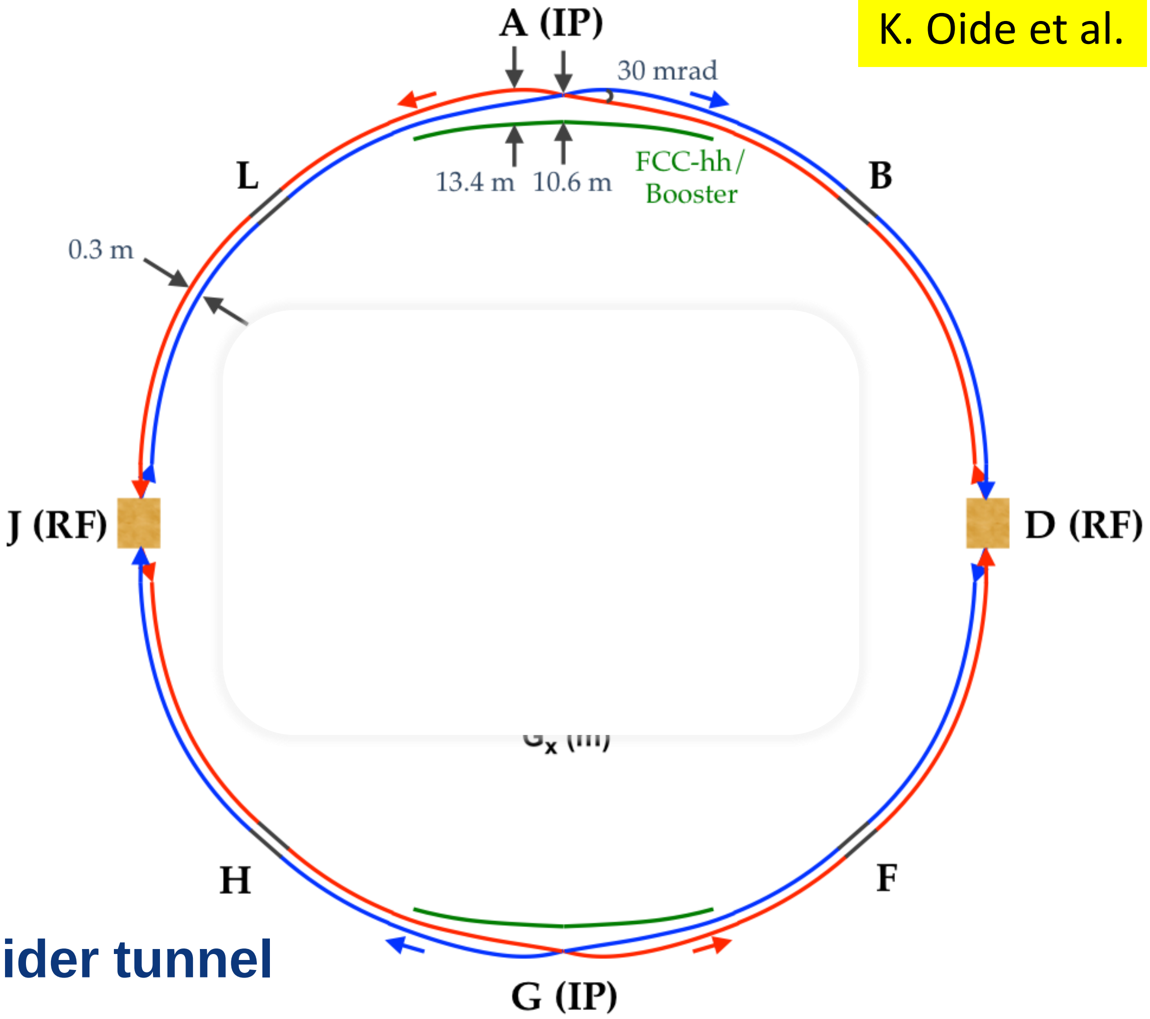
- **large** horizontal crossing angle **30 mrad**
- **crab-waist optics**
- **presently 2 IPs** (alternative layouts with 3 or 4 IPs under study),

synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy

common RF for $t\bar{t}$ running

top-up injection requires **booster synchrotron in collider tunnel**

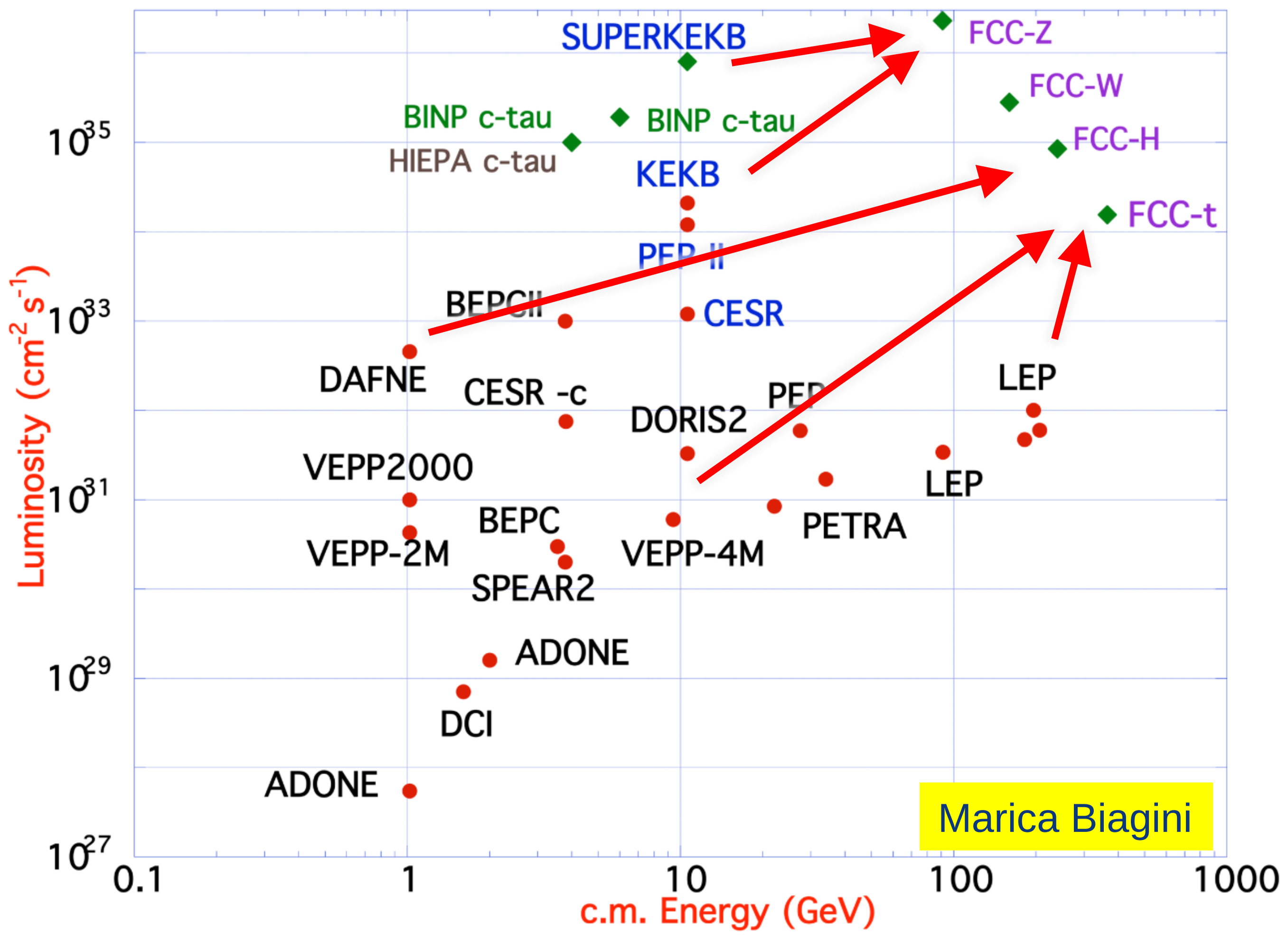
K. Oide et al.



FCC-ee: The Lepton Collider, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

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

KEKB: e^+ source
DAFNE: crab waist, double ring

S-KEKB: low β_y*, crab waist

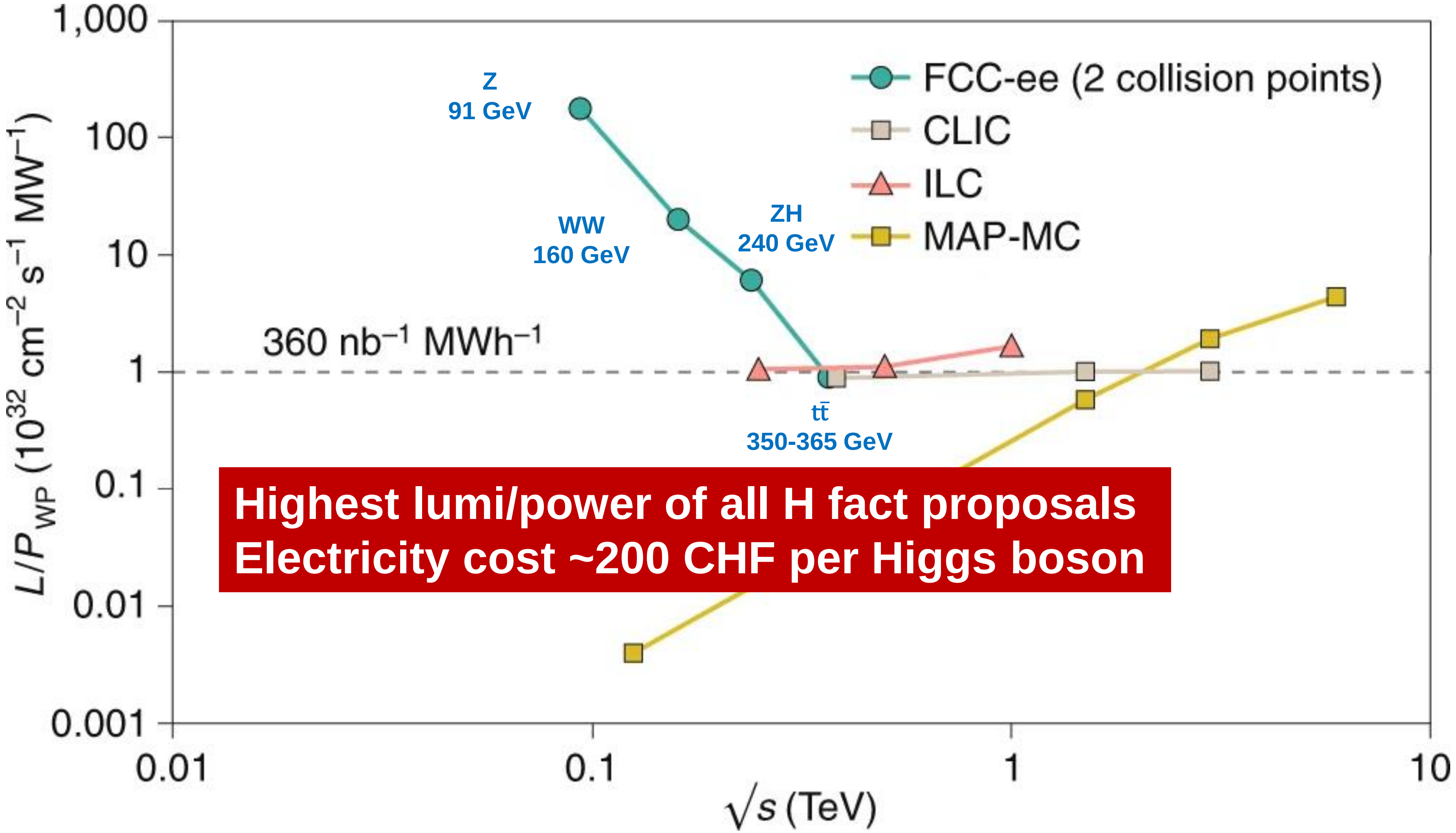
LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

HERA, LEP, RHIC: spin gymnastics

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

FCC-ee: efficient Higgs/electroweak factory



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

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 figures of merit

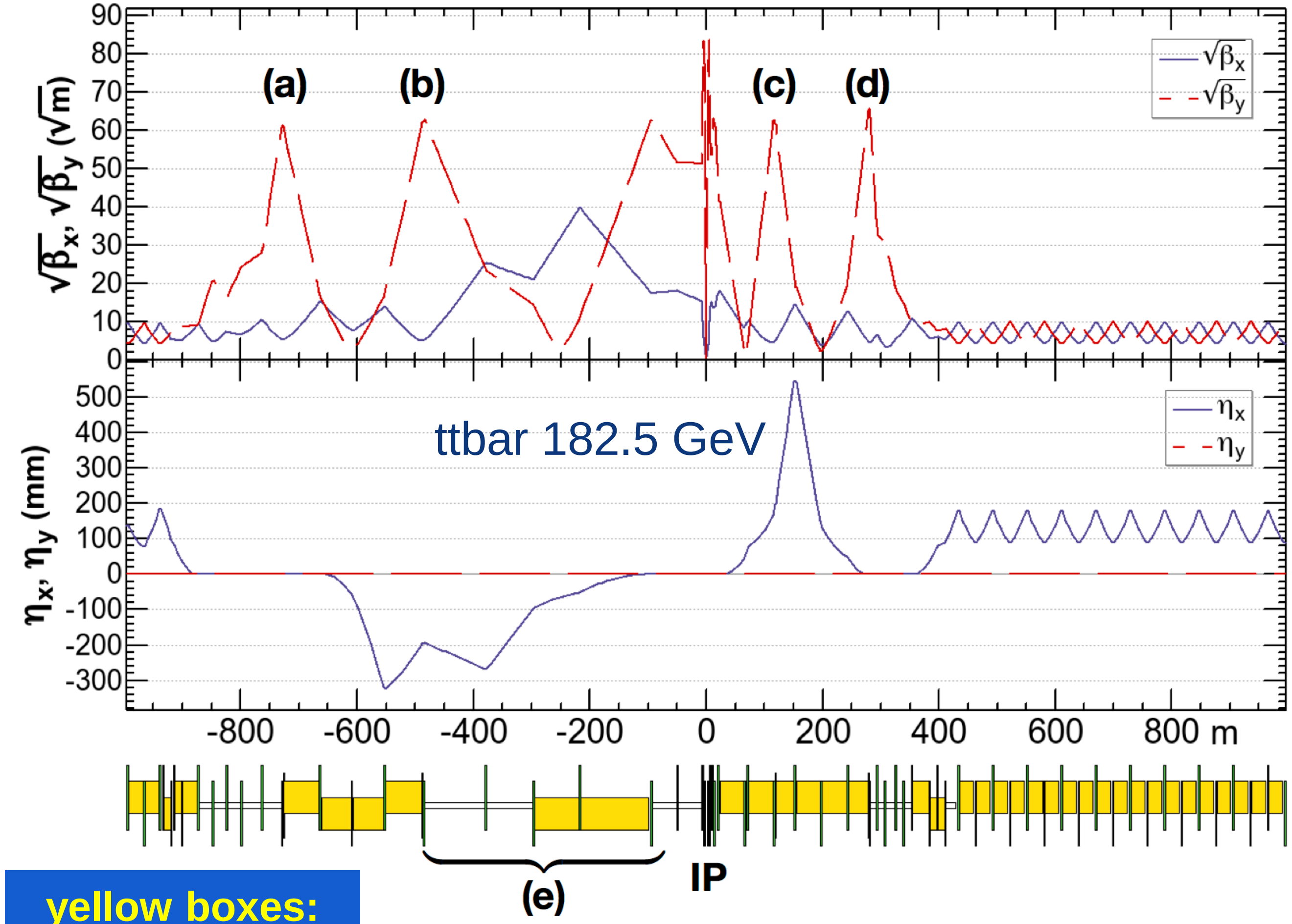
Luminosity vs. capital cost

- for the H running, **with 5 ab^{-1} accumulated over 3 years and 10^6 H produced**, the total investment cost (~10 BCHF) corresponds to **10 kCHF per produced Higgs boson**
- for the Z running with **150 ab^{-1} accumulated over 4 years and $5x10^{12}$ Z produced,** the total investment cost corresponds to **10 kCHF per 5×10^6 Z bosons**

This it the number of Z bosons collected by each experiment during the entire LEP programme !

Capital cost per luminosity dramatically decreased compared with LEP !

FCC-ee asymmetric crab-waist IR optics



yellow boxes: dipole magnets

Novel asymmetric IR optics to suppress synchrotron radiation toward the IP, **$E_{critical}$ <100 keV from 450 m from IP (e)** **– lesson from LEP**

H. Burkhardt, A. Blondel, M. Koratzinos, K. Oide, et al.

4 sextupoles (a–d) for local vertical chromaticity correction combined w. crab waist, optimized for each working point – **novel "virtual crab waist", standard crab waist demonstrated at DAFNE**

K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

FCC-ee RF staging

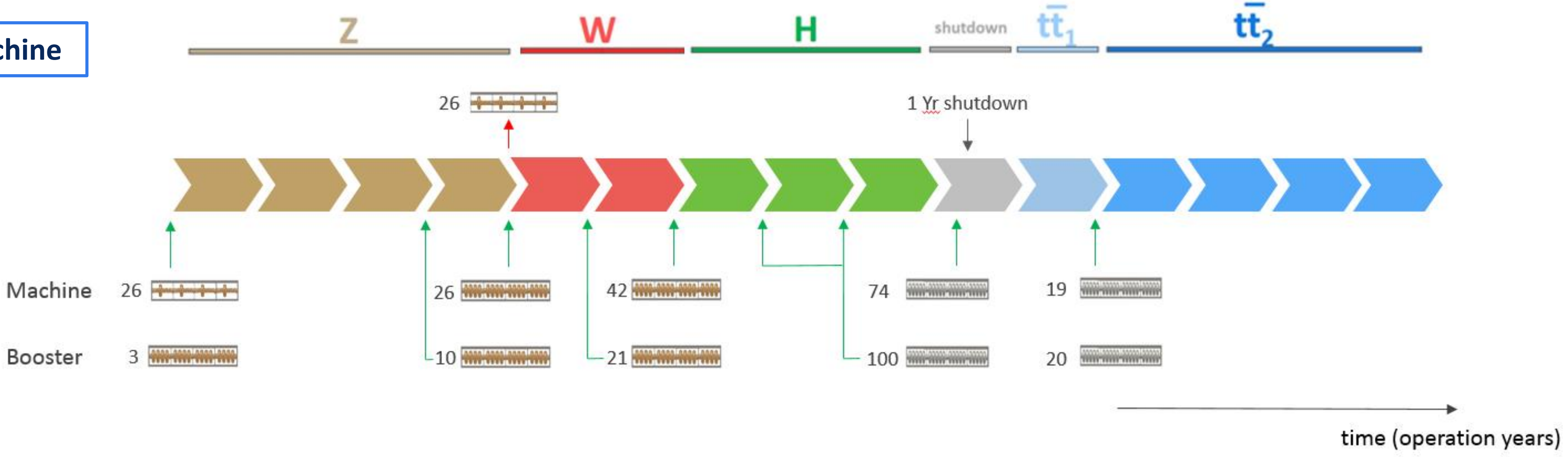
"Ampere-class" machine

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)**



FCC-ee R&D: RF, cryo-modules, power sources

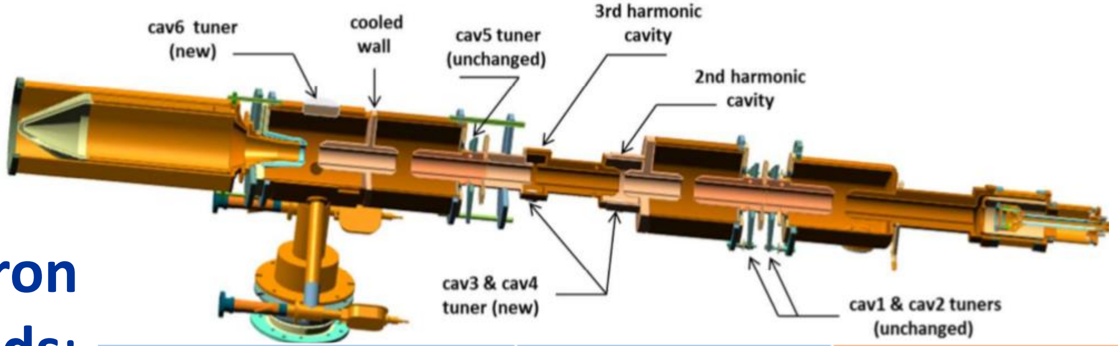
R&D aimed at improving performance & efficiency and reducing cost:

- improved Nb/Cu coating/sputtering, partner STFC (e.g. ECR fibre growth, HiPIMS)
- new cavity fabrication techniques, partner STFC (e.g. EHF, improved polishing, seamless)
- coating of A15 superconductors (e.g. Nb_3Sn), · cryo-module design optimisation
- bulk Nb cavity R&D at FNAL, Cornell, JLAB, also KEK and CEPC/IHEP
- MW-class fundamental power couplers for 400 MHz; · novel high-efficiency klystrons

Seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL

Tooling fabricated and successfully tested with an Aluminium cavity.

high-efficiency klystron at CERN



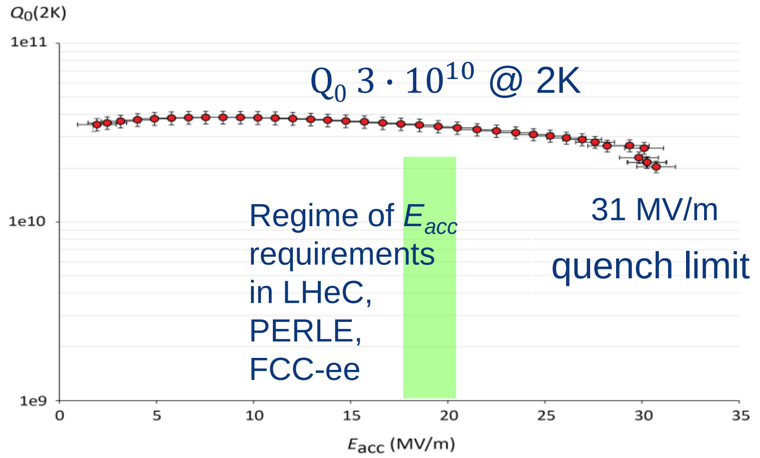
novel klystron bunching methods: LHC klystron retrofit as proof of principle for FCC

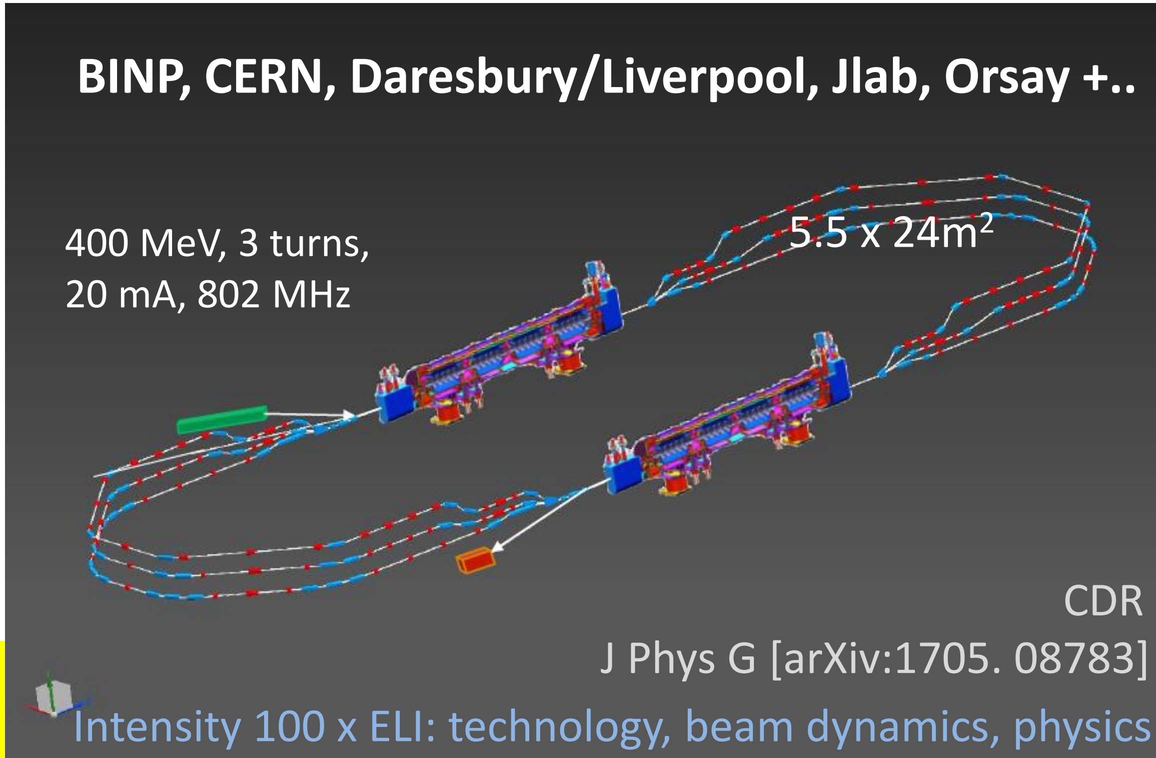
Parameter	present TH2167	CSM upgrade
Frequency [MHz]	400	
Beam voltage [kV]	54	
Saturated RF power [kW]	300	350
Efficiency [%]	60	70

SRF R&D program, FCC-eh option and ERL

5-cell 800 MHz cavity, JLAB prototype for FCC-ee (top mode) & FCC-eh; also single-cell cavities for all FCC's

optimized for high energy operation





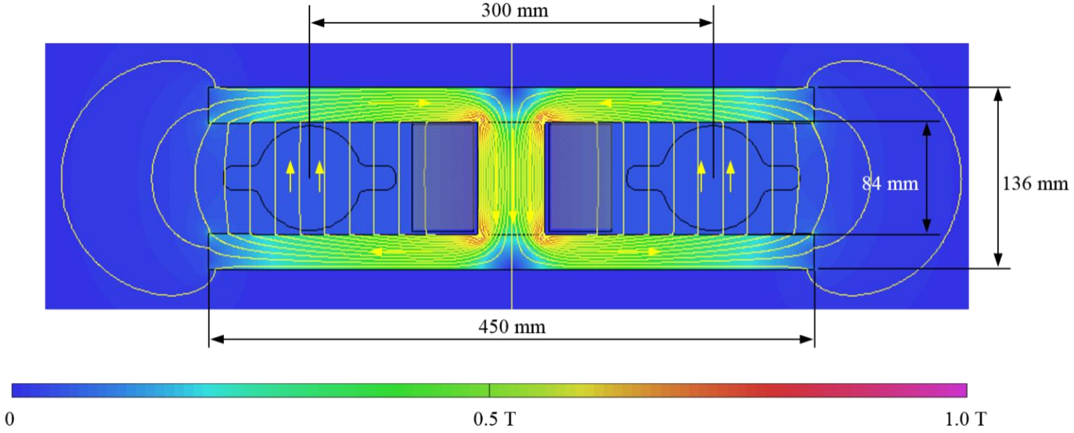
FCC-eh: 60 GeV e$^-$ from

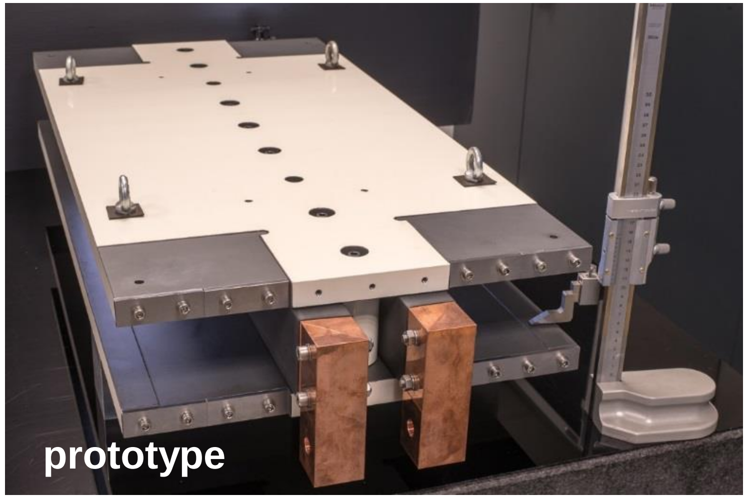
Energy Recovery Linac (ERL)

PERLE@Orsay ERL test facility

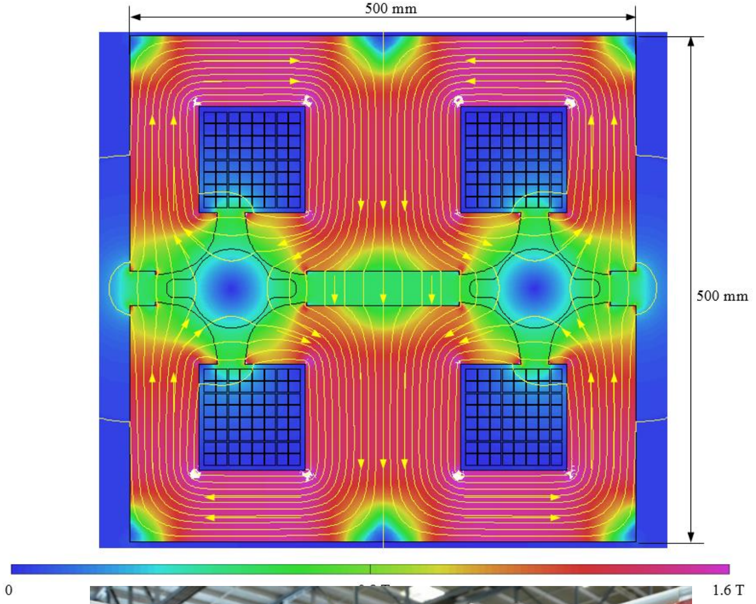
Prototypes of FCC-ee low-power magnets

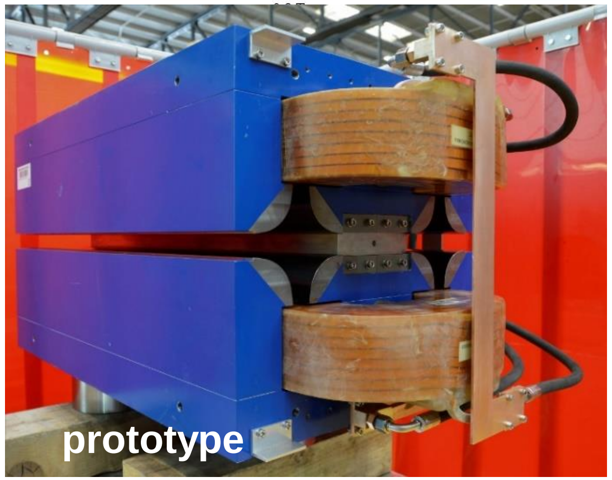
Twin-dipole design with 2× power saving
16 MW (at 175 GeV), with Al busbars



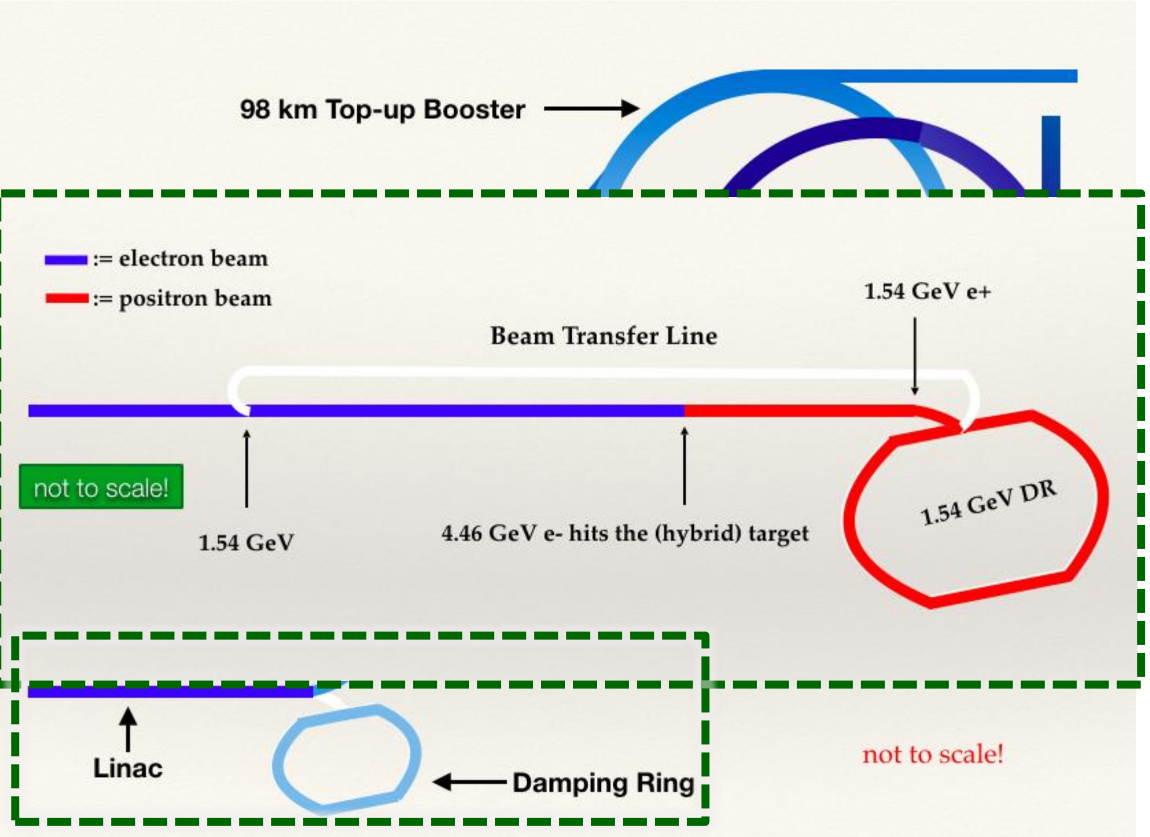


Twin F/D arc quad design with 2× power saving
25 MW (at 175 GeV), with Cu conductor





FCC-ee injector complex (baseline)



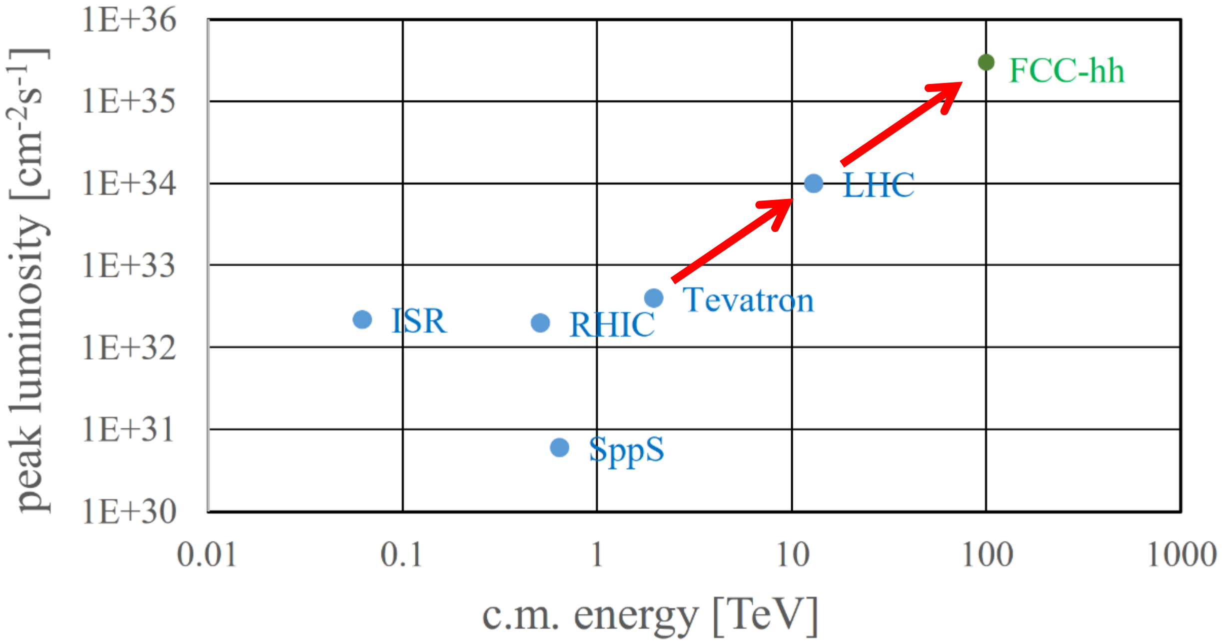
SLC/SuperKEKB-like 6 GeV S-band linac accelerating **1** or **2** bunches (2E10/b), with repetition rate **100-200 Hz**

Same linac used for e+ production @ **4.46 GeV**
e+ beam emittances reduced in DR @ **1.54 GeV**

Injection @ **6 GeV** into pre-booster Ring (SPS or new ring) & accel. to 20 GeV, or 20 GeV linac

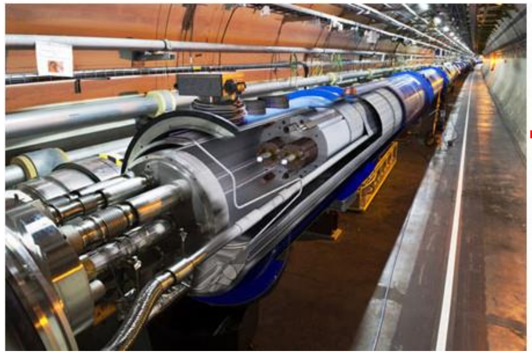
injection to main Booster @ **20 GeV** and interleaved filling of e+/e- (**<20 min for full filling**) and continuous top-up, typical rate 1/minute (Z) to 1/10s (tt)

FCC-hh: highest collision energies

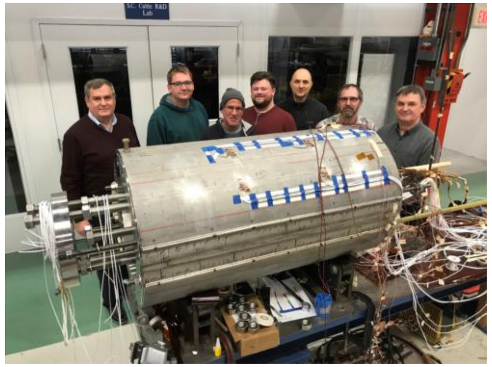


- **order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- **key technology: high-field magnets**

from
LHC technology
8.3 T NbTi dipole



via
HL-LHC technology
12 T Nb_3Sn quadrupole

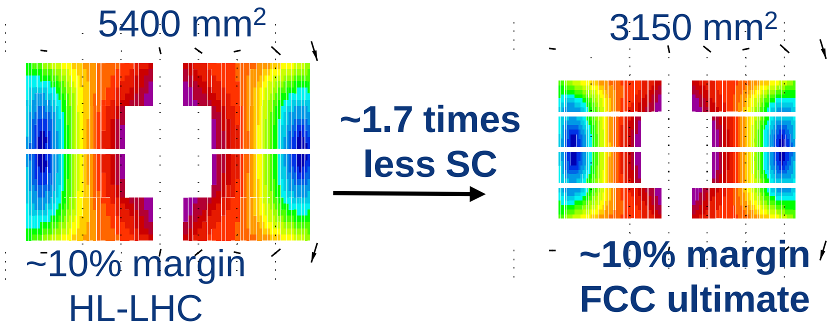


FNAL dipole demonstrator
14.5 T Nb_3Sn

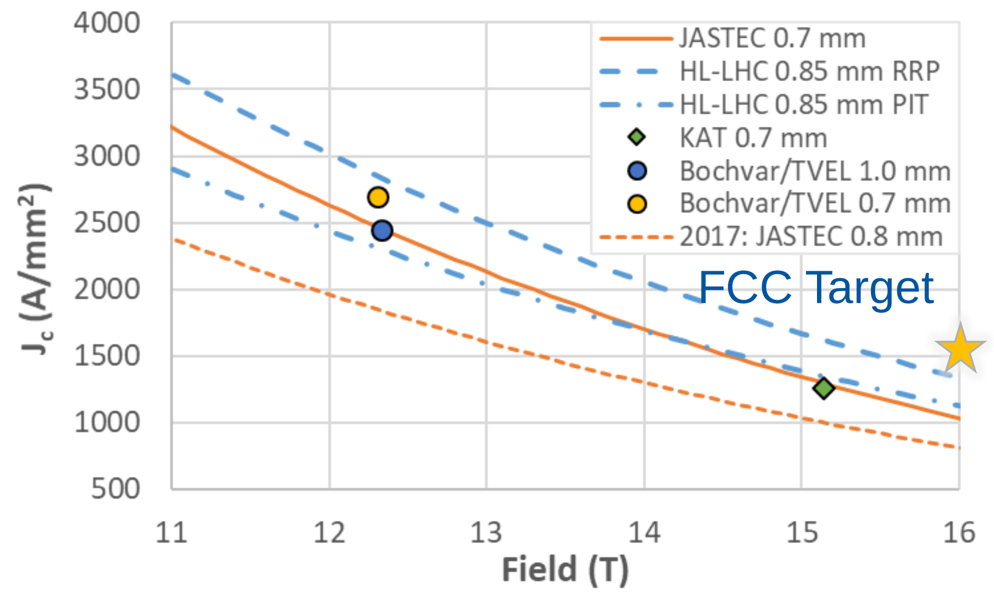
Worldwide FCC Nb_3Sn program

Main development goal is wire performance increase:

- **J_c (16T, 4.2K) > 1500 A/mm² →50% increase wrt HL-LHC wire**
- **Reduction of coil & magnet cross-section**



After 1-2 years development, **prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC J_c performance**



FCC conductor development collaboration:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea, Columbus, Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy, University of Freiberg, Germany**
- **Bruker, Germany, Luvata Pori, Finland**

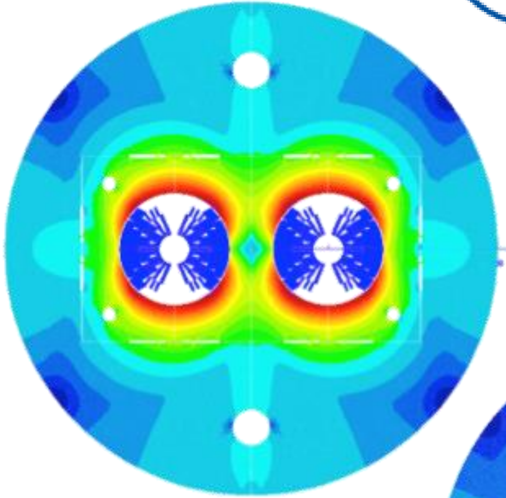
2019/20 results from US, meeting FCC J_c specs:

- **Florida State University:** high-J_c Nb_3Sn via Hf addition
- **Hyper Tech /Ohio SU/FNAL**: high-J_c Nb_3Sn via artificial pinning centres based on Zr oxide.

16 T dipole design activities and options

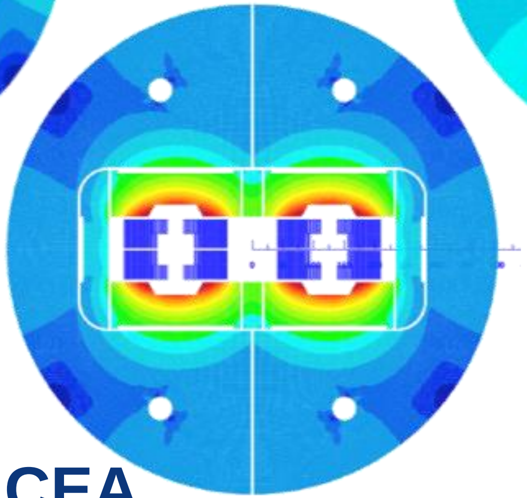
H2020 EuroCirCol

Cos-theta



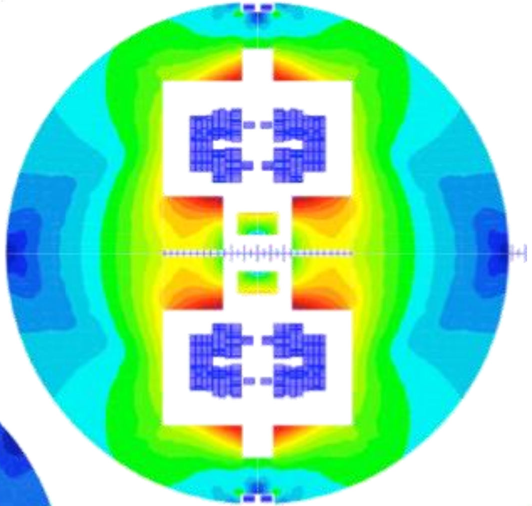
INFN

Blocks



CEA

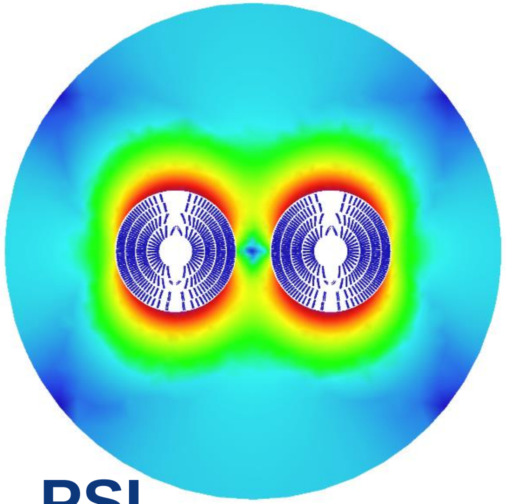
Common coils



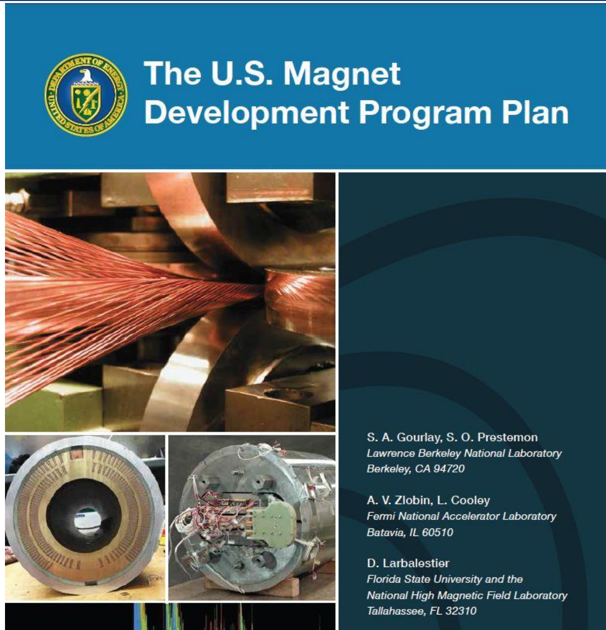
CIEMAT

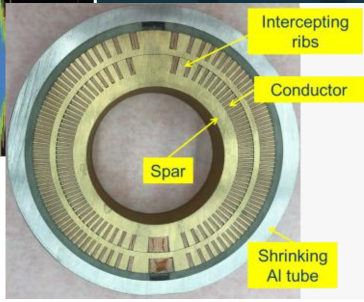
Swiss contribution

Canted Cos-theta

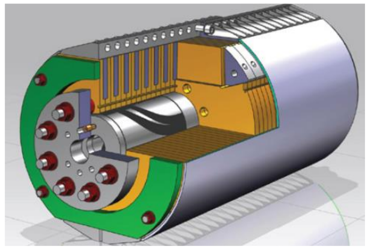


PSI





LBNL



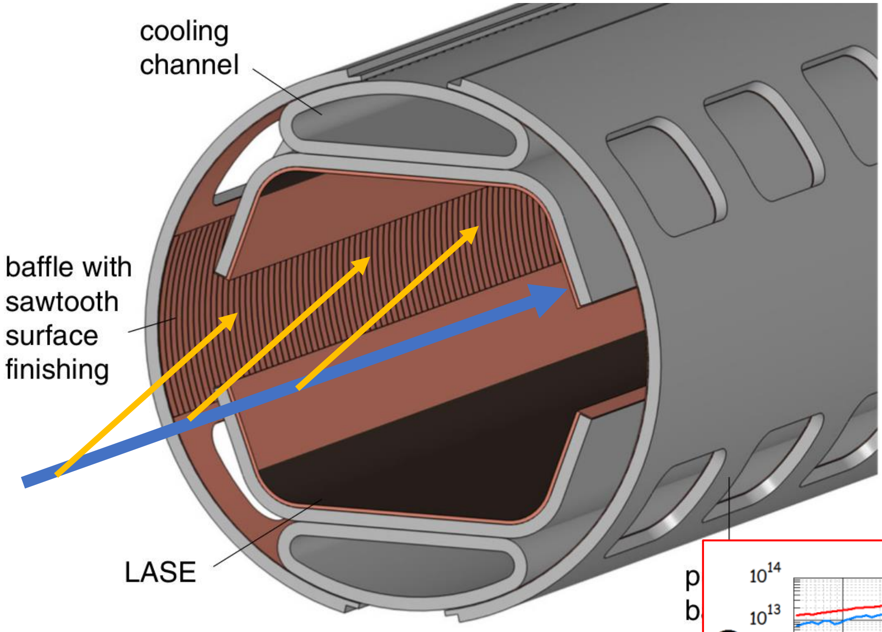
FNAL

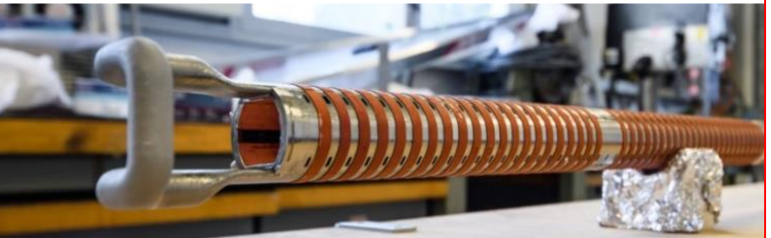
Short model magnets (1.5 m lengths) will be built until 2025

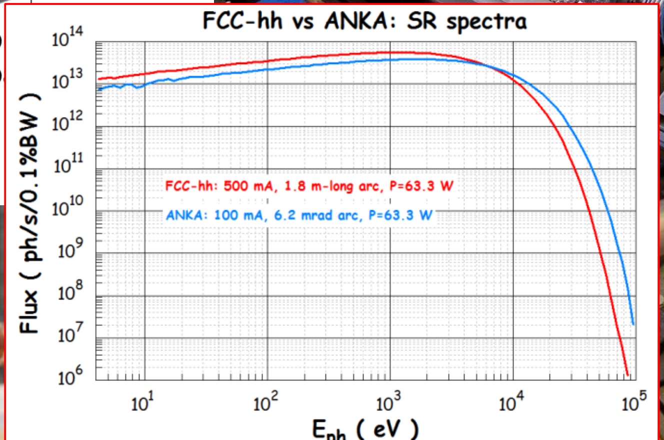
Succesful test of FCC-hh beam screen

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.



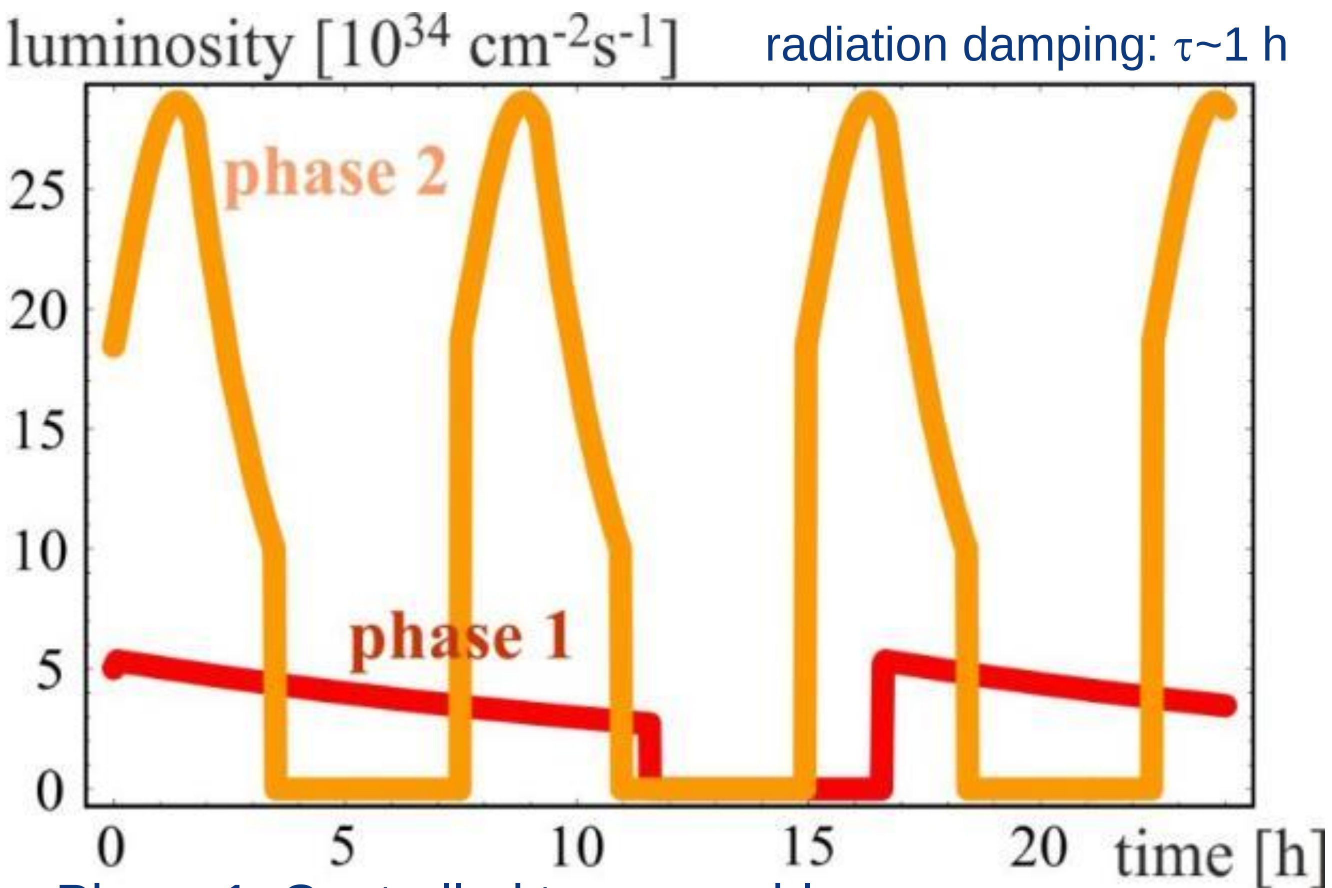




FCC-hh beam-screen test set-up at ANKA/Germany:

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

FCC-hh operation phases and luminosity



Phase 1: Controlled transvers blow-up
Phase 2: High beam-beam tune shift

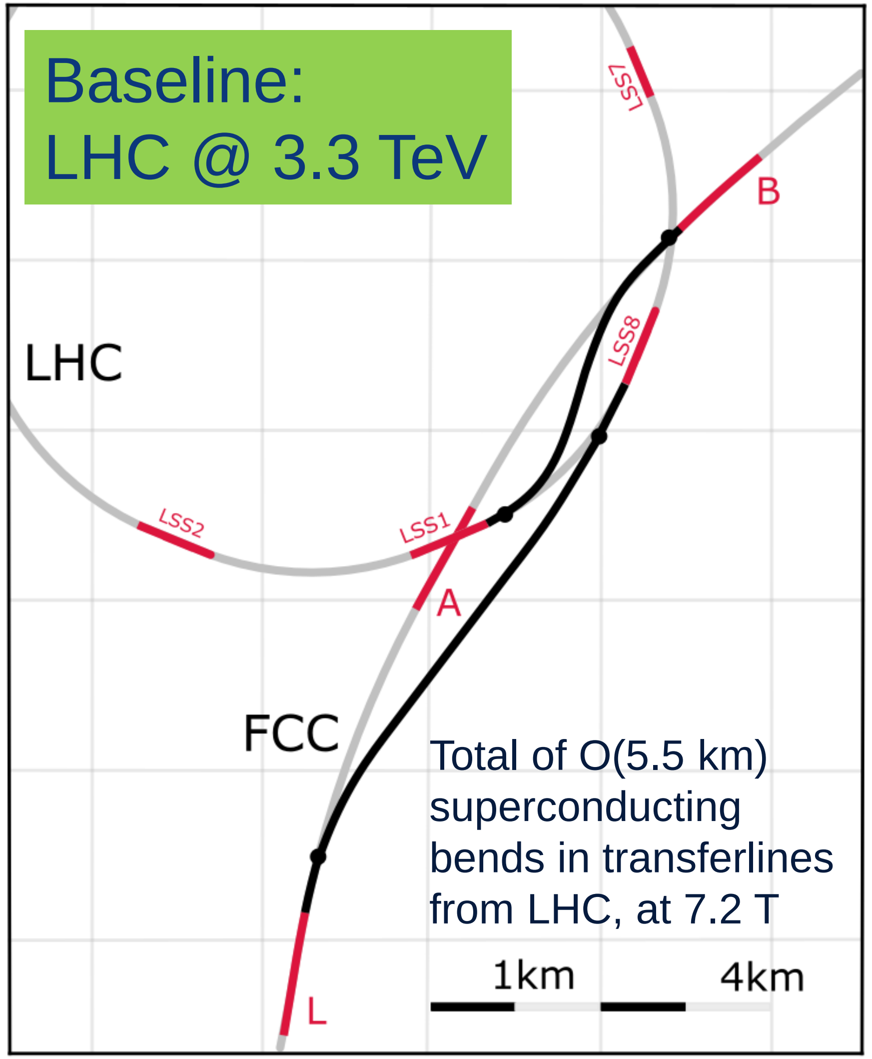
phase 1:
β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h
250 fb^{-1} / year

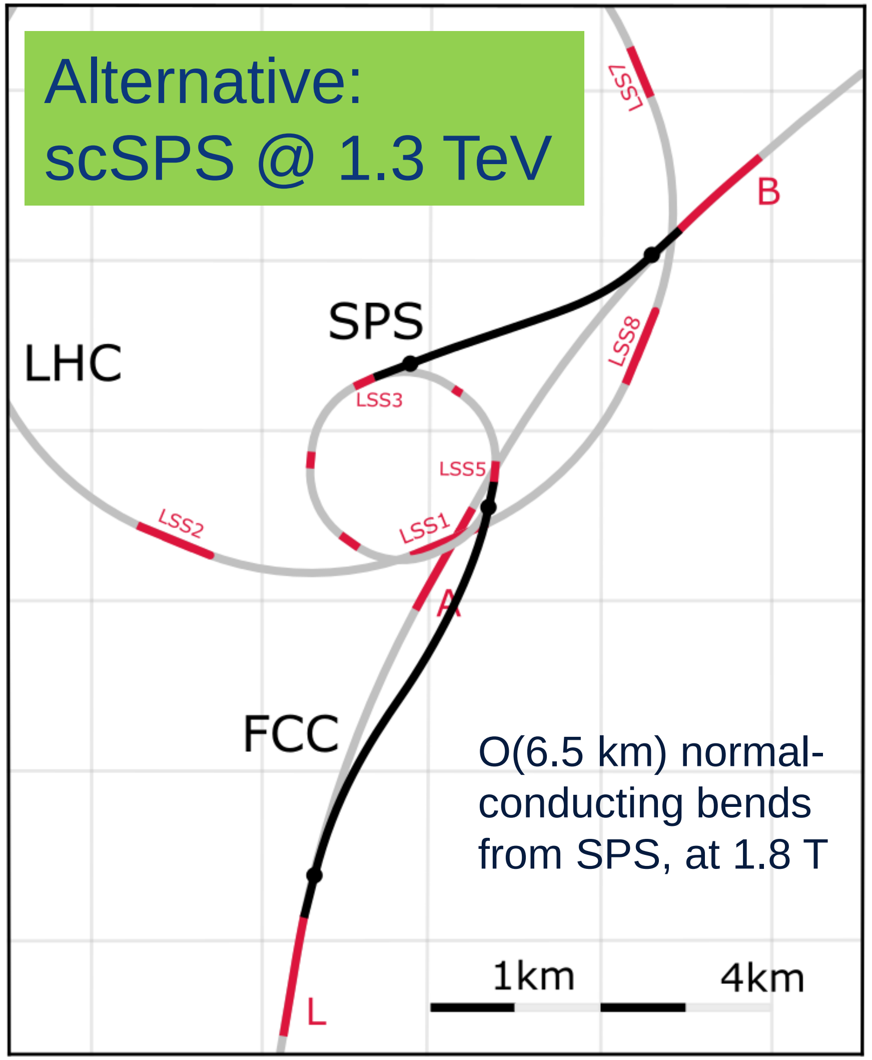
phase 2:
β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h
1 ab^{-1} / year

Transition via operation experience, no HW modification

Total integrated luminosity over 25 years operation:
O(20) ab^{-1}/experiment
consistent with physics goals

FCC-hh injector options and transfer lines





Current baseline:

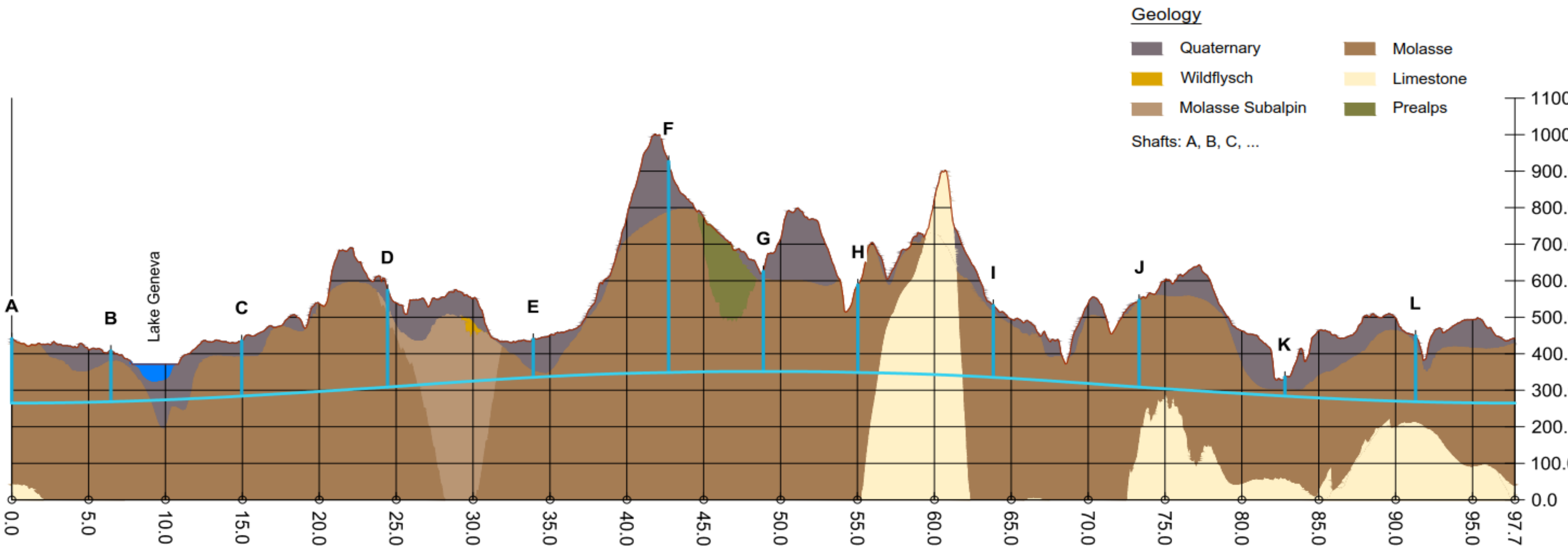
- **Injection energy 3.3 TeV LHC**

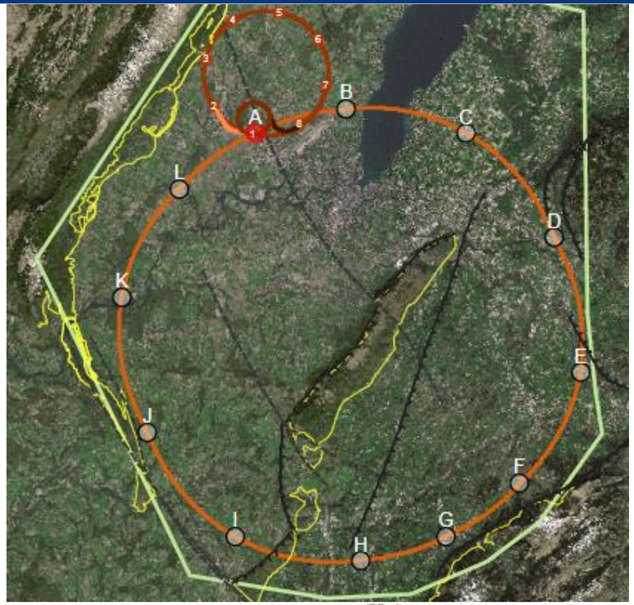
→ Field-swing FCC-hh like LHC

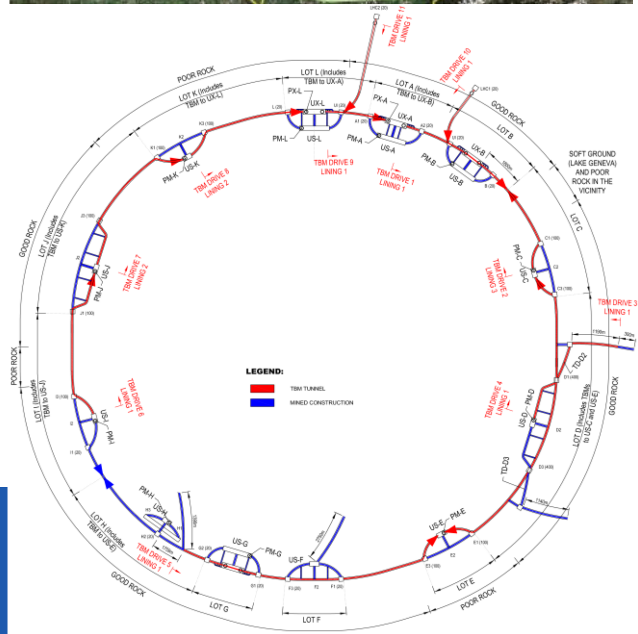
Alternative option:

- **Injection from $SPS_{upgrade}$ around 1.3 TeV**
- **$SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp, cf. SIS 300 design**

FCC implementation - footprint baseline







present baseline position was established considering:

- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

- **90 – 100 km circumference**
- **12 surface sites with few ha area each**

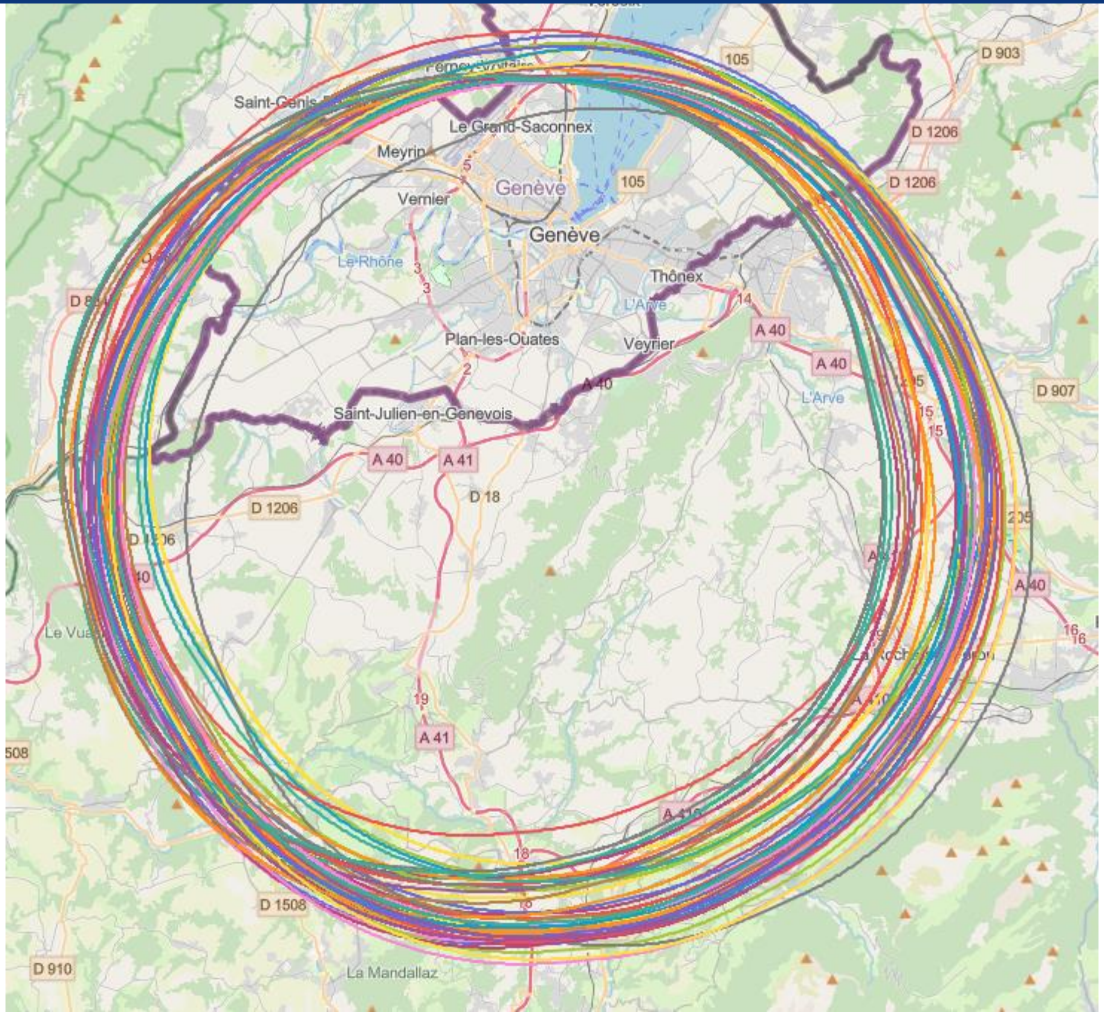
collider placement optimisation

layout & placement optimisation across both host states (Switzerland and France) ;

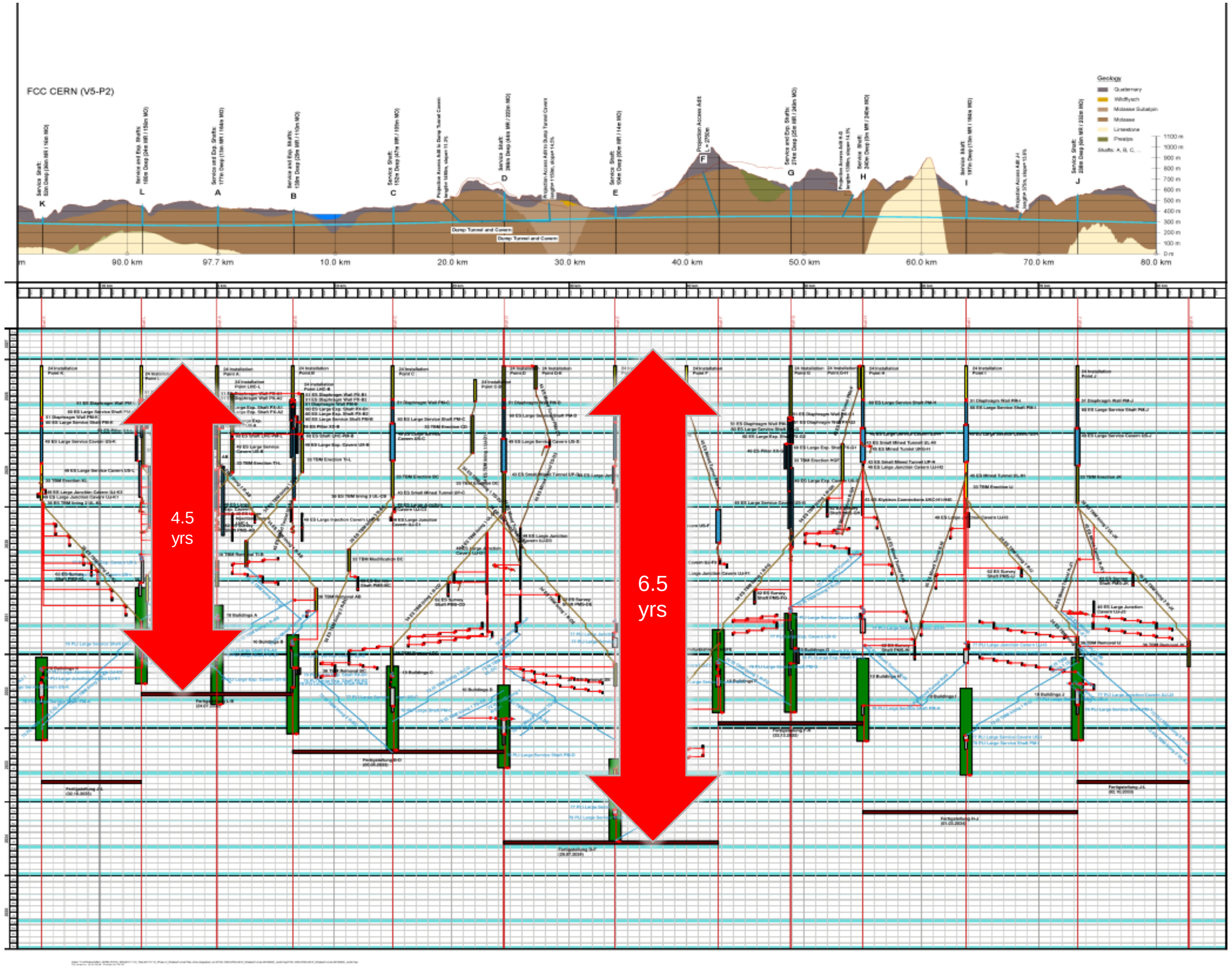
following "avoid-reduce-compensate" directive of European & French regulatory frameworks ;

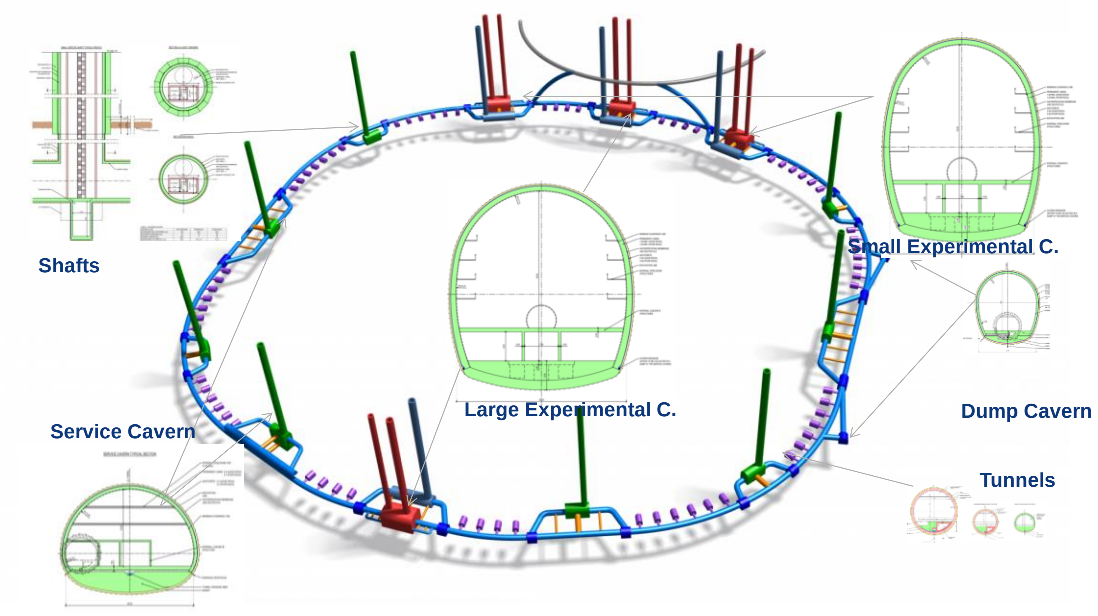
- permitting **world-leading** diverse requirements and constraints:
- **scientific research**
- **technical feasibility of civil engineering** and subsurface constraints
- **territorial constraints on surface** and subsurface
- **nature, accessibility**, technical infrastructure, resource needs & constraints
- economic factors including benefits for, and synergies, with the **regional developments**
- ...

collaborative effort: CERN technical experts, consulting companies, government-notified bodies



civil engineering studies





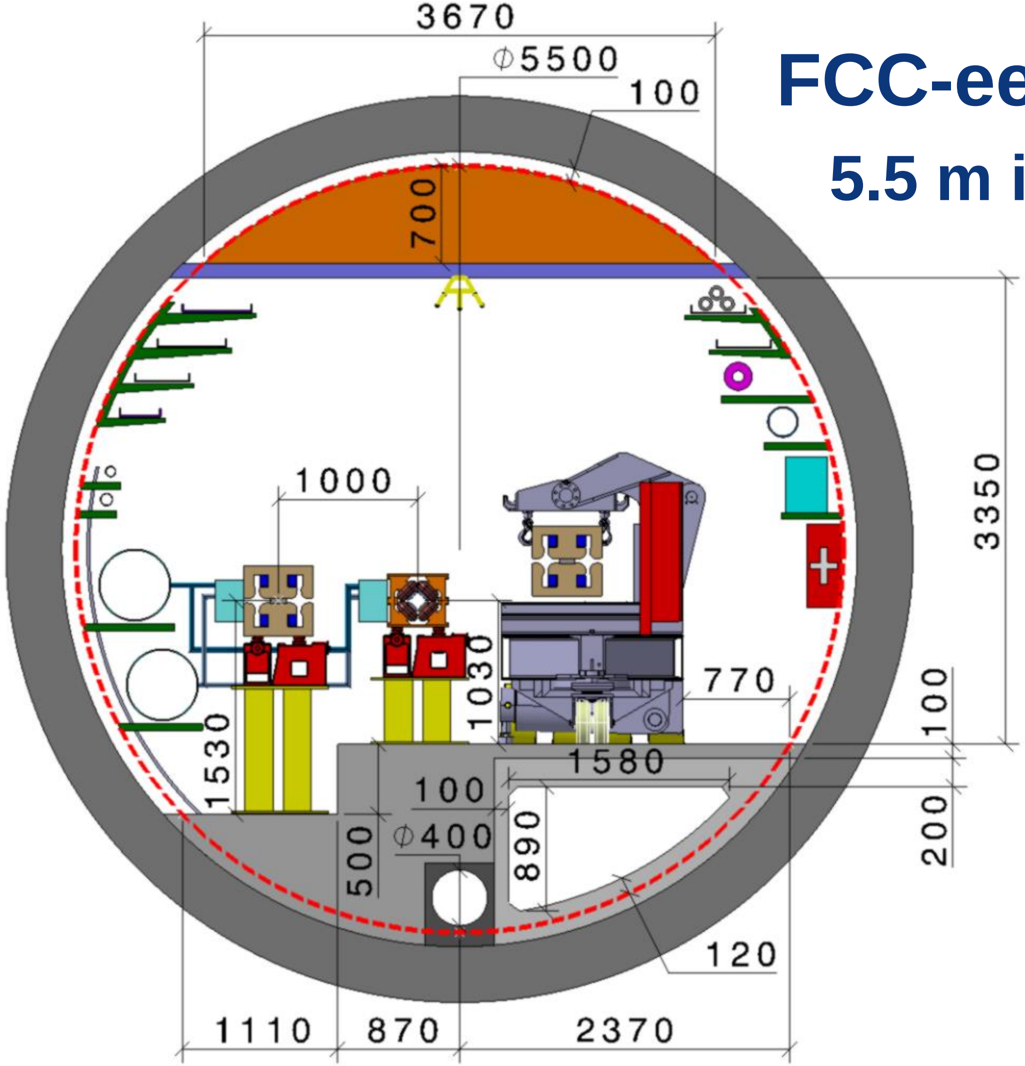
- Total construction duration 7 years
- First sectors ready after 4.5 years

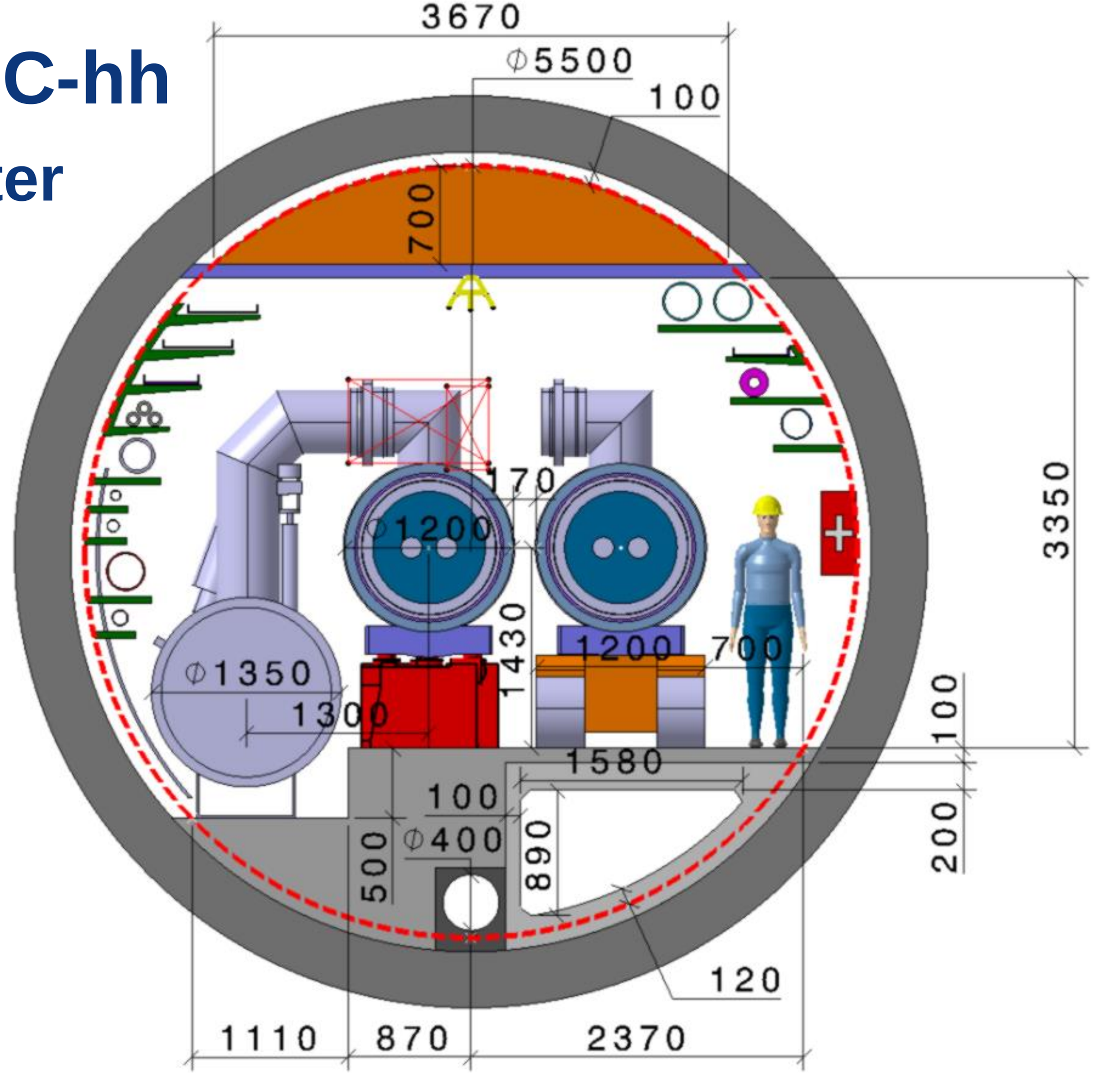
FCC-tunnel integration in the arcs

FCC-ee

FCC-hh

5.5 m inner diameter

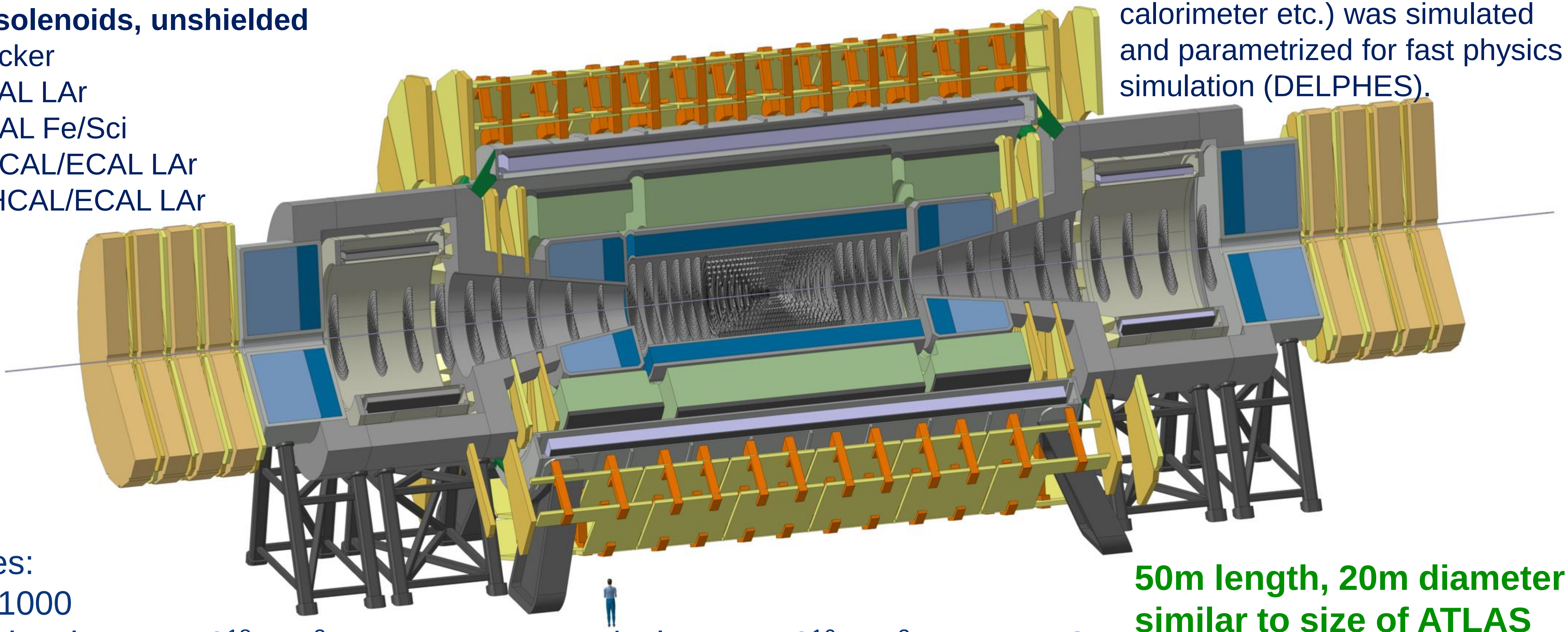




FCC-hh reference detector

- **4T, 10m solenoid, unshielded**
- **Forward solenoids, unshielded**
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

Subdetector performance (tracker, calorimeter etc.) was simulated and parametrized for fast physics simulation (DELPHES).

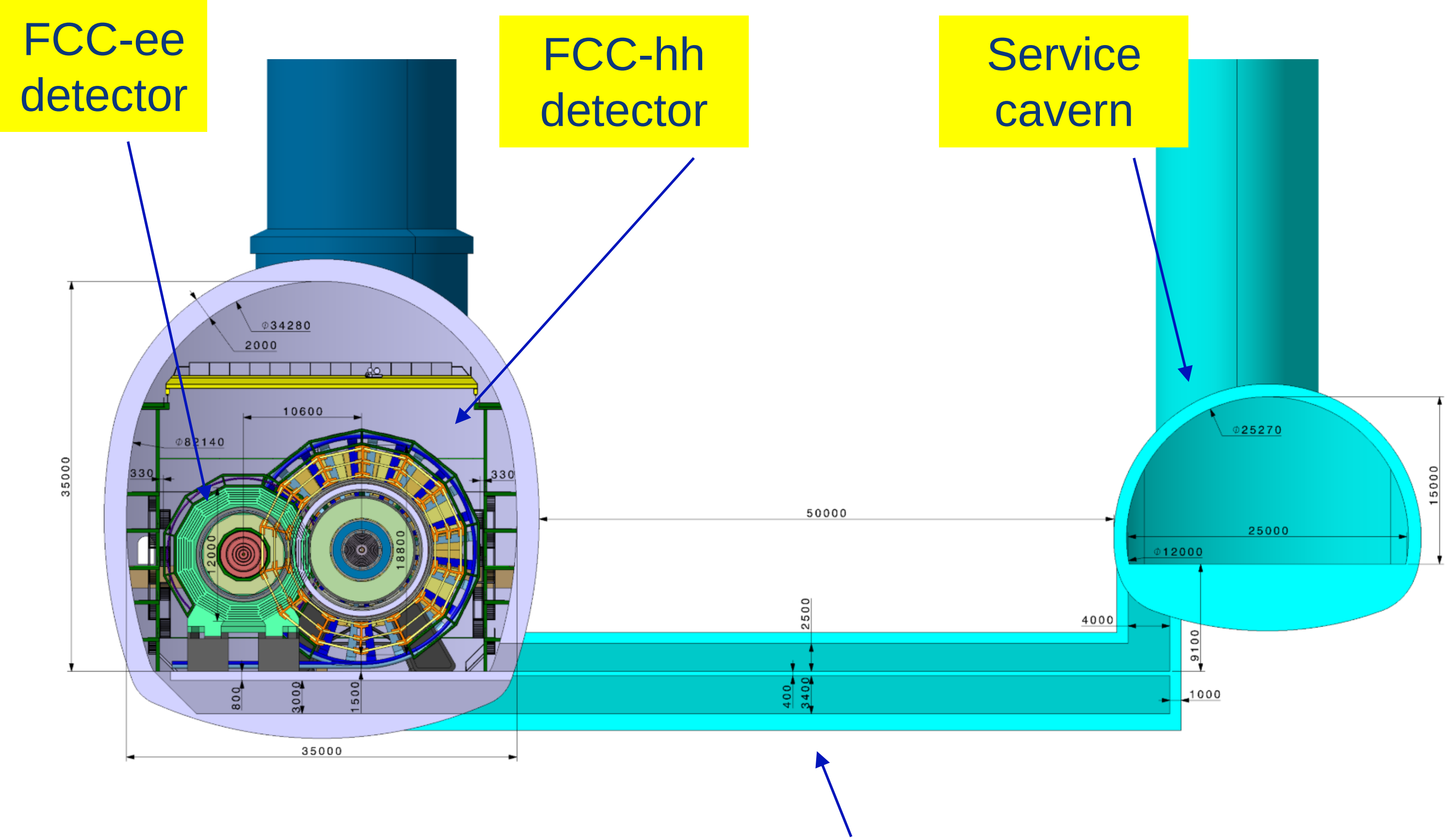


50m length, 20m diameter similar to size of ATLAS

- Challenges:
- Pileup of 1000
- Radiation levels up to 10^{18} cm^{-2} 1MeV neutron equivalent vs. 10^{16} cm^{-2} at HL-LHC
- Integration, opening and maintenance scenarios

Common experimental points (A, G)

Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.



Preliminary design of access and cable paths

FCC integrated project technical schedule

1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 15 years operation | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permis-sions

Update Permis sions

Funding strategy

Funding and in-kind contribution agreements

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and magnet R&D, short models

Long model magnets, prototypes, preseries

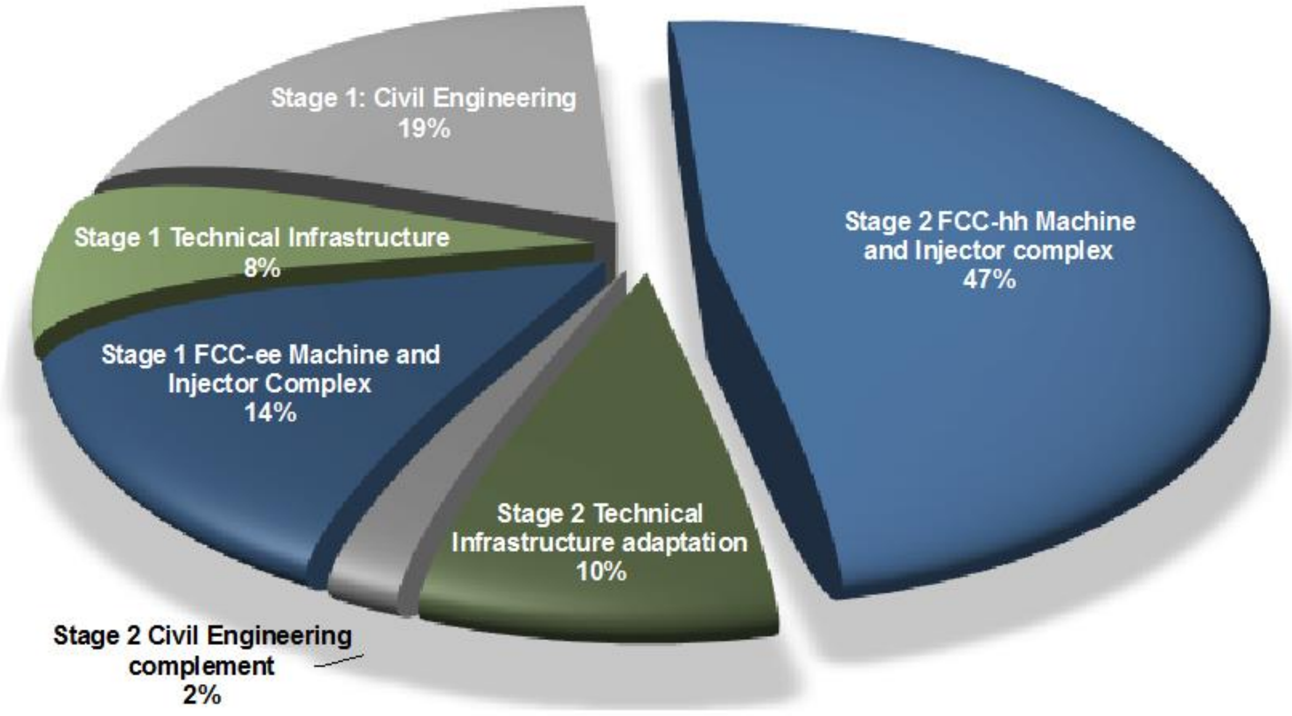
16 T magnet industrialization and series production

engineering design, energy efficiency, maintainability

conductors & high-field magnet technology

FCC-integrated project cost estimate

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



total construction cost FCC-ee (Z, W, H) : ~10,500 MCHF & 1,100 MCHF (tt)

total construction cost for subsequent FCC-hh: 17,000 MCHF.

(FCC-hh stand alone cost ~25 BCHF)

FCC CDR and Study Documentation

>1350 contributors from > 350 institutes , a truly global effort as suggested by EPPSU 2013

- **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)**

    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

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

Status and Outlook

- **1st phase** of FCC design study **completed → baseline machine designs,** performance matching physics requirements, in **4 CDRs.**
- **Integrated FCC programme** submitted to European Strategy Update 2019/20 **→ Request for feasibility study as basis for project decision by 2026/27**
- **Next steps: concrete local/regional implementation scenario** in collaboration **with host state authorities**, accompanied by **machine optimization, physics studies and technology R&D**, performed **via global collaboration** and supported by **EC H2020 Design Study FCCIS, to prove feasibility by 2025/26**
- Long term goal: **world-leading HEP infrastructure for 21st century** to push the particle-physics **precision and energy frontiers** far beyond present limits.
- **Success of FCC relies on strong global participation !**

from ESPPU 2020 document

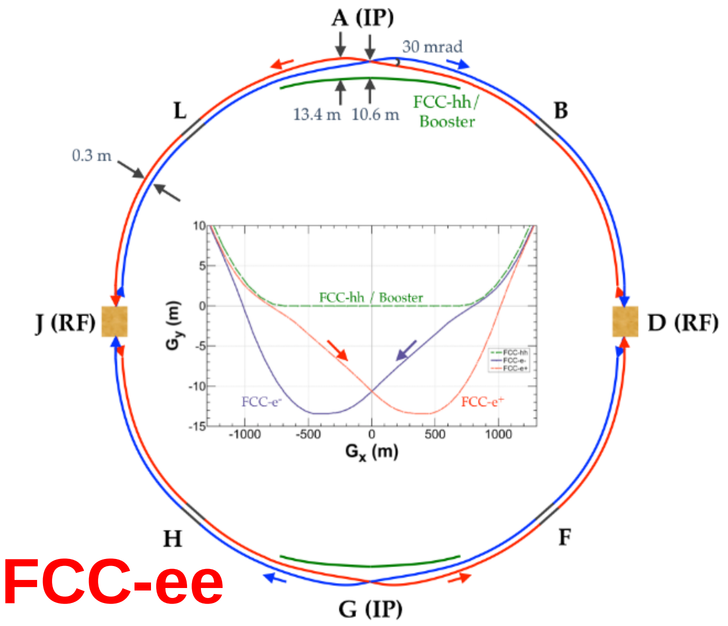
Core sentence and main request "order of the further FCC study":

"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."

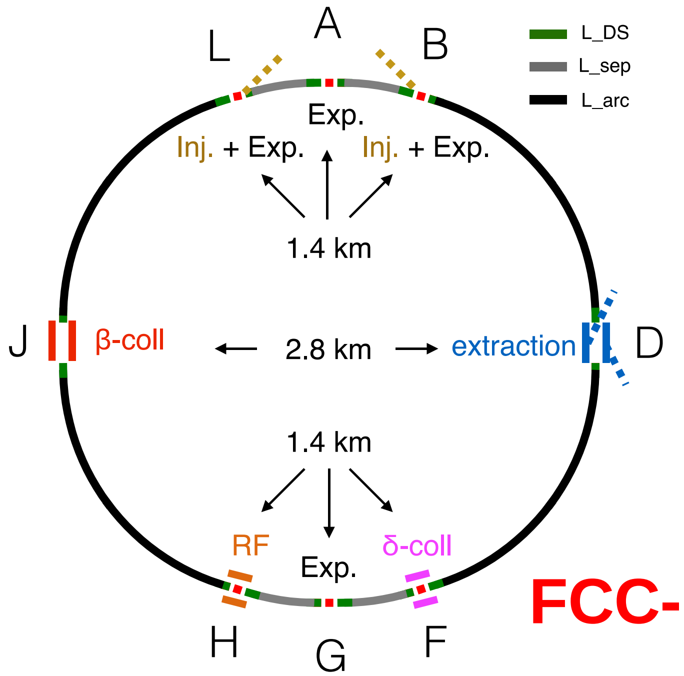
FCC integrated program
inspired by successful LEP – LHC programs at CERN

comprehensive cost-effective program maximizing physics opportunities

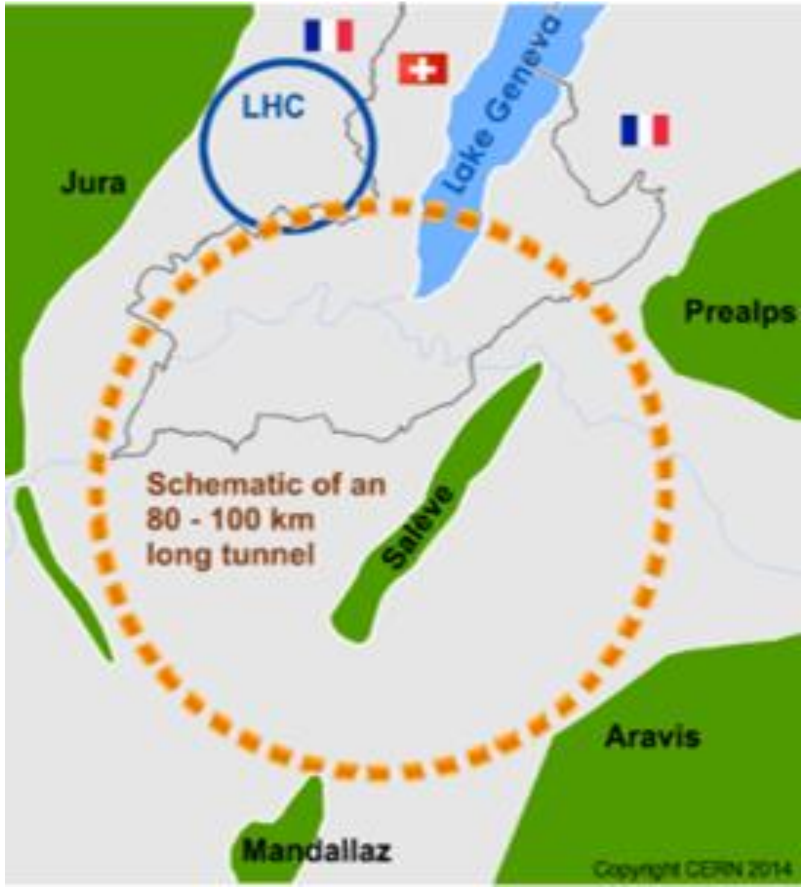
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures
- building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC



FCC-ee



FCC-hh



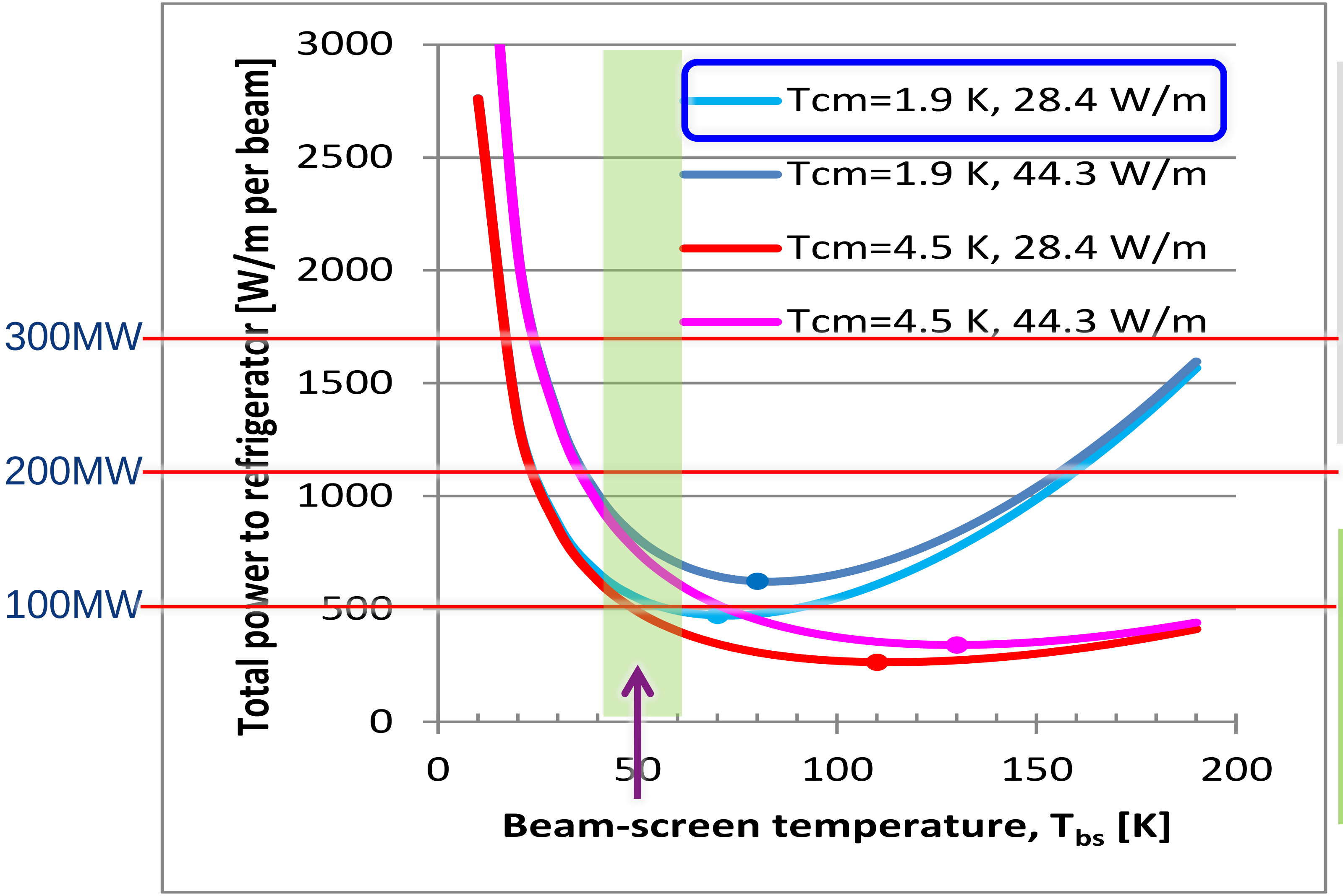
FCC-ee Collider Parameters (stage 1)

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-hh (pp) collider parameters (stage 2)

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		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]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		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]	8.4		0.7	0.36

Cryoplants – energy efficiency



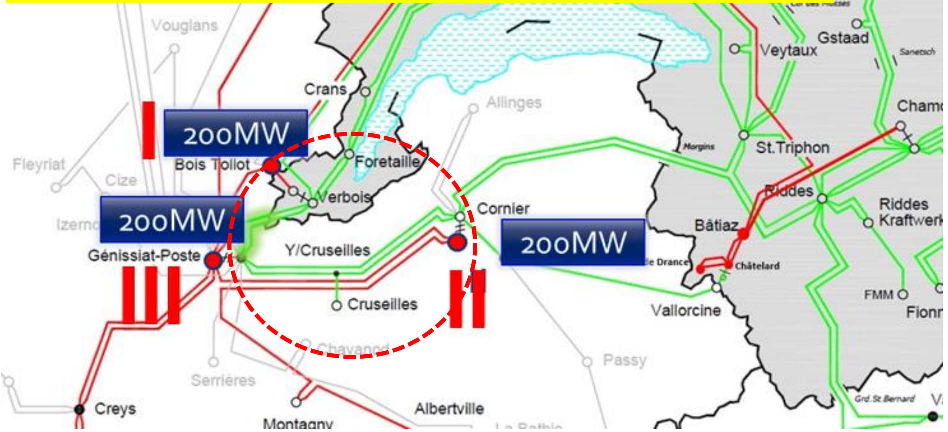
BS temperature choice is overall optimisation of:

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

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

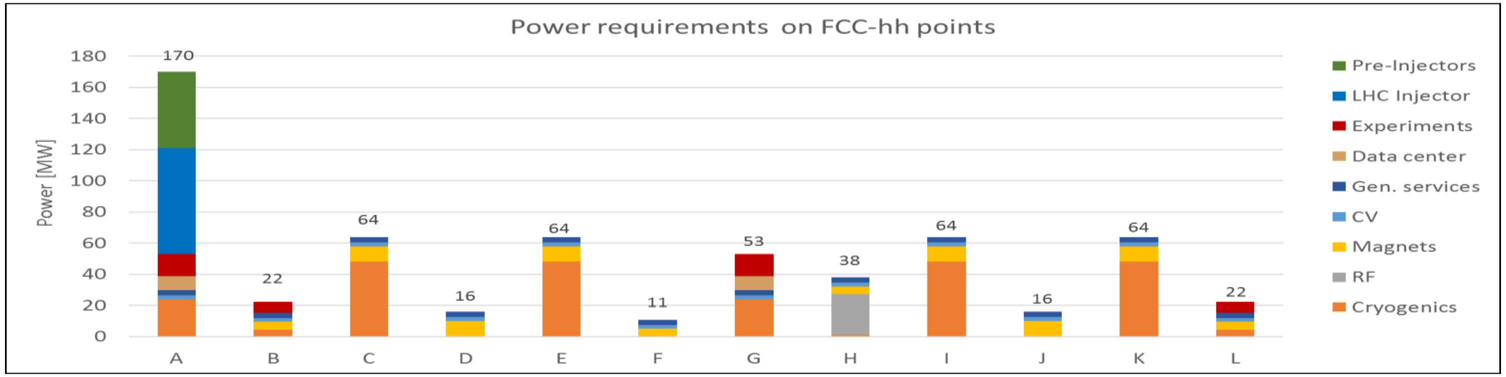
supply & distribution of electrical energy

additional 200 MW available for FCC at each of the three 400 kV sources

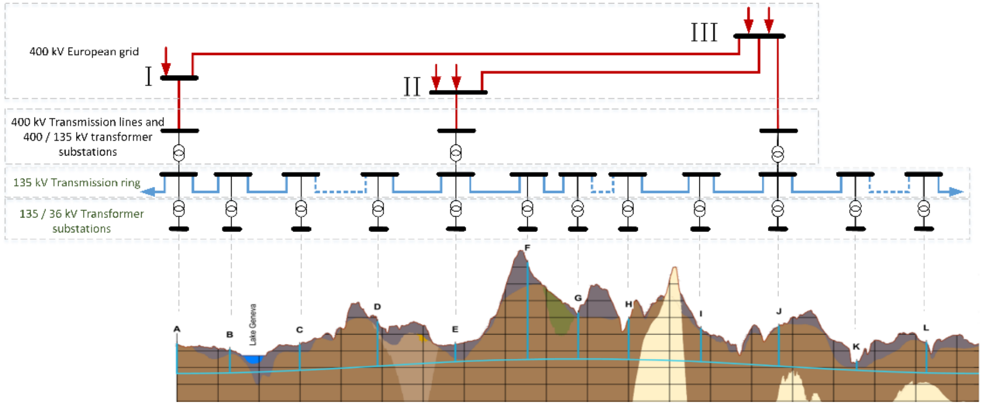


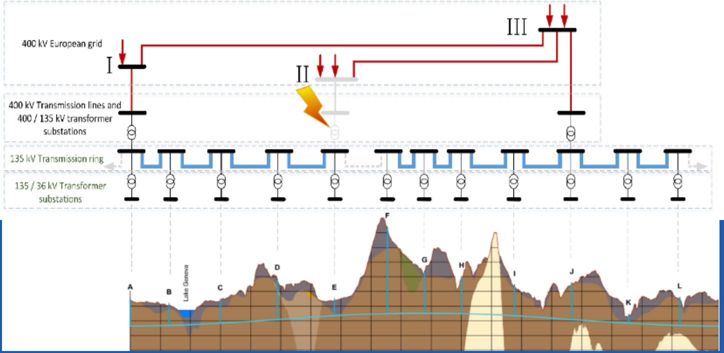
---- 400 kV ---- 230 kV

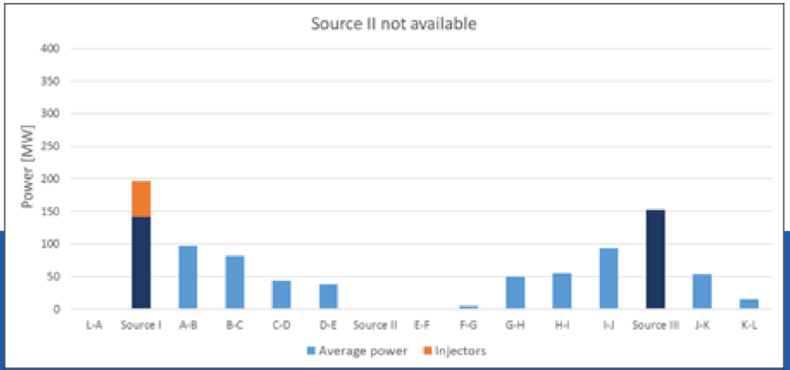
per-point power requirements as input for infrastructure-optimized conceptual design (peak FCC-ee: 260-340 MW, total FCC-hh: 550 MW)



If one power source goes down fall back to “degraded mode“: FCC remains cold, vacuum preserved, controls on, RF off, no beam (“standby”); all FCC points supplied from 2 other 400 kV points, through the power transmission line







3 x 400 kV connections
+ 135 kV underground power distribution (NC)

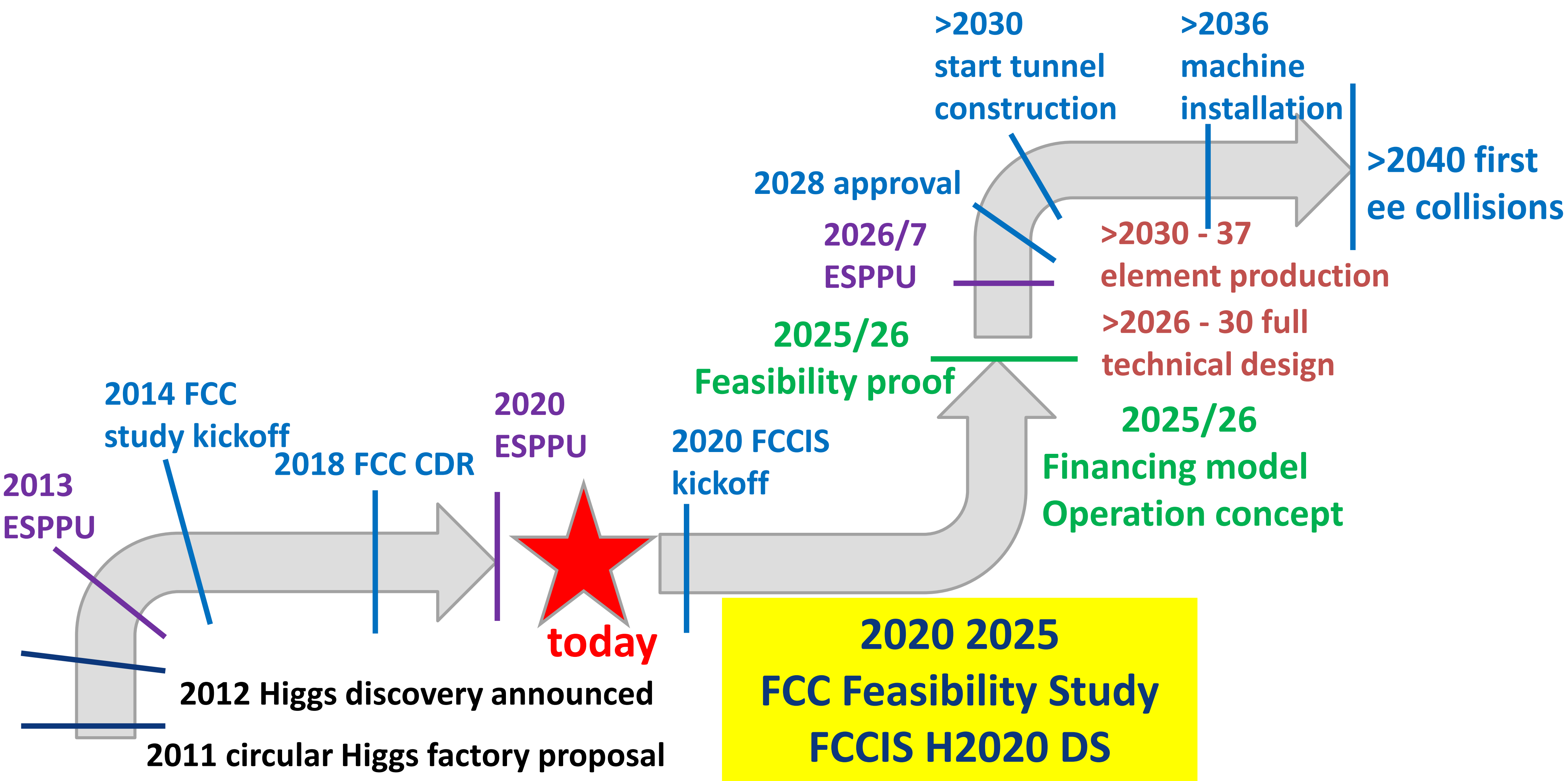
FCC-ee physics program staging

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
***Z* first 2 years**	100 (50% nominal)	26 ab^{-1}/year	**150 ab^{-1}**	**4**
***Z* later**	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	**10 ab^{-1}**	**2**
H	7.0	1.7 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8 (50% nominal)	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	0.34 ab^{-1}/year	**1.5 ab^{-1}**	**4**

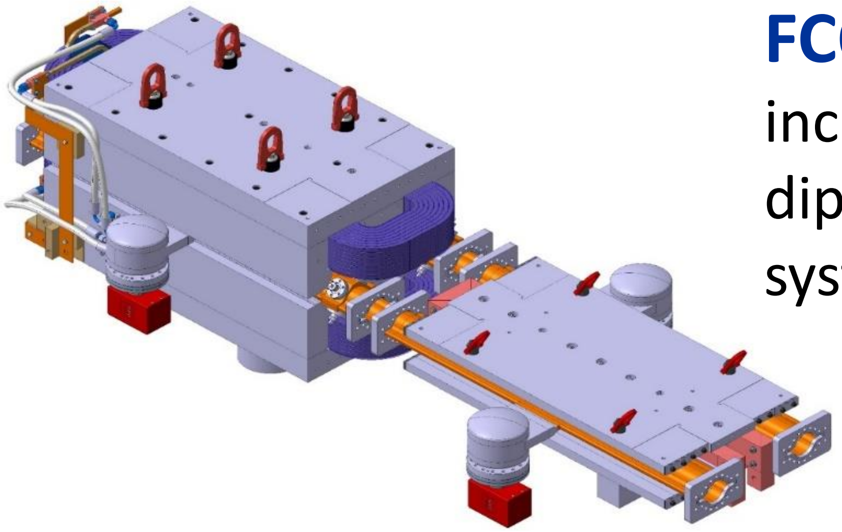
total program duration: 15 years - ***including machine modifications***

phase 1 (*Z*, *W*, *H*): 9 years, phase 2 (top): 6 years

FCC roadmap towards stage 1

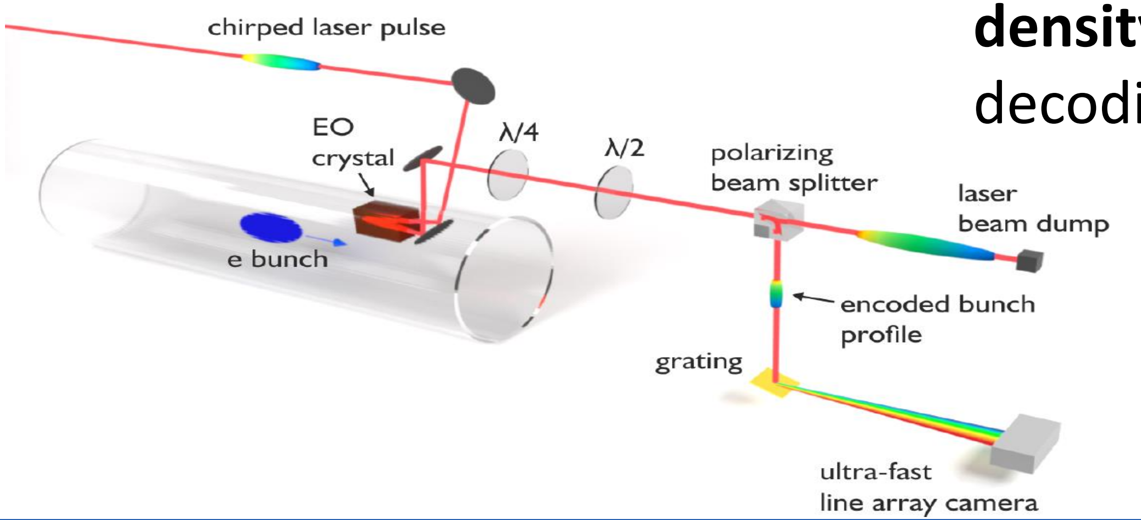


FCC key deliverables: prototypes by 2025



FCC-ee complete arc half-cell mock up

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



key beam diagnostics elements

bunch-by-bunch turn-by-turn **longitudinal charge density profiles** based on electro-optical spectral decoding (beam tests at KIT/KARA) ;

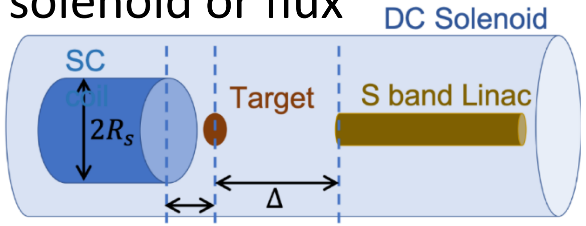
ultra-low emittance measurement (X-ray interferometer tests at SuperKEKB, ALBA) ;
beam-loss monitors (IJCLab/KEK?) ;
beamstrahlung monitor (KEK);
polarimeter ; **luminometer**

FCC key deliverables: prototypes by 2025

400 MHz SRF cryomodule, + prototype multi-cell cavities for FCC ZH operation
High-efficiency RF power sources

high-yield positron source

target with DC SC solenoid or flux concentrator

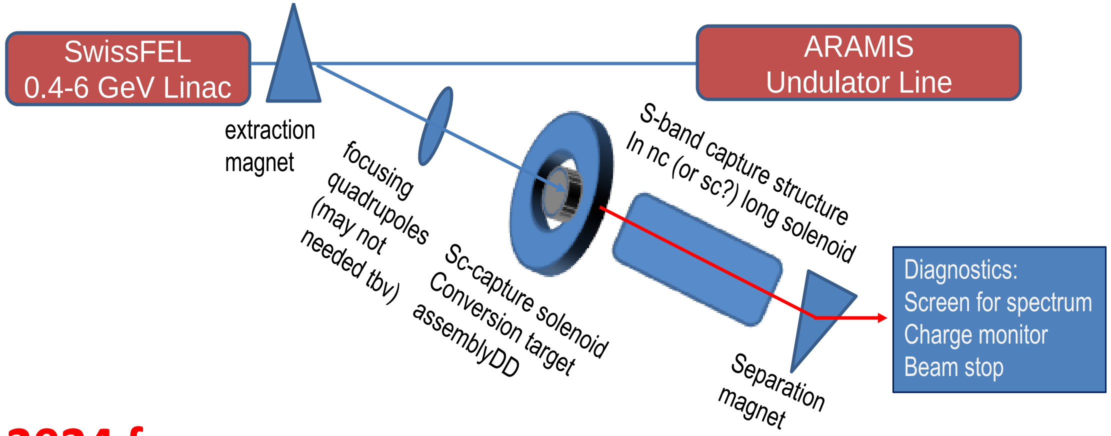


positron capture linac

large aperture S-band linac

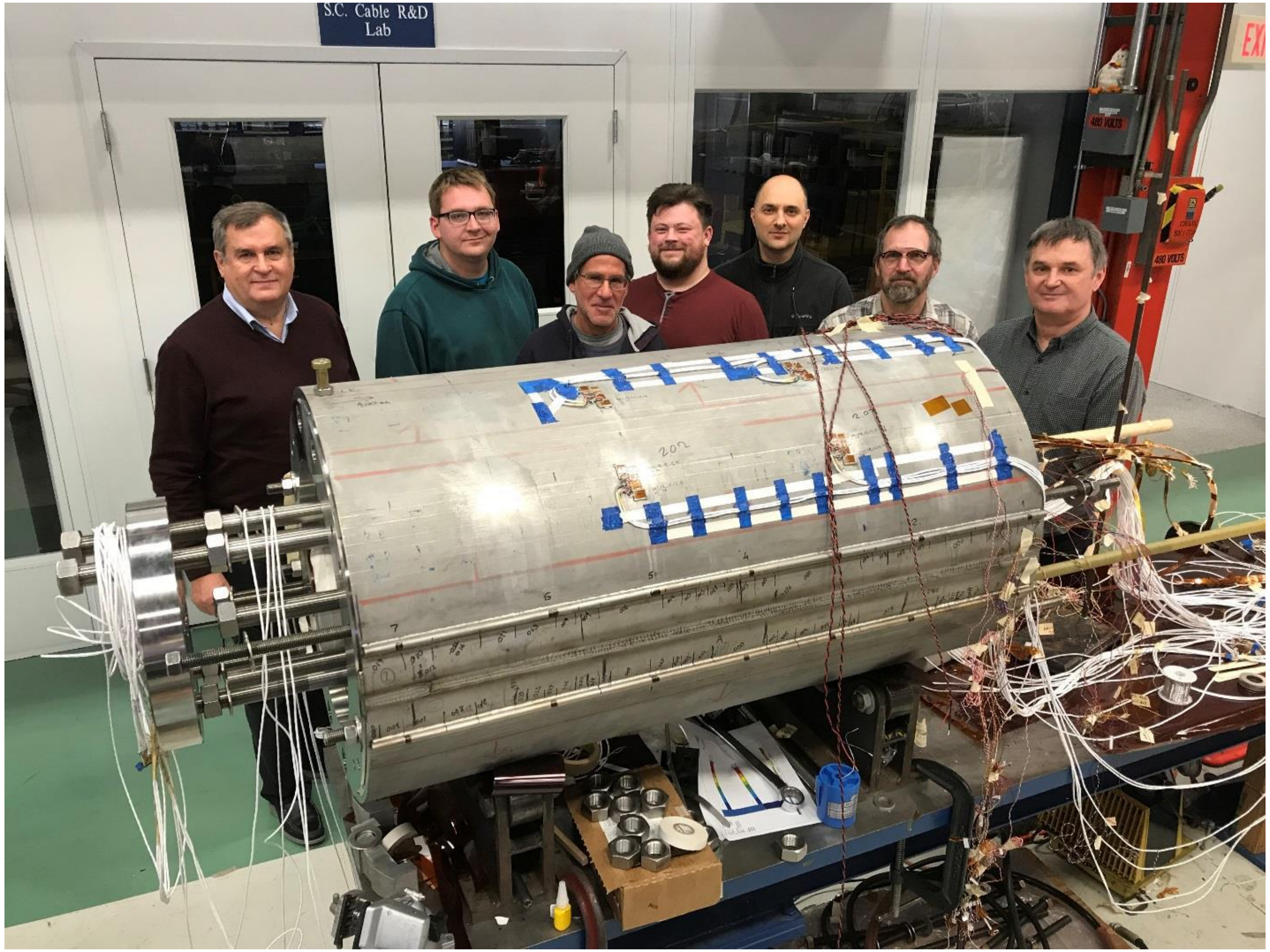
- Freq : 2.856 GHz
- 90 cells per structure
- Length: 3.254 m
- Distance between two TWs: 45 cm
- Gradient: 20 MV/m
- Aperture: 30 mm

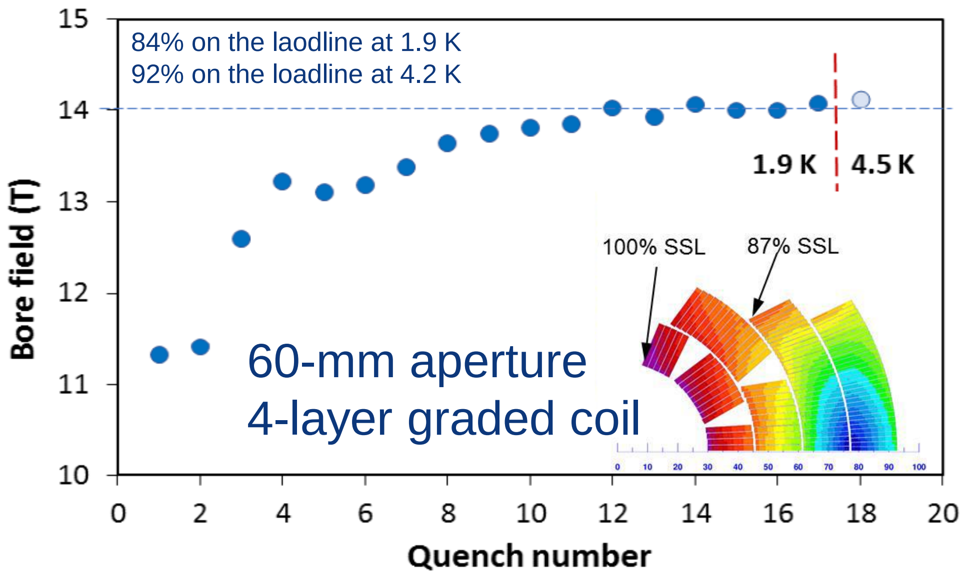
beam test of e^+ source & capture linac at SwissFEL – yield measurement



strong support from Switzerland via CHART II program 2019 – 2024 for FCC-ee injector, HFM, beam optics developments, geology and geodesy activities.

US – MDP: 14.5 T magnet tested at FNAL



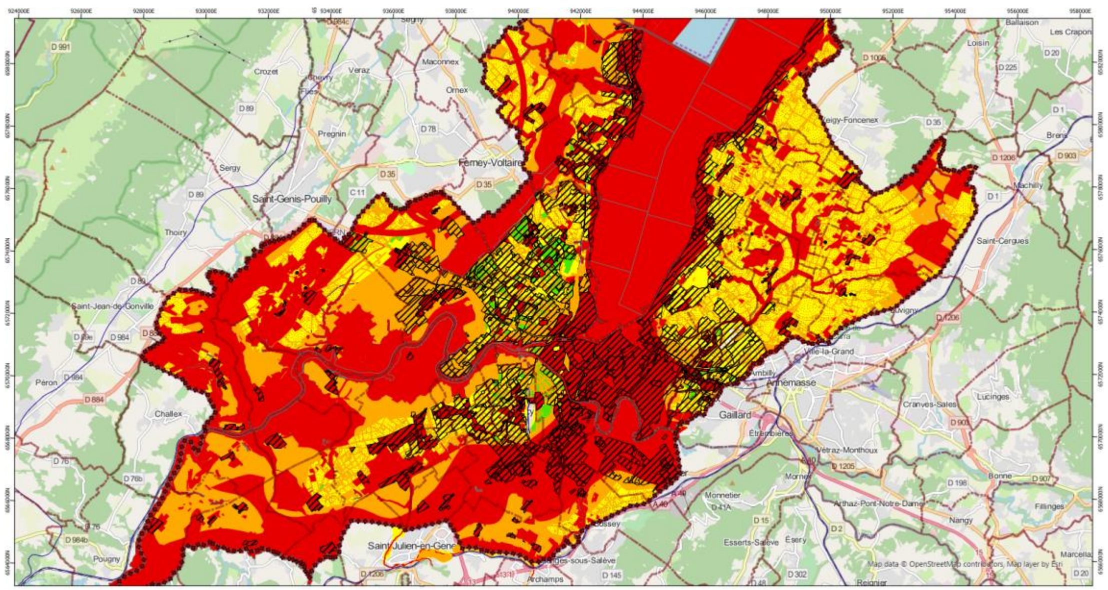


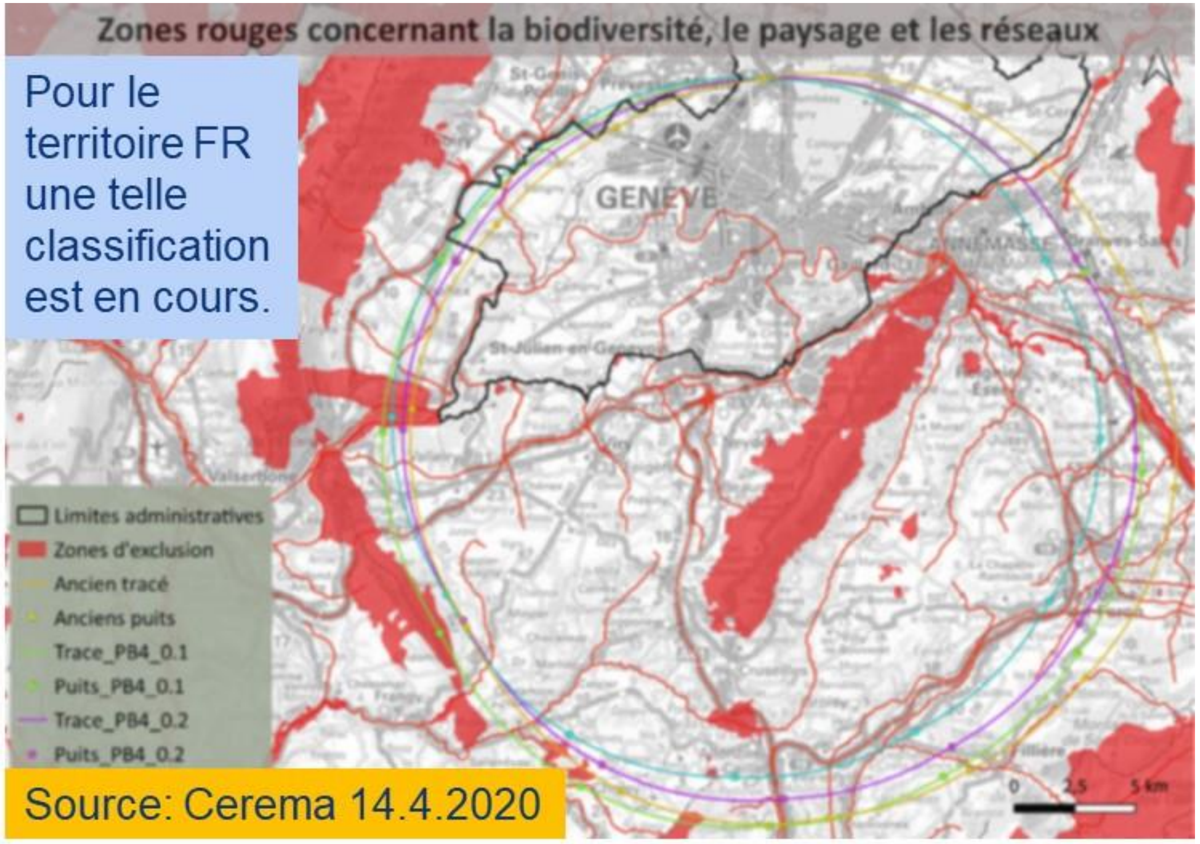
- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2019 with additional pre-stress reached 14.5 T

Implementation studies with host states

- Classification of zones along/around the perimeter of FCC according to „realisation risk levels“ defined with host states.
- Study of variants following the approach „Avoid – Reduce – Compensate“

Territorial constraints – Canton Geneva





Feasibility Study of FCC integrated project

Feasibility study to be delivered end 2025 as **input for next ESPP Update expected by 2026/2027, to enable a project decision**:

- ***feasibility study of the 100 km tunnel*** *(infrastructure aspects, administrative aspects, local authorities, environment, energy, etc.)*
- ***high-risk areas site investigations included****, to confirm principle feasibility*
- ***host-state related processes,*** *to* ***allow start of construction early 2030ies****.*
- ***CDR+ for colliders and injectors, including key technology proofs.***
- ***HFM program intermediate milestones,*** *in line with long-term R&D plan.*
- ***physics and experiments CDR + for FCC integrated project.***
- ***financing concept & organization model for project and operation phases.***
- for all these activities sequential nature of implementation and overall timeline need to be taken into account !