Status and Plans of the FCC Project

Michael Benedikt, CERN

on behalf of the FCC collaboration

http://cern.ch/fcc

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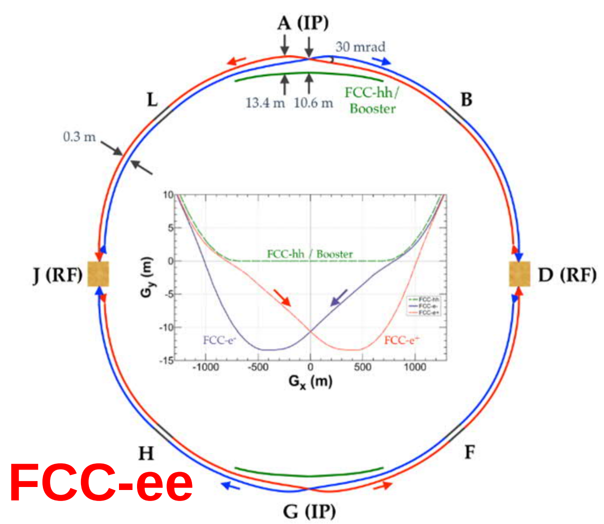
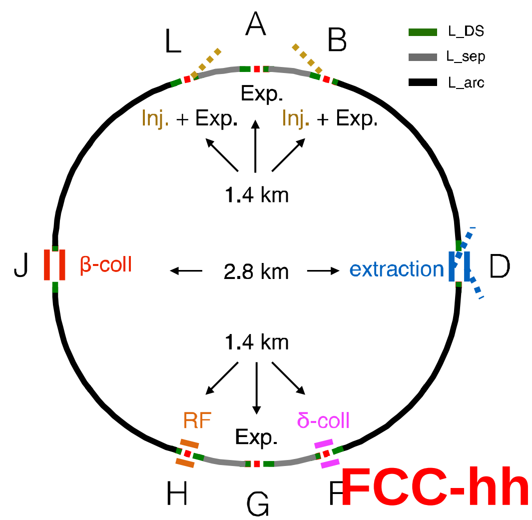
photo: J. Wenninger

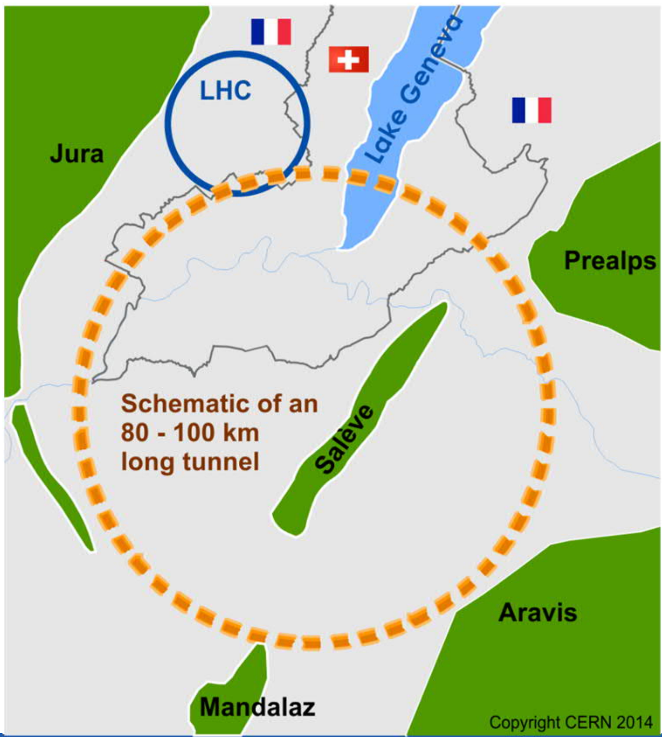
The FCC integrated program inspired by successful LEP – LHC programs at CERN

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 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

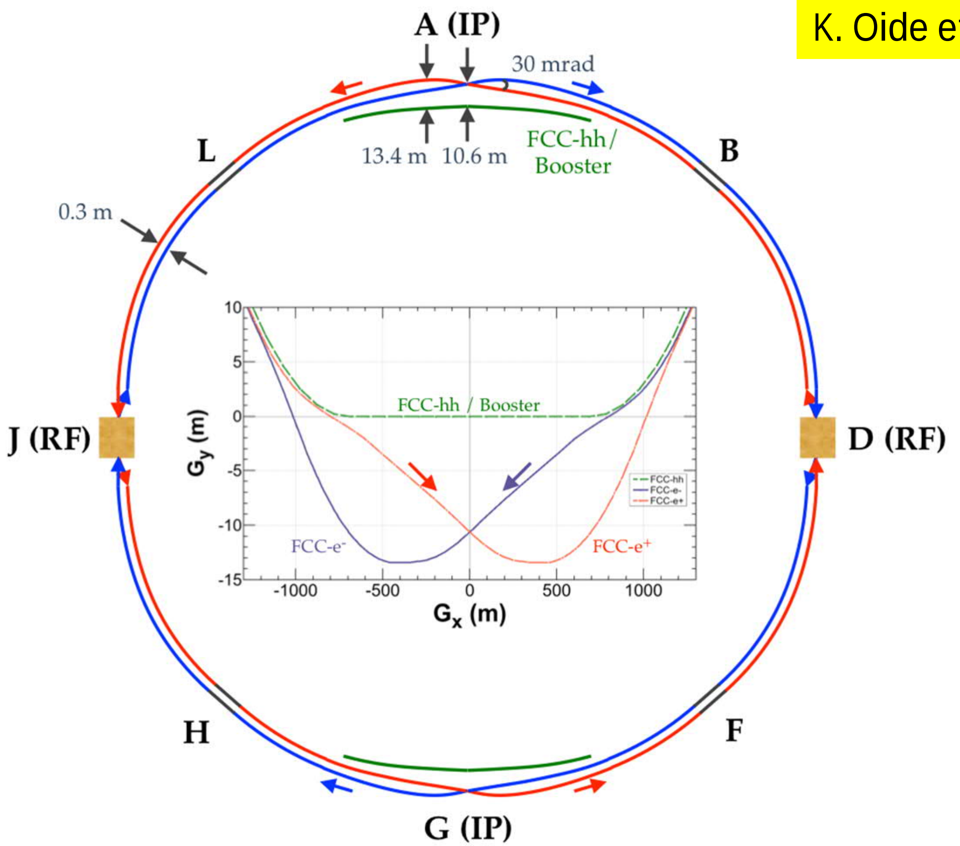
presently 2 IPs (alternative layouts with 3 or 4 IPs under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**

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 **full energy booster synchrotron in collider tunnel**

K. Oide et al.

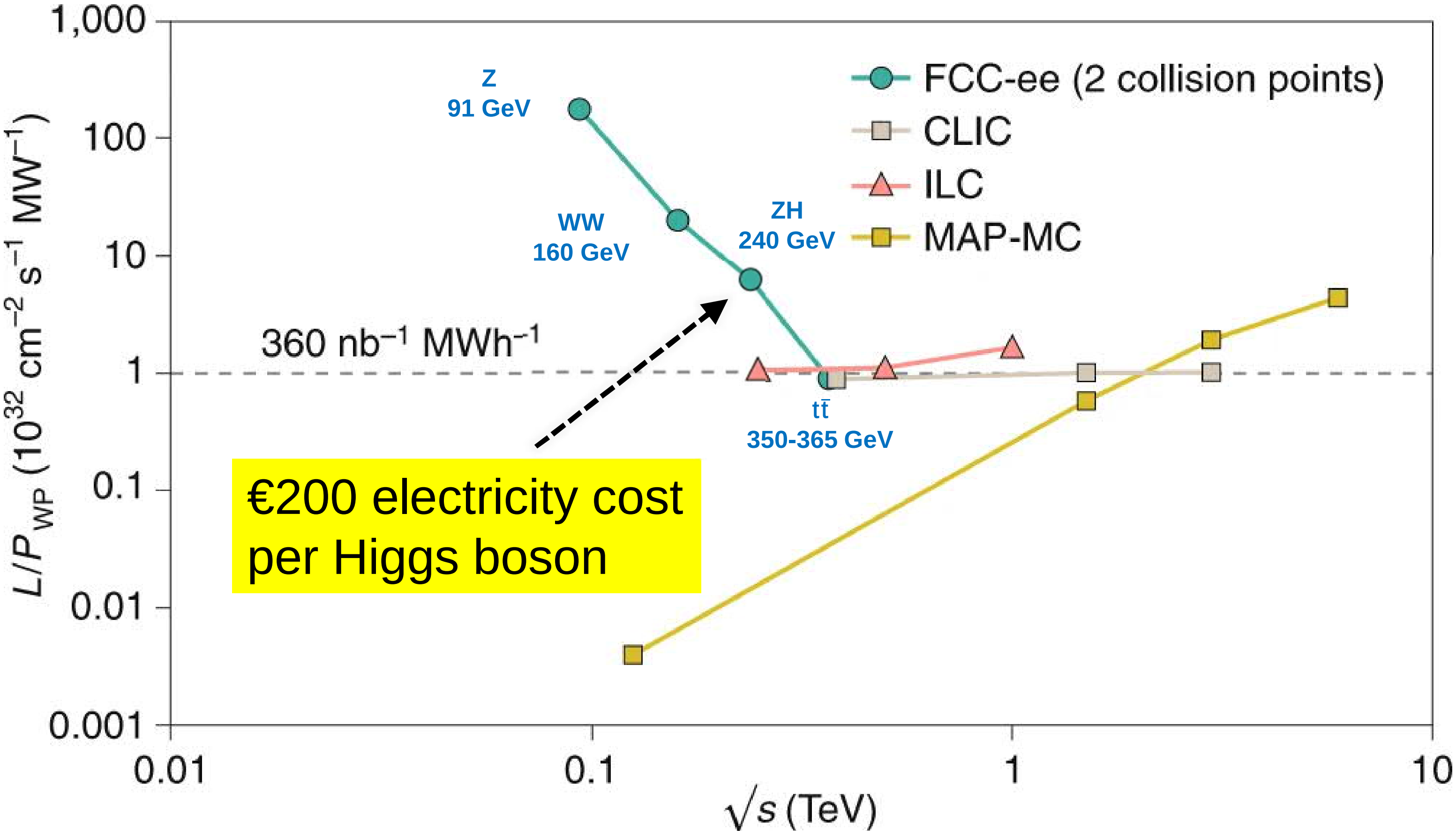


FCC-ee: The Lepton Collider, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

FCC-ee Collider Parameters

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-ee: efficient Higgs/electroweak factory



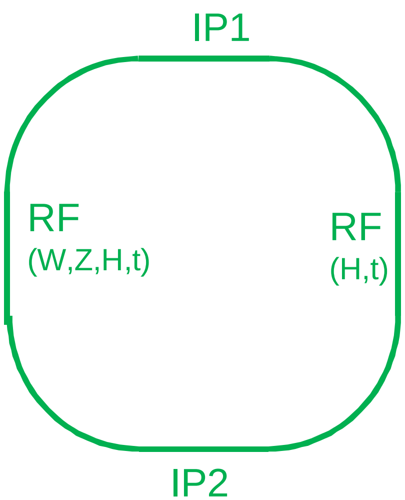
Luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders.

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 2 vs. 4 IPs studies

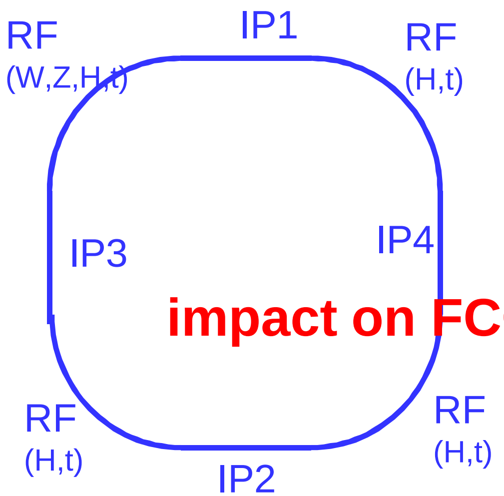
- Potentially up to 1.7x higher total luminosity
- Major impact on layout,RF sections, additional caverns, infrastructure, etc.

baseline w 2 IPs



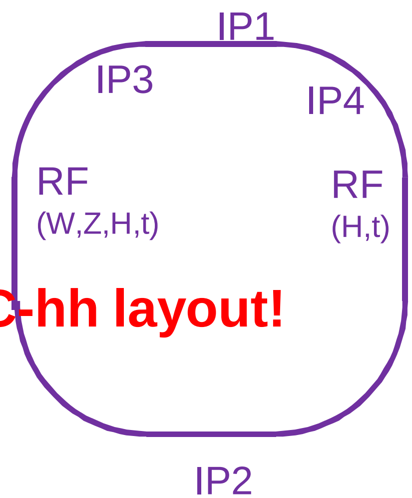
works fine

periodic alternative with 4 IPs



so far OK for lattice and beam-beam

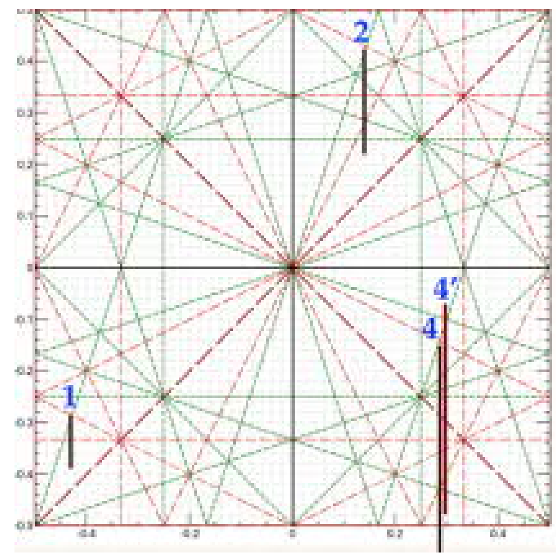
less symmetric alternative with 4 IPs



not yet studied, but considered challenging

impact on FCC-hh layout!

beam-beam footprint Z

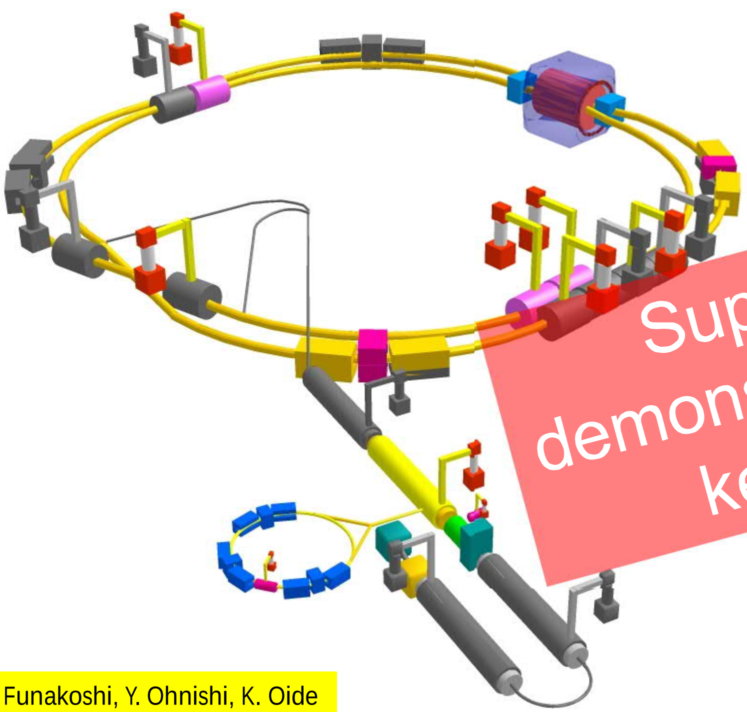


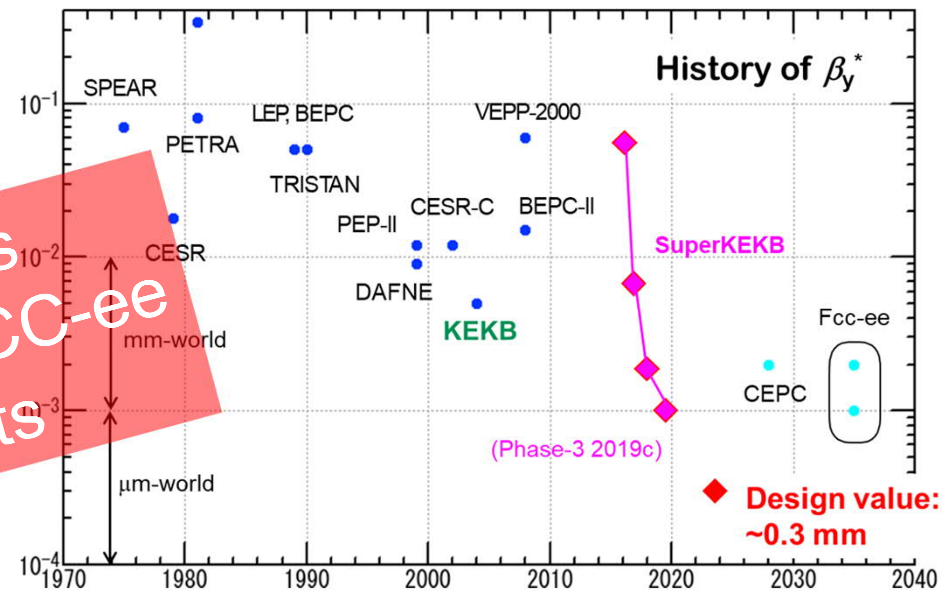
"1":perfect periodicity for 2 or 4 IP
"2":2 IP with imperfections
"4":4 IP with imperfections
"4' ":an alternative vertical tune to avoid ν_y = half integer

K. Oide, D. Shatilov

SuperKEKB – pushing luminosity and β*

Design: double ring e^+e^- collider as B-factory at 7(e^-) & 4(e^+) GeV; design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; β_y^* ~ 0.3 mm; nano-beam – large crossing angle collision scheme (crab waist w/o sextupoles); beam lifetime ~5 minutes; top-up injection; e^+ rate up to ~ 2.5 10^{12} /s ; under commissioning





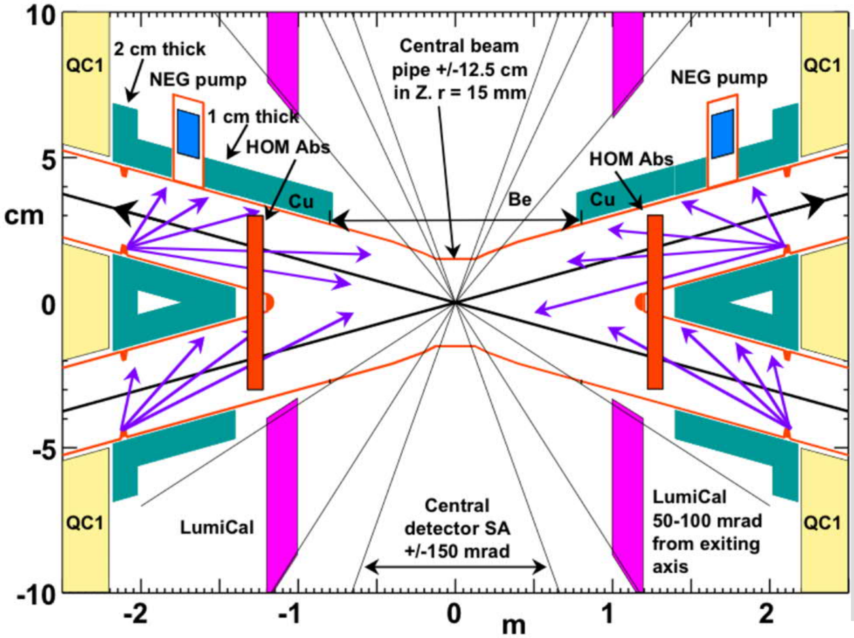
SuperKEKB is demonstrating FCC-ee key concepts

Y. Funakoshi, Y. Ohnishi, K. Oide

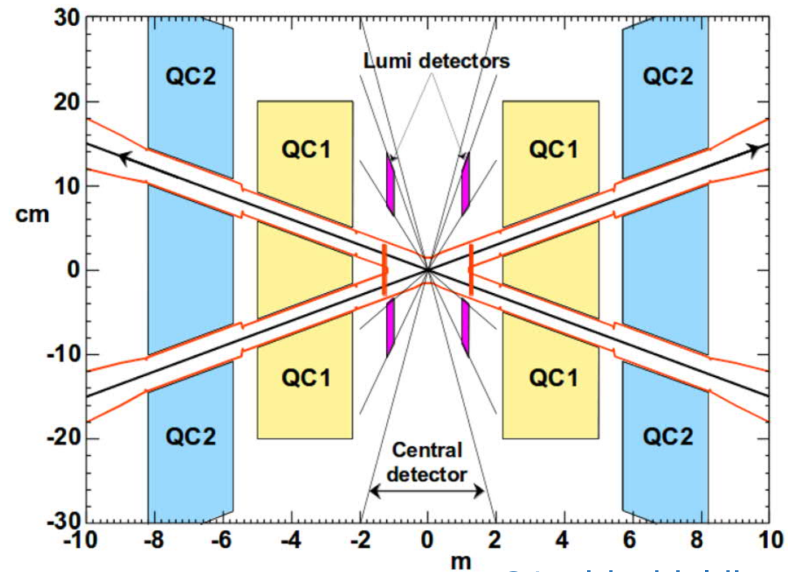
β_y^* =1 mm achieved in both rings - world record
crab-waist collisions implemented recently

→ IPAC'20 Talk by K. Shibata

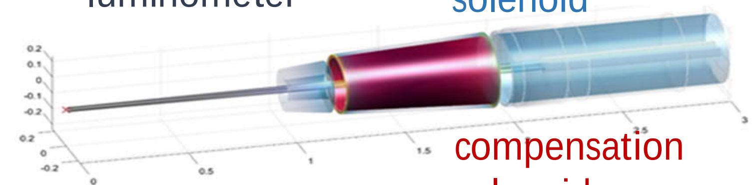
FCC-ee Interaction Region Design



IR heat loads:
rad Bhabha (kW), beamstrahlung (MW), resistive wall (kW), HOMs, quadrupole synchrotron radiation



3D sketch of key IR systems over first 3 m from IP



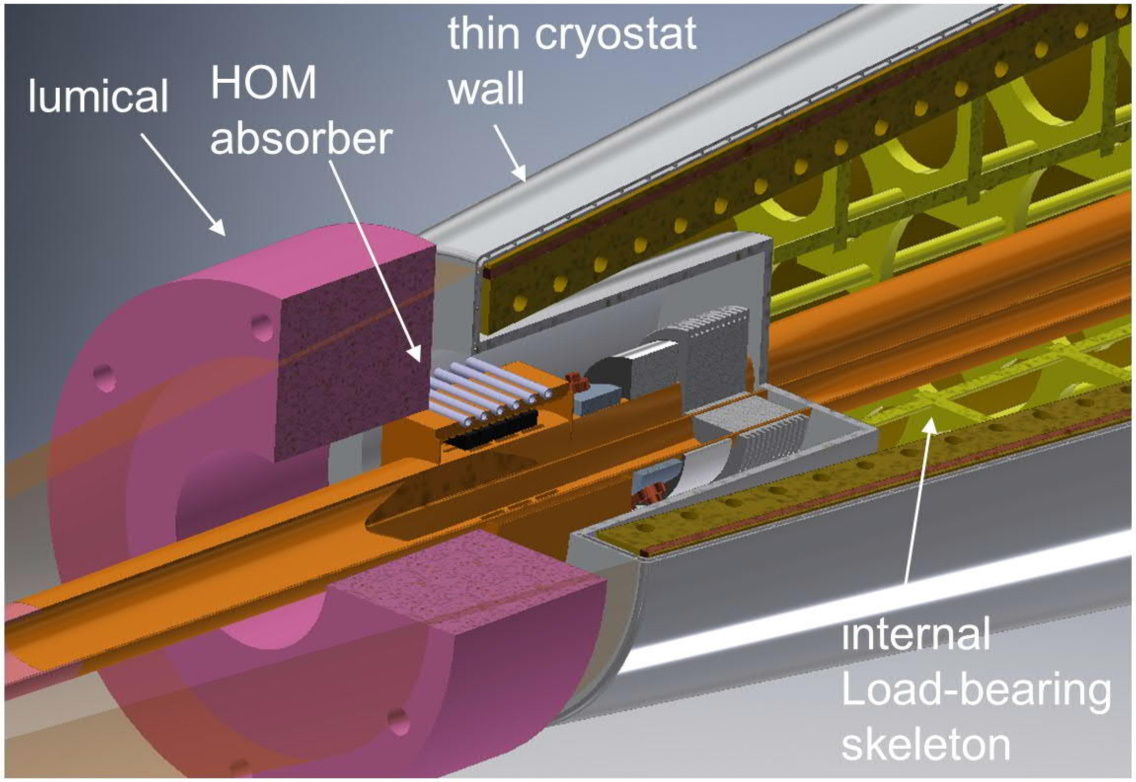
stiff-skeleton cryostats?

M. Boscolo, N. Bacchetta, A. Bogomyagkov, H. Burkhardt, M. Dam, D. El Khechen, M. Koratzinos, E. Levichev, M. Luckhof, A. Novokhatski, L. Pellegrino, S. Sinyatkin, M. Sullivan, et al.

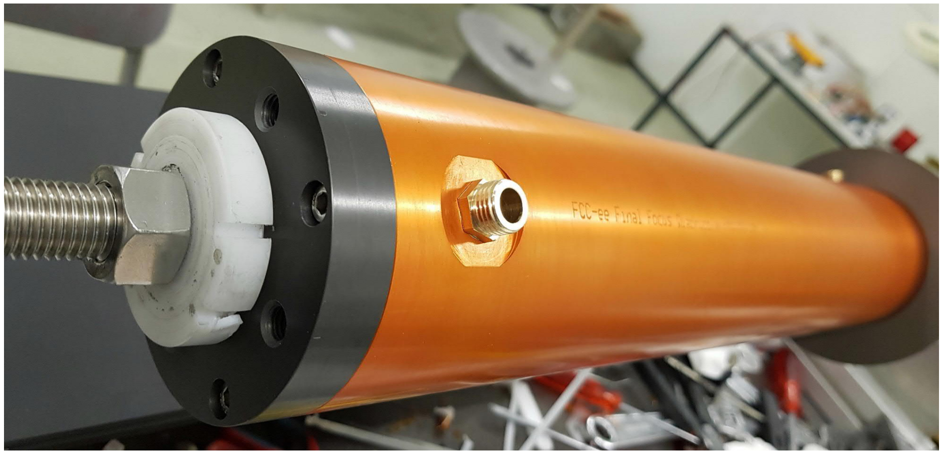
M. Boscolo, H. Burkhardt, and M. Sullivan, **Phys. Rev. Accel. Beams 20**, 011008 (2017)
A. Novokhatski, M. Sullivan, E. Belli, M. Gil Costa, and R. Kersevan, **Phys. Rev. Accel. Beams 20**, 111005 (2017)

FCC-ee MDI early conceptual design
FF CCT quad prototype

Thin-wall cryostat studies

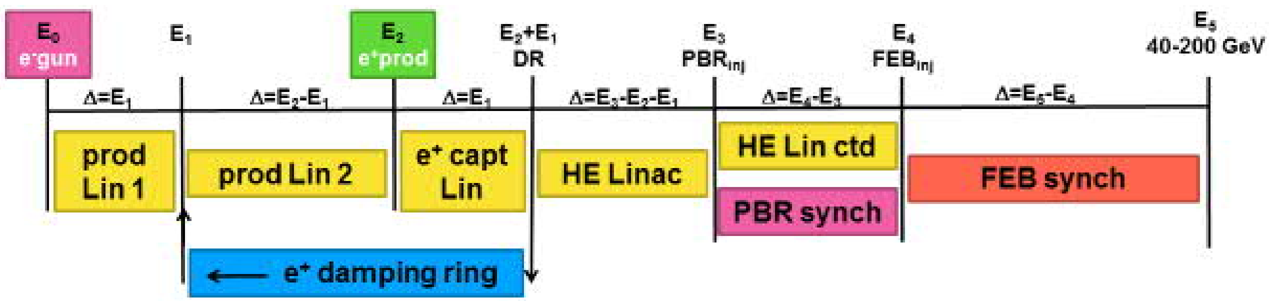


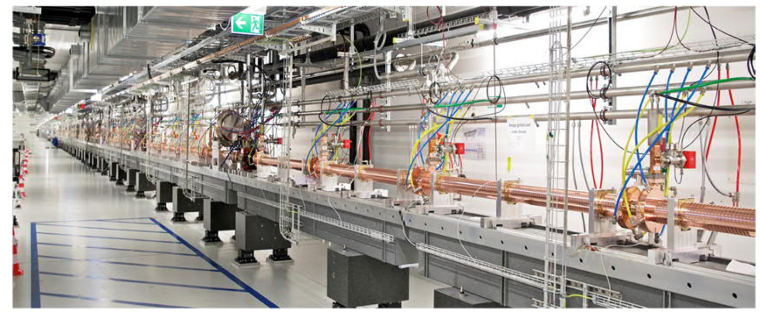
Final Focus CCT Quadrupole
Assembled Dec. 2019
Ready for testing



M. Koratzinos

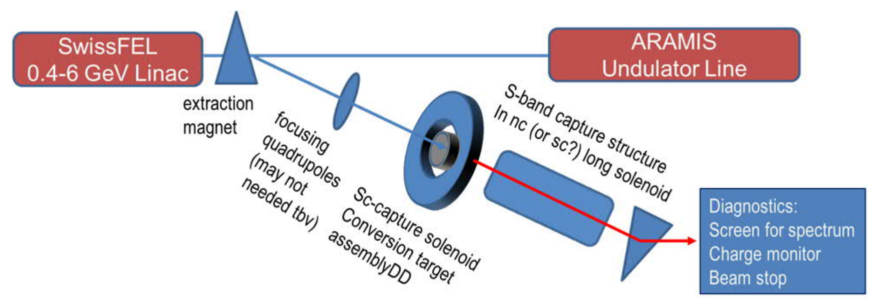
FCC-ee pre-injector work program





SwissFEL 6 GeV C-band Linac

Task 0 Coordination and parameter optimization - PSI/CERN
Task 1 e+/e- 6 GeV Injector Linacs – CERN/PSI
Task 2 e+ and e- Linac extension study (Linac 4) - PSI/CERN
Task 3 Positron source: target and capture system – IJCLab/CERN/PSI/BINP
Task 4 Damping ring and transfer lines – LNF/CERN
Task 5 CDR+ PSI/CERN,IJClab/LNF,BINP
Task 6 PoP e+ source in SwissFEL – PSI/CERN/IJClab/BINP



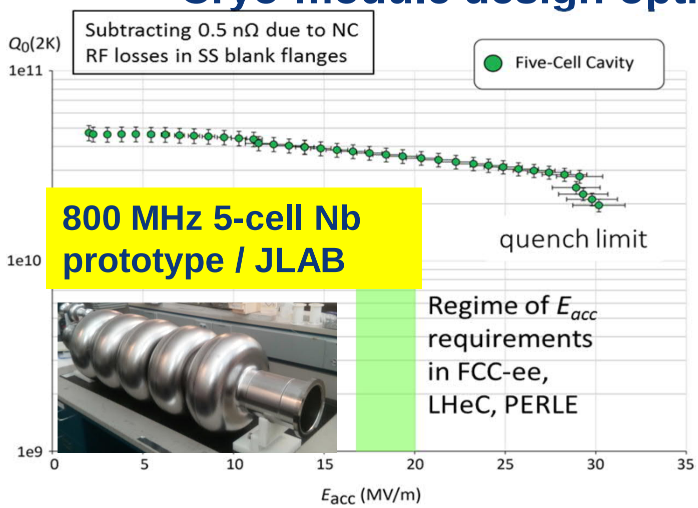
FCC-ee demonstrator e+ source at SwissFEL for e⁻/e⁺ conversion & capture efficiency

P. Craievich., A. Grudiev

SRF , cryo-modules, RF power sources R&D

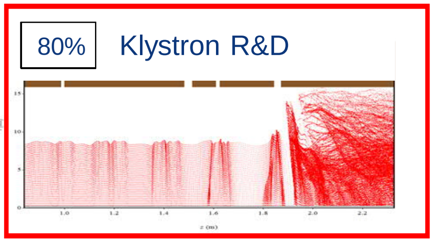
Several R&D lines aim at improving performance & efficiency and reducing cost:

- **Improved Nb/Cu coating/sputtering (e.g. ECR fibre growth, HiPIMS)**
- **New cavity fabrication techniques (e.g. EHF, improved polishing, seamless…)**
- **Coating of A15 superconductors (e.g. Nb_3Sn)**
- **Bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP**
- **High efficiency klystrons – synergy with HL-LHC and CLIC**
- **MW-class fundamental power couplers for 400 MHz**
- **Cryo-module design optimisation**



cryo-modules for FCC-ee:

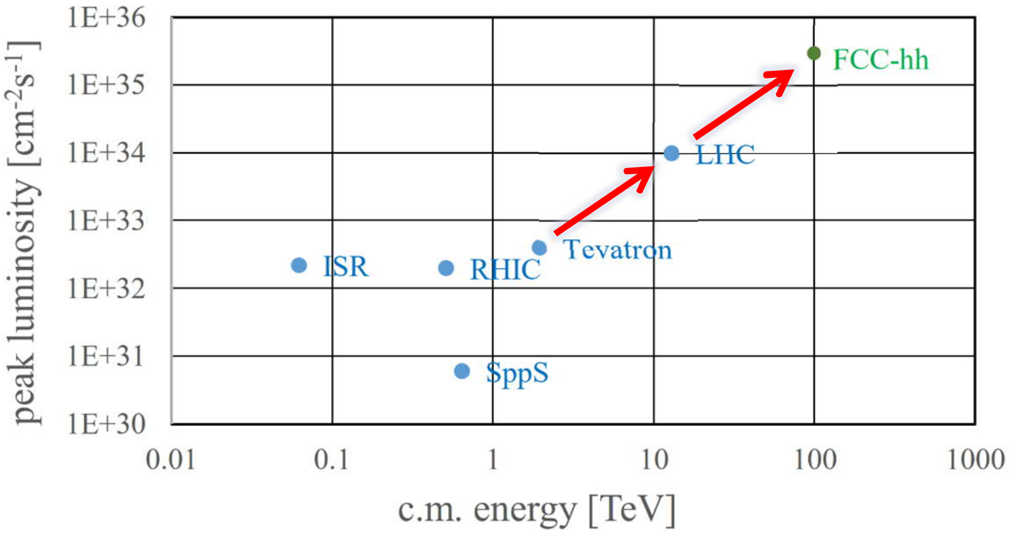
- **30 CM with four single cell 400 MHz cavities**
- **100 CM with four 4-cell 400 MHz cavities**
- **200 CM with four 5-cell 800 MHz cavities**



FCC-hh (pp) collider parameters

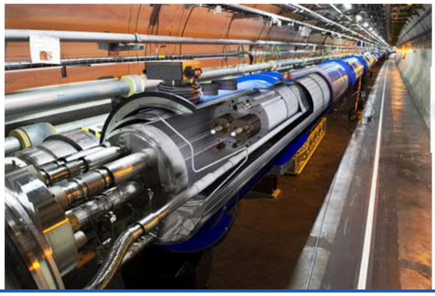
parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	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

FCC-hh: performance

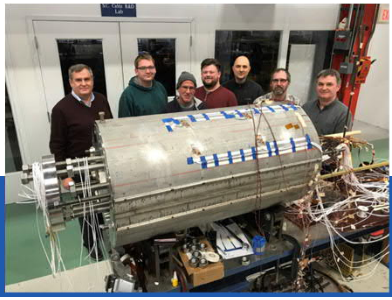


- **order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- **key technology: high-field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

from
LHC technology
8.3 T NbTi



via
HL-LHC technology
11 T Nb_3Sn

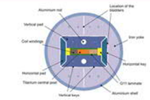


FNAL demonstrator
14.1 T Nb_3Sn
(Accelerating News)

FCC-hh 16 T dipole development at CEA

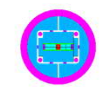
- CEA has completed the conceptual design of a 16 T block model dipole: 3D study of coil assemblies, magnetic & mechanical FEM computations.
- This activity has been the basis for establishing a model program.
- Staged program towards the development of a final 16T demonstrator.
- The first two steps (SMC + R2D2) are included in the present program

1. **SMC 11T** (=**S**hort **M**odel **C**oil) [10]
Racetrack coils
No grading → **Demonstrate field ≥ 12 T**



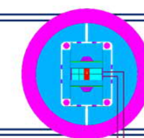
+Grading

2. **R2D2** (=**R**esearch **R**acetrack **D**ipole **D**emonstrator)
Racetrack + **Grading ≥ 12 T**



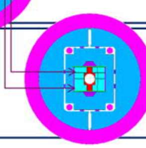
+Flared ends

3. **FD** (=**F**lared **D**ipole)
Grading + **Flared-end coils ≥ 14 T**

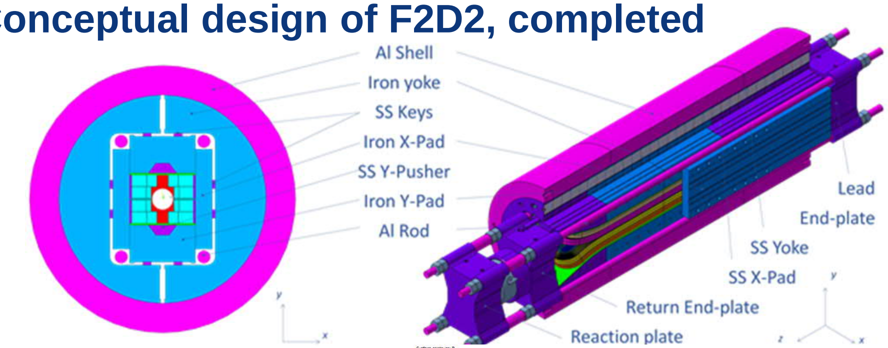


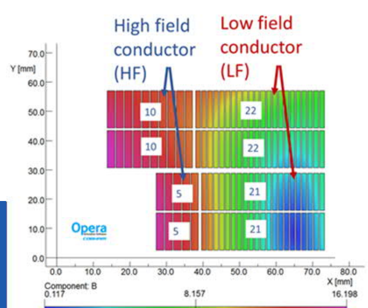
+Aperture

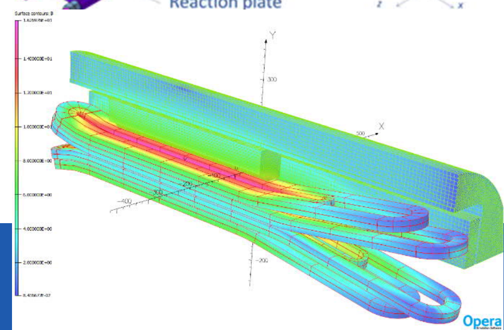
4. **F2D2** (=**F**CC **F**lared-ends **D**ipole **D**emonstrator)
Reuse FD coils + structure
Grading + Flared-end coils + **Aperture = 16 T**



Conceptual design of F2D2, completed





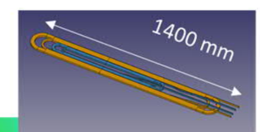


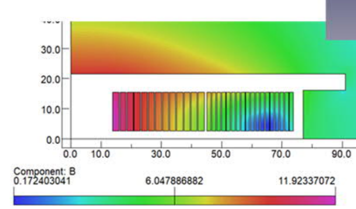
11 T SMC coil

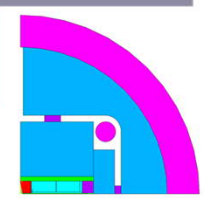
Coutesy of CERN

- Subscale coil allowing practice on:
  - Winding, heat treatment, instrumentation and impregation

Simplified graded demonstrator R2D2



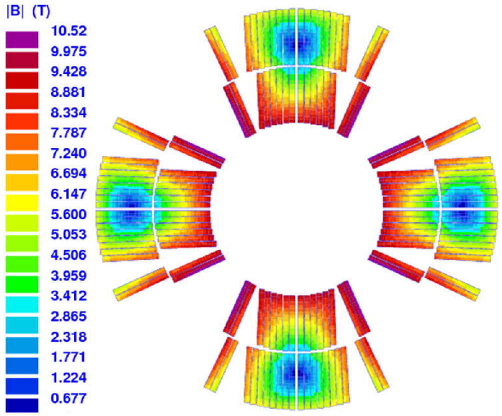




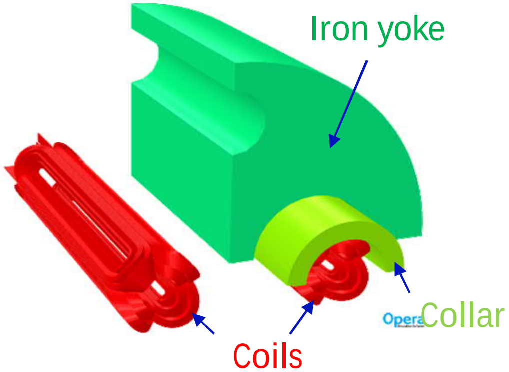
	Nominal	Max
Operating T	1.9 K	
I (A)	14724	18405
LL marg HF / LF	21.3% / 20.0%	0%
B @ (0,0)	11.83 T	14.05 T
B peak HF	12.81 T	15.28 T
B peak LF	8.46 T	10.20 T

FCC-hh arc quadrupole design at CEA

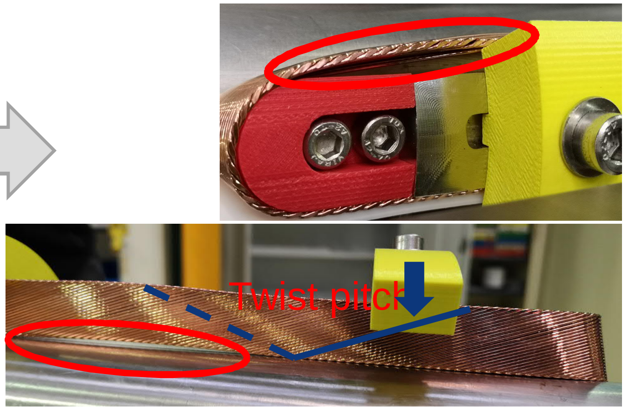
- CEA has completed a conceptual design of an up to 360 T/m quadrupole for the FCC.
- This work included 3D studies with magnetic finite element computations and preliminary 3D mechanical analysis.
- Winding trials have suggested to explore the use of a cable with 0.7 mm strands, as for the 11 T dipole for HiLumi.



2D magnetic design



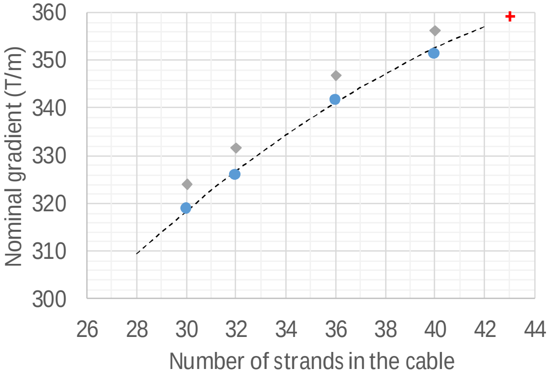
3D magnetic design



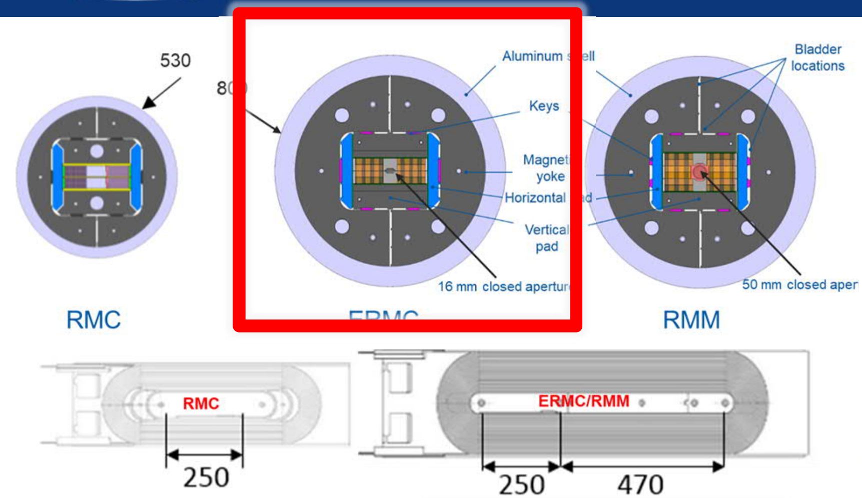
winding trials

Preference for a 0.7 mm strand

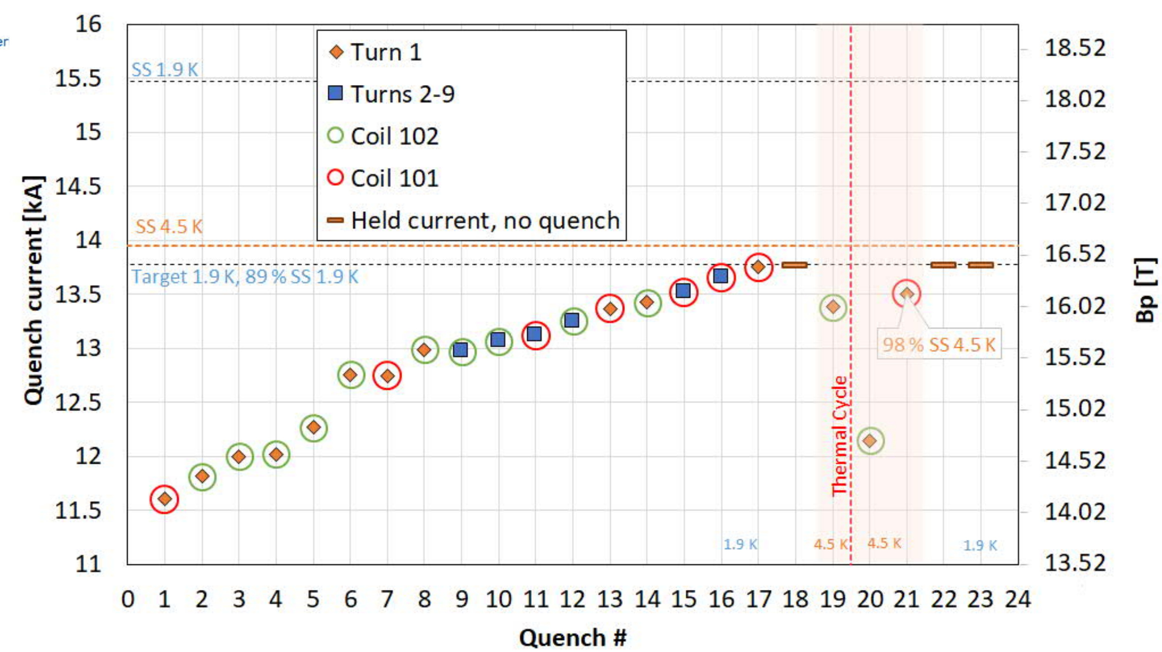
Feasible quadrupole strength for FCC-hh



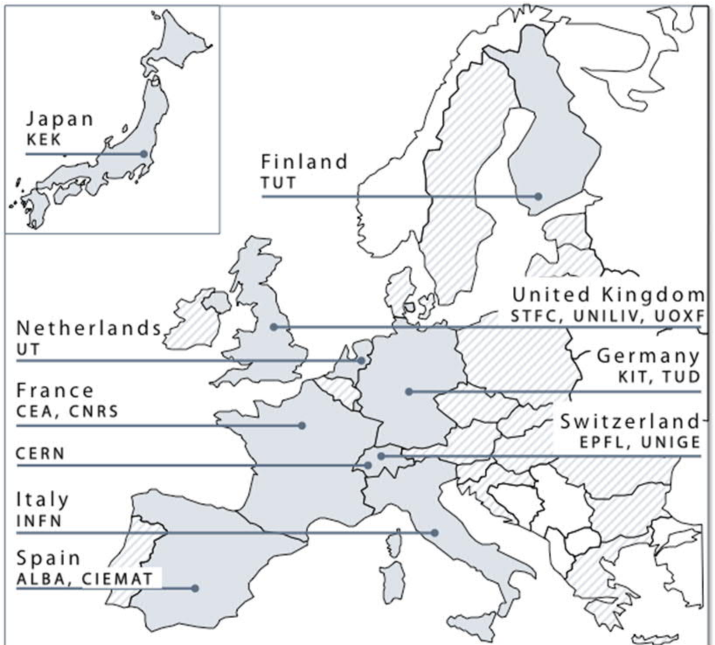
enhanced Racetrack Model Coil at CERN exceeded 16.3 T



16 mm aperture; measured: quench location, quench phenomenology, mechanical behavior → next prototype: 50 mm FCC aperture



EU H2020 Design Study EuroCirCol



EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

European Union Horizon 2020 program

- **3 MEURO co-funding**
- **Completed in December 2019**
- **15 European beneficiaries & KEK & associated FNAL, BNL, LBL, NHFML**

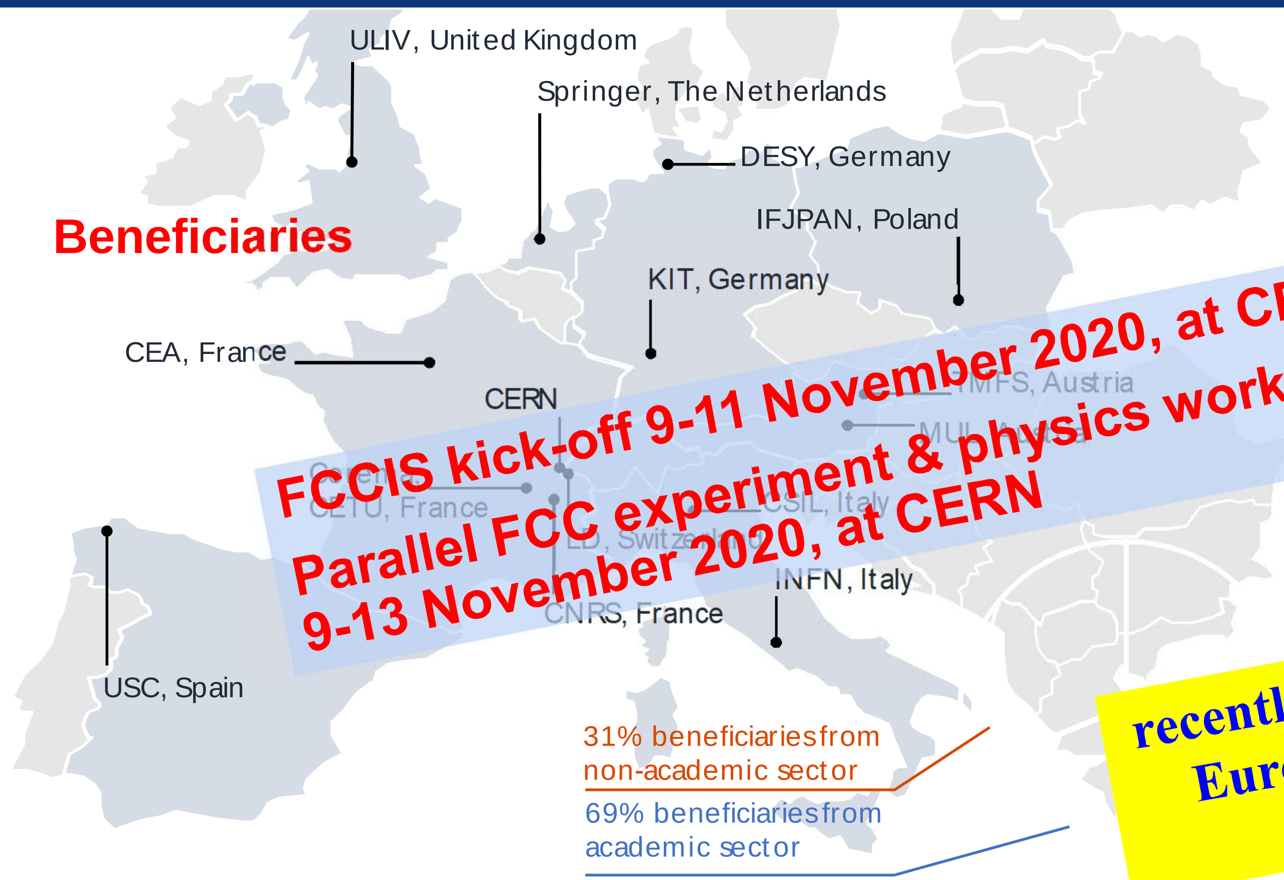
Scope:

FCC-hh collider key work packages

- **Optics Design Arc and IR**
- **Cryogenic beam vacuum system design including beam tests at ANKA**
- **16 T dipole design, construction folder demonstrator**

H2020 DS FCC Innovation Study 2020-24

Beneficiaries



FCCIS kick-off 9-11 November 2020, at CERN

Parallel FCC experiment & physics workshop, 9-13 November 2020, at CERN

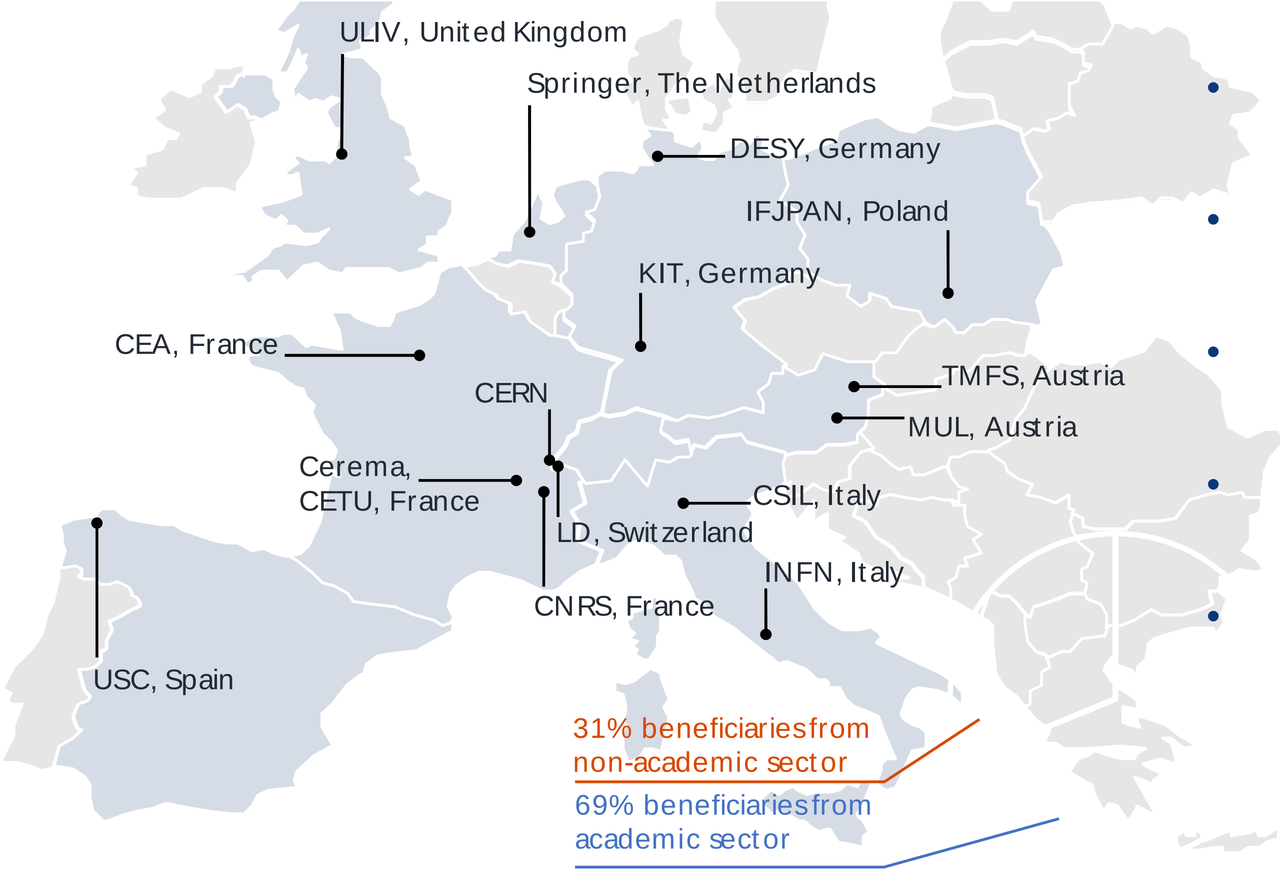
Partners

- D.R.R.T. (F)
- Etat de Geneve (CH)
- DOE (US)
- BINP (Ru)
- U Oxford (UK)

recently accepted for funding by the European Commission with the highest achievable score

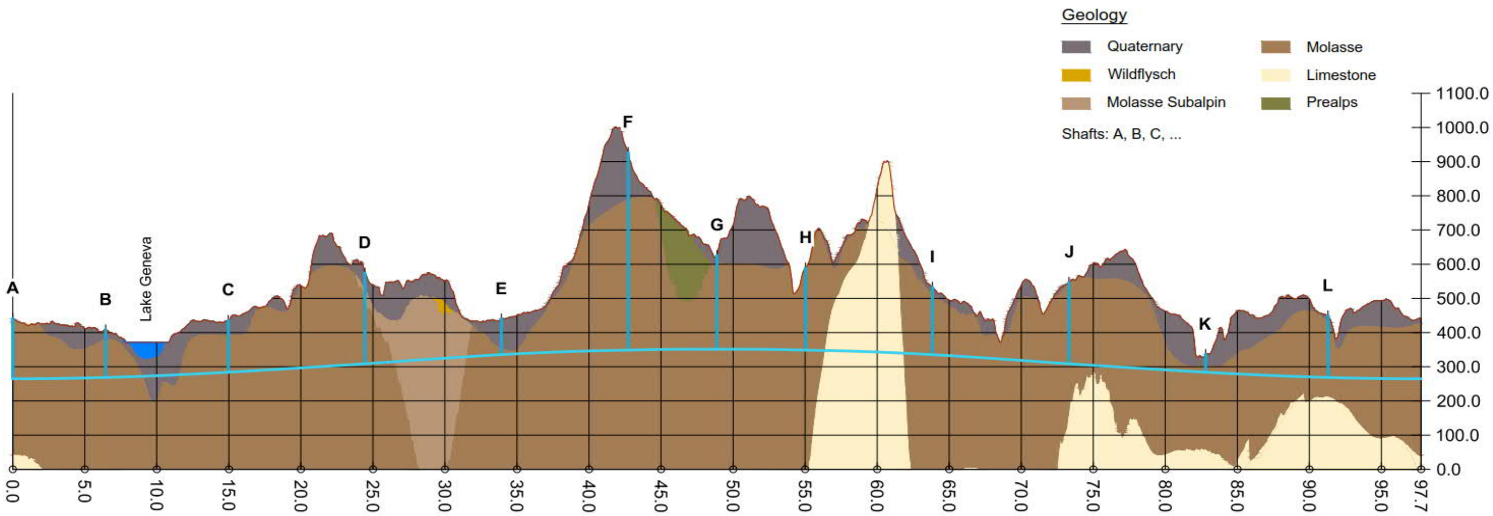
FCC-ee design optimisation, construction planning, environmental impact assessment, management of excavation materials, user community building and public engagement, socio-economic impact,…

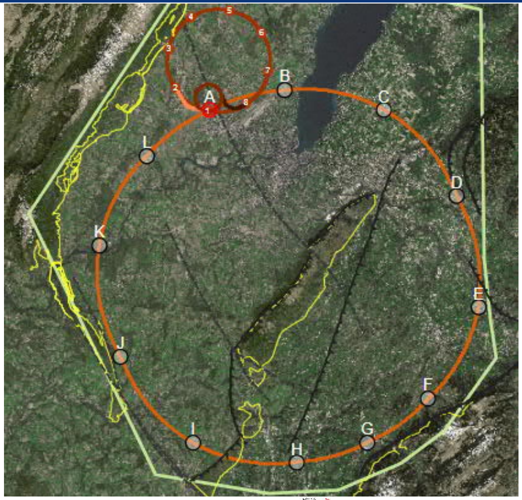
FCCIS French contributions

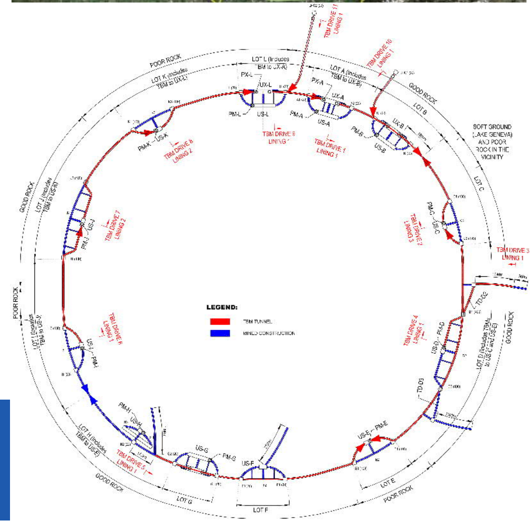


- **Full Energy Booster design**
  - **Task Leader CEA Saclay**
- **Excavation material management**
  - **CETU**
- **MDI alignment and positioning**
  - **CNRS LAPP Annecy**
- **Communication, regional impact**
  - **CNRS LAPP Annecy**
- **Placement studies and administrative processes**
  - **CEREMA**

FCC implementation - footprint baseline







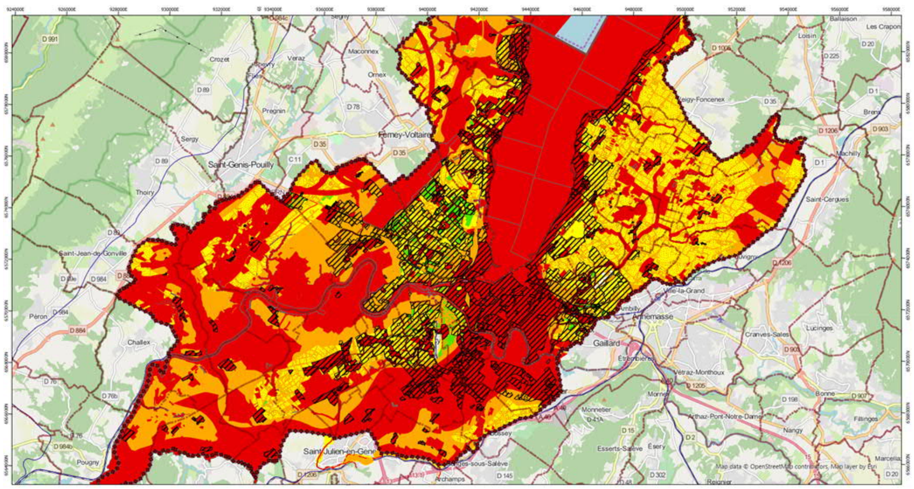
- **Present baseline position was established considering:**
- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

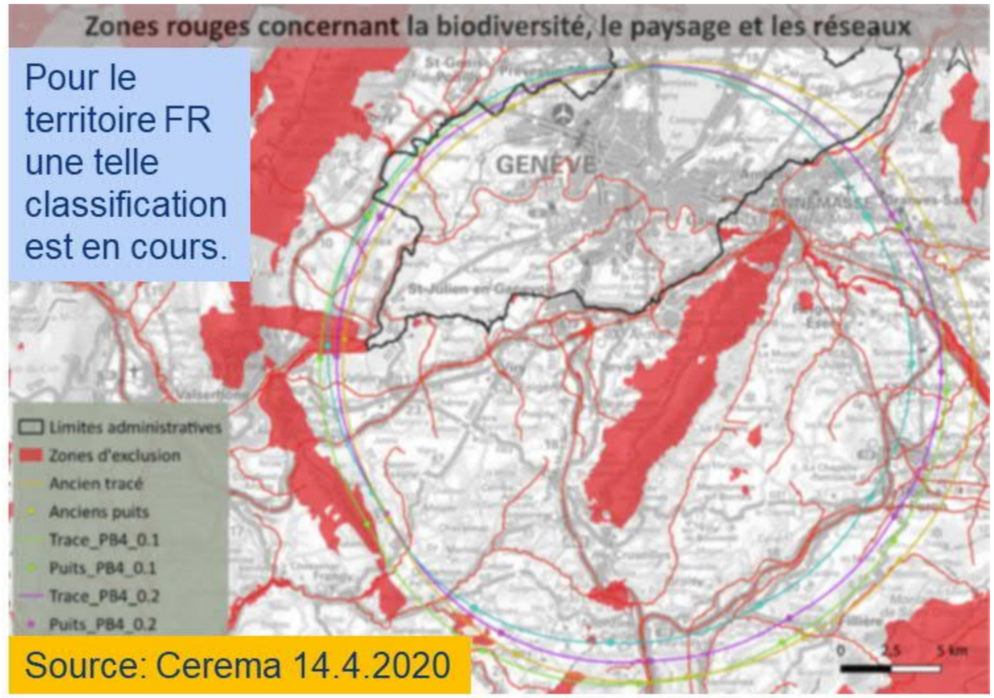
- **More than 75% tunnel in France, 8 (9) / 12 access points in France.**
- **next step: review of surface site locations and machine layout**

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





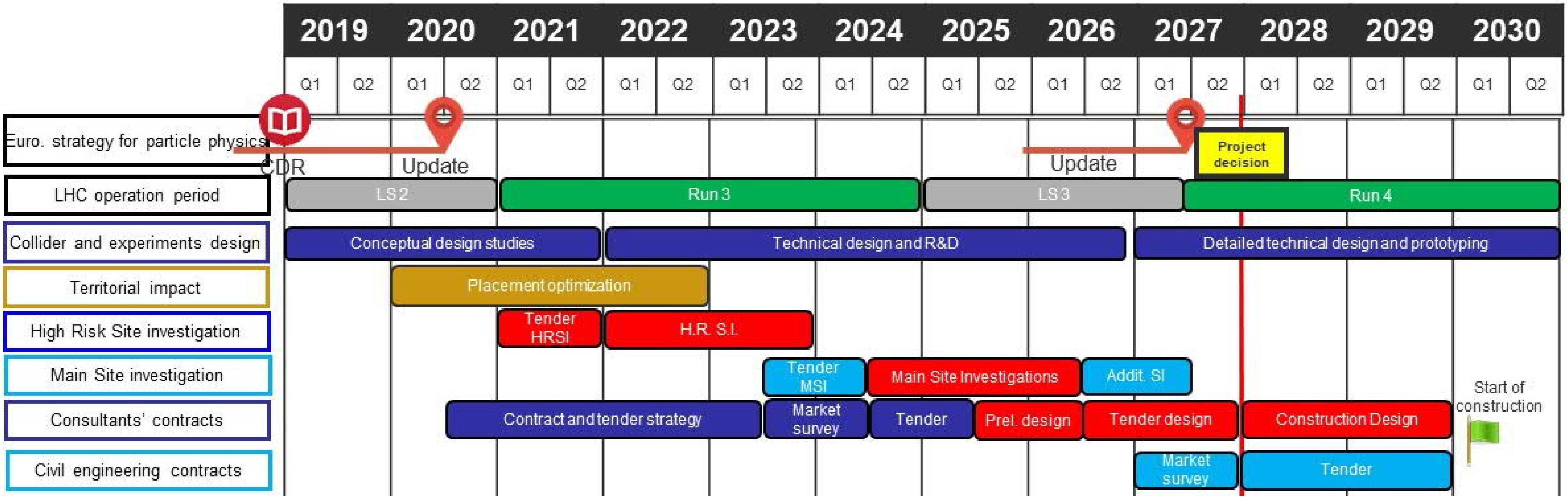
FCC implementation – variant studies

Nombreuses variantes étudiées,
au fur et à mesure des informations
supplementaires sur la classification
des zones furent reçues.

L'activité est actuellement intensifiée.

Source: A.-L. Verdier

Timeplan for CE project preparation



- **Feasibility study of the 100 km tunnel completed by 2025, including** infrastructure aspects, administrative aspects, local authorities, environment, energy, etc.
- **Host-state related processes** included to **allow start of construction begin 2030**.

FCC main goals for 2020 - 2026

Overall goal:

- Perform all necessary steps and studies to enable a definitive project decision by 2026/27, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2029/30.

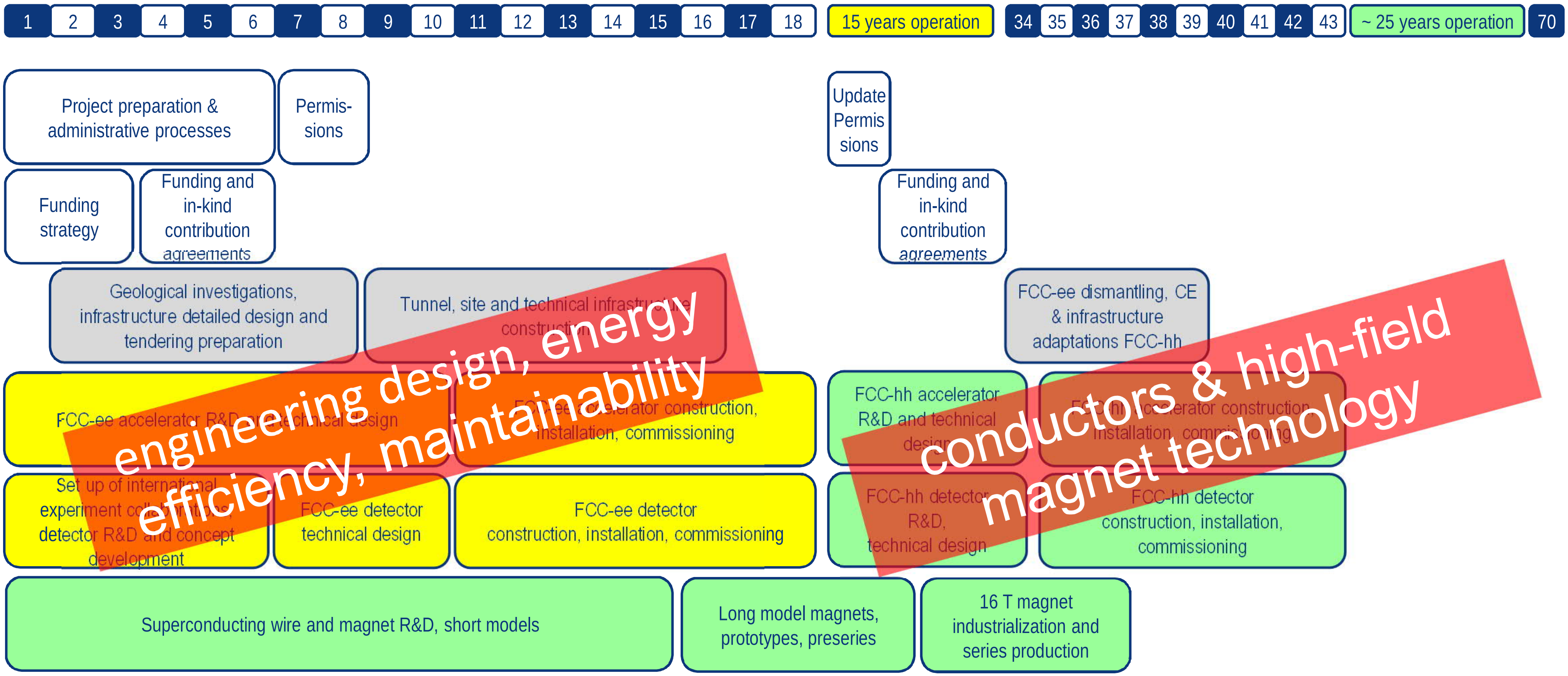
This requires successful completion of the following four main activities:

- Develop and establish a governance model for project construction and operation
- Develop and establish a financing strategy, including in-kind contributions
- Prepare and successfully complete all required project preparatory and administrative processes with the host states (debat public, EIA, etc.)
- Perform site investigations to enable CE planning and to prepare CE tendering.

In parallel preparation of CDR+/TDRs and physics/experiment studies:

- Machine designs and main technology R&D lines
- Establish user communities, work towards proto experiment collaboration by 2026/27.

FCC integral project technical schedule

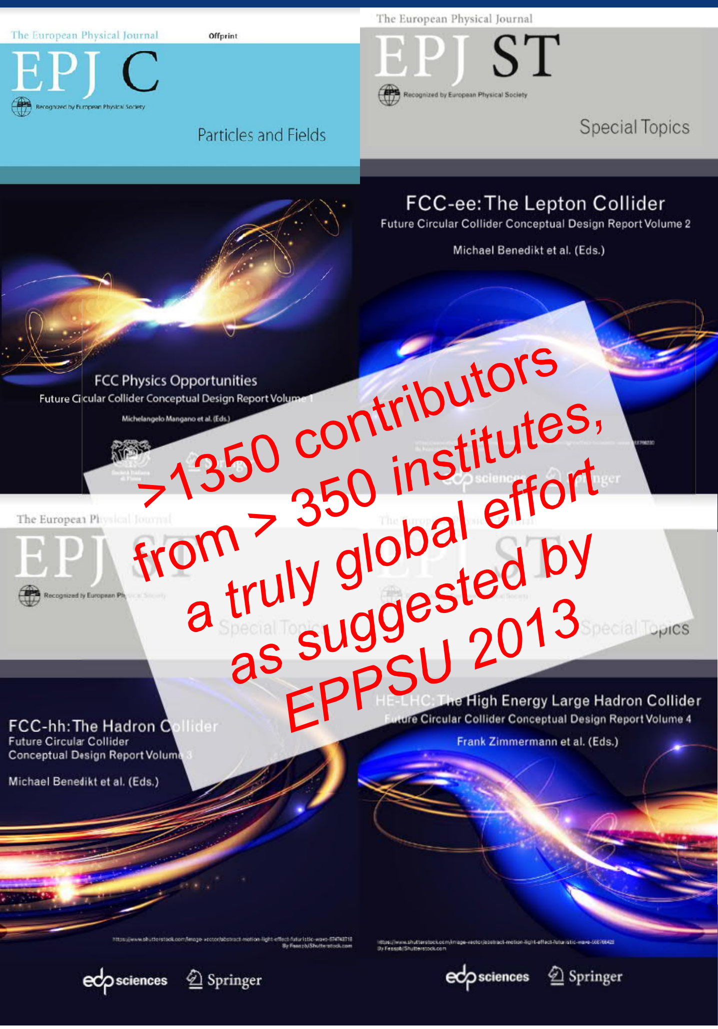


Status of Global FCC Collaboration

Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

FCC CDR and 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)

    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/

Summary

FCC-ee = most efficient Higgs & electro-weak factory at c.m. energies from 90 to 365 GeV

- **FCC-ee key concepts, ingredients, and parameters already demonstrated or exceeded at various past & present machines** (crab waist collisions, β_y^*~1 mm, ~1.5 A beam current, e^+ source with required rate, target emittances, top up, SR power / unit length, MeV photon energies,…)
- **main technologies for FCC-ee exist today; strong R&D program with industry for optimizing energy efficiency** (efficient SRF, highly efficient RF power sources, energy-efficient magnets,…) **maintainability, machine availability** (modular design, early involvement of industry,…) **and construction cost**

FCC-hh = highest energy collider conceivable in 21st century, solid design based on LHC lessons

- **required technology – high-field 16 T magnets – not yet available; rigorous conductor & magnet R&D program** to have **magnets available towards the end of FCC-ee operation ~2050/55**

FCC-ee/FCC-hh integrated programme: efficient coherent long-term strategy: sharing of tunnel, technical infrastructure (electricity, C&V, …), perhaps detector modules + complementary physics + exploiting existing CERN infrastructure and LEP/LHC experience

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 the European Strategy Update 2019/20
- **Next steps: concrete local/regional implementation scenario** in collaboration with host state authorities, accompanied by machine optimization, physics studies and technology R&D, supported by **EC H2020 Design Study FCCIS**
- **FCCIS kickoff 9-11 November 2020, CERN**; parallel FCC Physics Workshop 9-13 November 2020; **FCC Week 2021 in Paris**, exact date tbd.
- Long term goal: a **world-leading HEP infrastructure for the 21st century** to push the particle-physics **precision and energy frontiers** far beyond the present limits