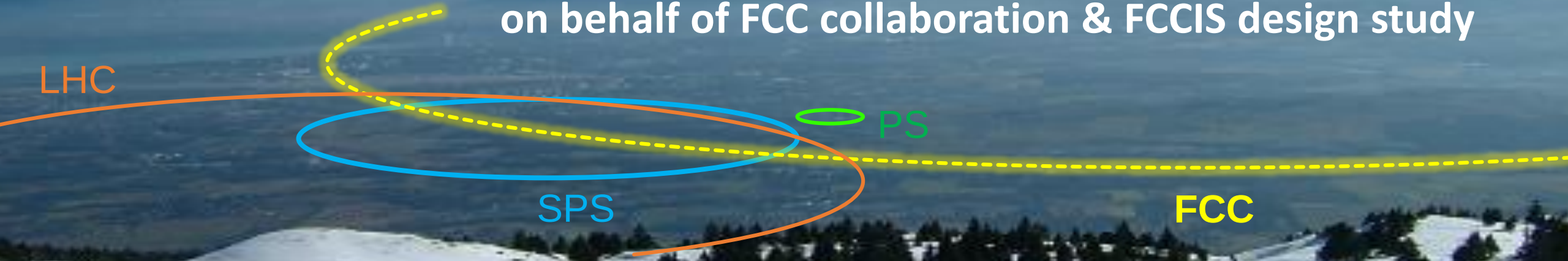
# Future Circular Collider Study – Status and Plans

Michael Benedikt, CERN

**on behalf of FCC collaboration & FCCIS design study**




http://cern.ch/fcc

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **ARIES**, grant agreement 730871, **FCCIS**, grant agreement 951754, and **E-JADE,** contract no. 645479*

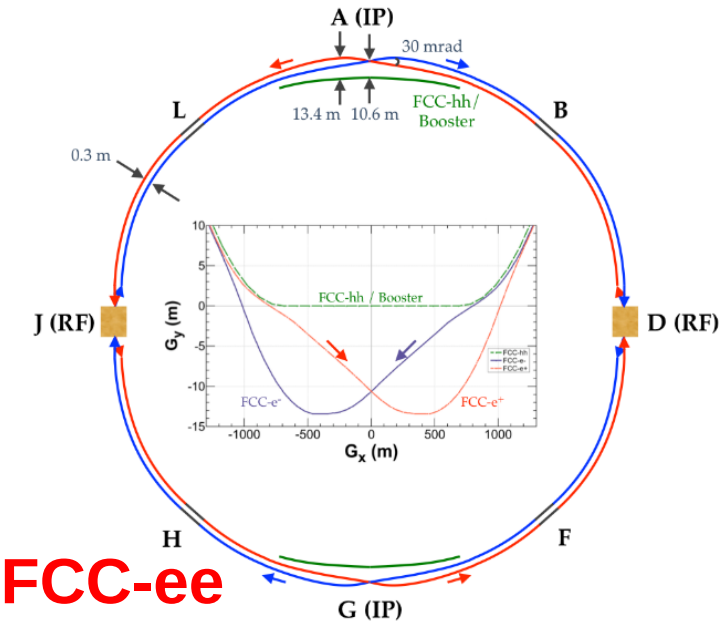
European Commission | Horizon 2020 European Union funding for Research & Innovation

photo: J. Wenninger

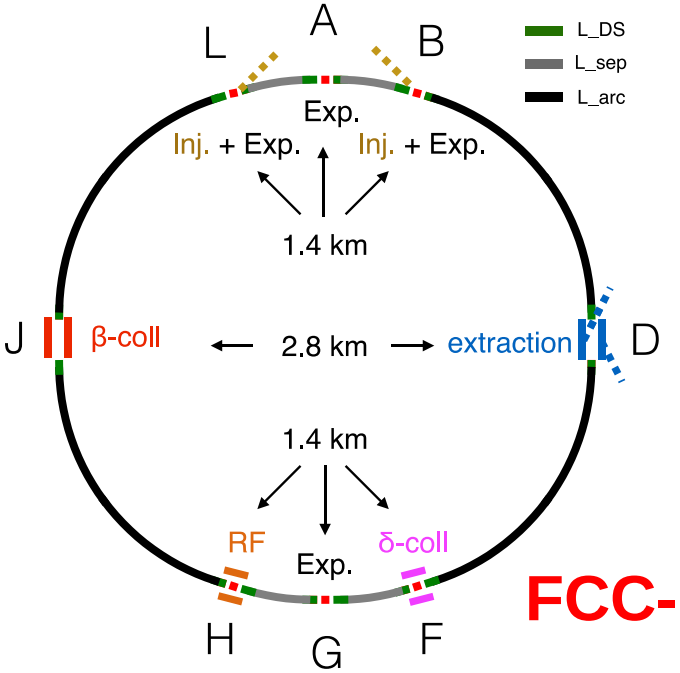
# FCC integrated program
# inspired by successful LEP – LHC programs at CERN

**comprehensive cost-effective program maximizing physics opportunities**

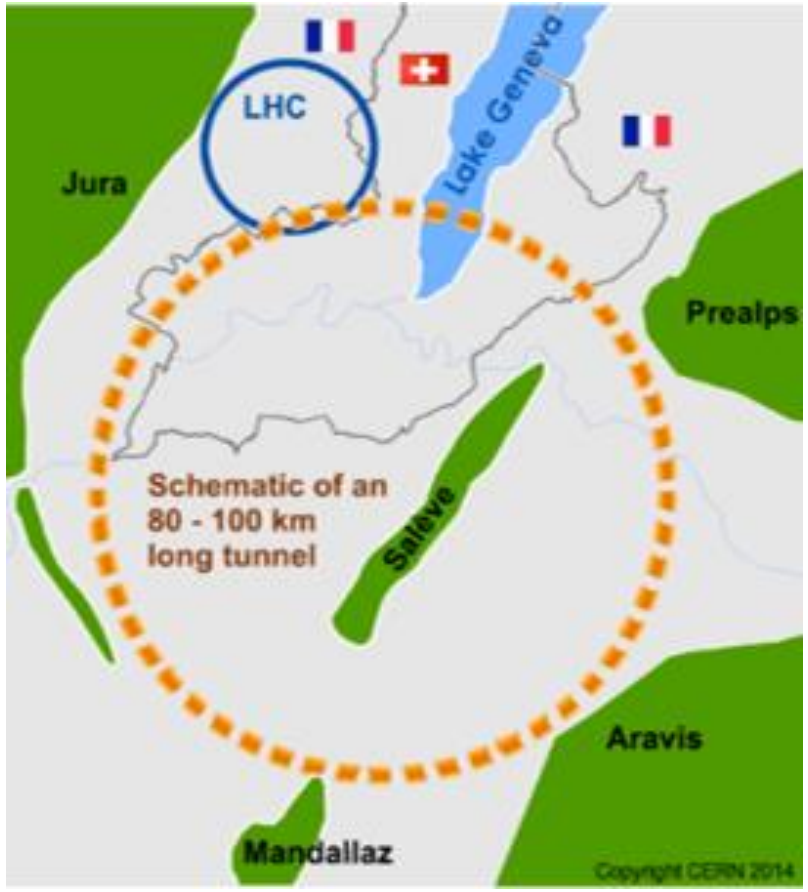
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures
- building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




**FCC-ee**




**FCC-hh**



# FCC-ee 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

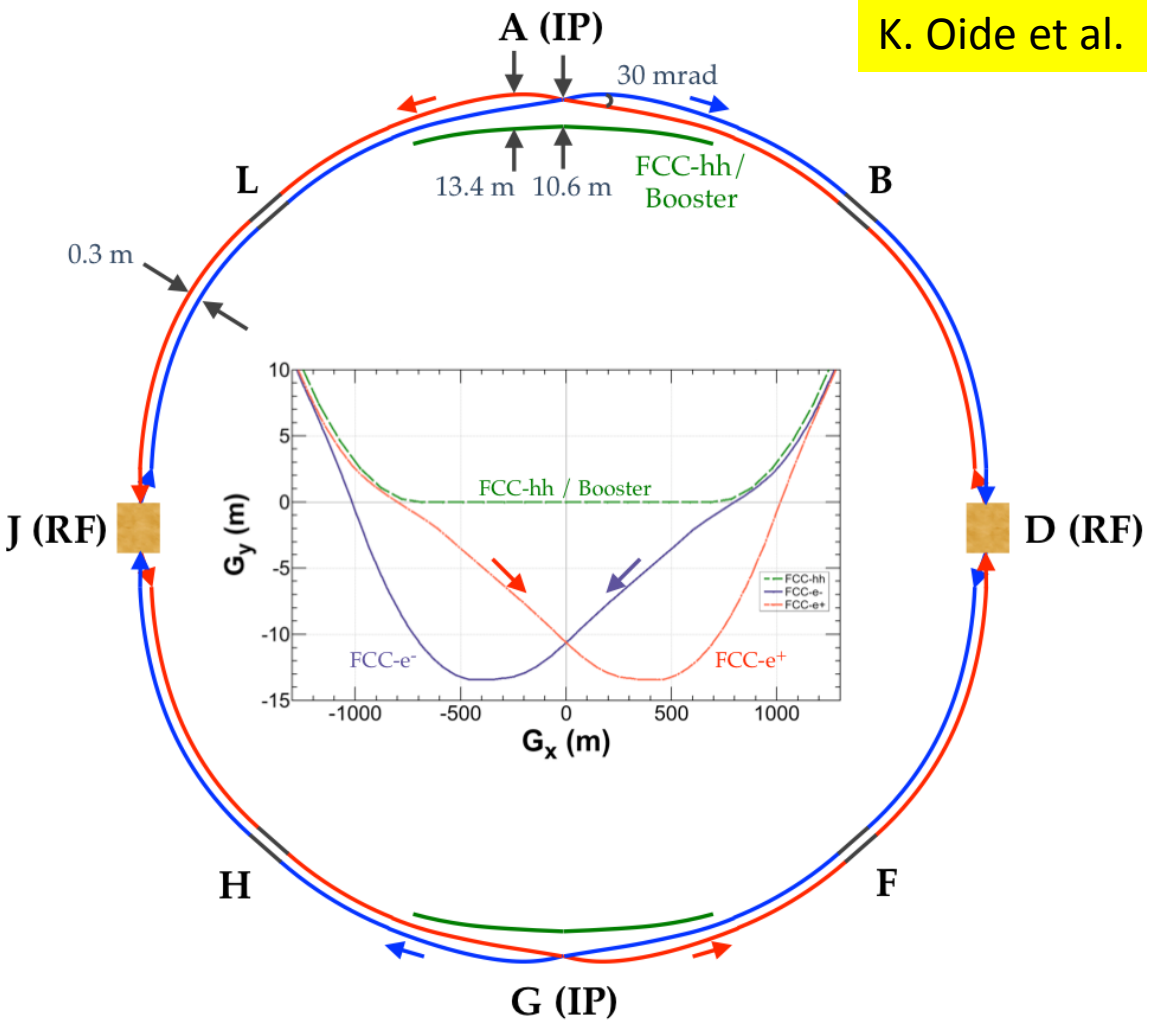
**presently 2 IPs** (alternative layouts with 3 or 4 IPs under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**

**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 **booster synchrotron in collider tunnel**

K. Oide et al.



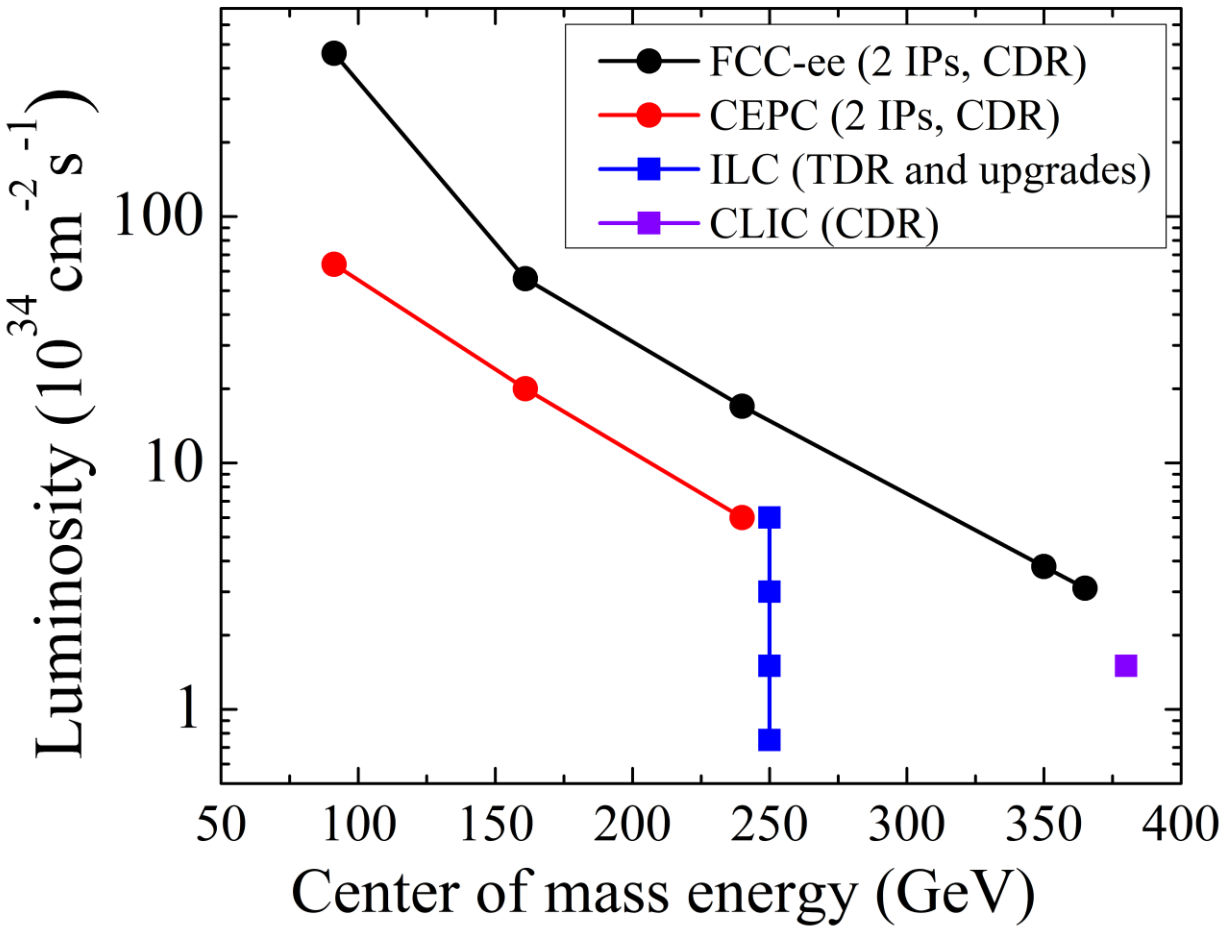



*FCC-ee: The Lepton Collider*, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

# 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: high-luminosity Higgs/electroweak factory

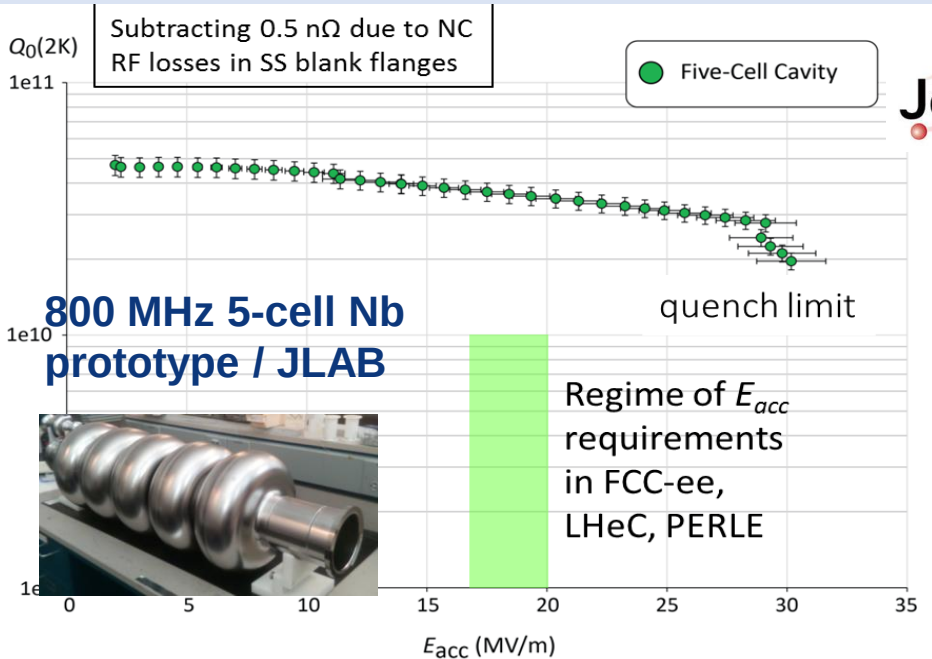


# FCC-ee R&D: RF, cryo-modules, power sources

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

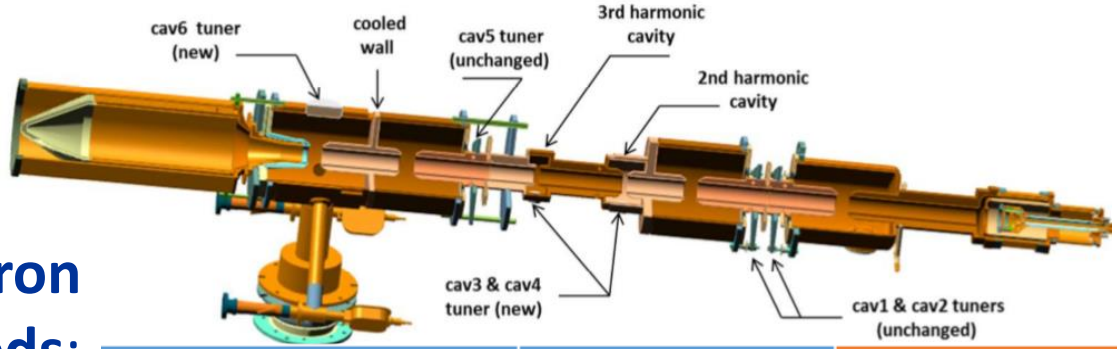
- improved Nb/Cu coating/sputtering, partner STFC (e.g. ECR fibre growth, HiPIMS)
- new cavity fabrication techniques, partner STFC (e.g. EHF, improved polishing, seamless)
- coating of A15 superconductors (e.g. $Nb_3Sn$), · cryo-module design optimisation
- bulk Nb cavity R&D at FNAL, JLAB, Cornell,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

## prototype FCC SRF cavities at JLAB




Jefferson Lab

## high-efficiency klystron at CERN



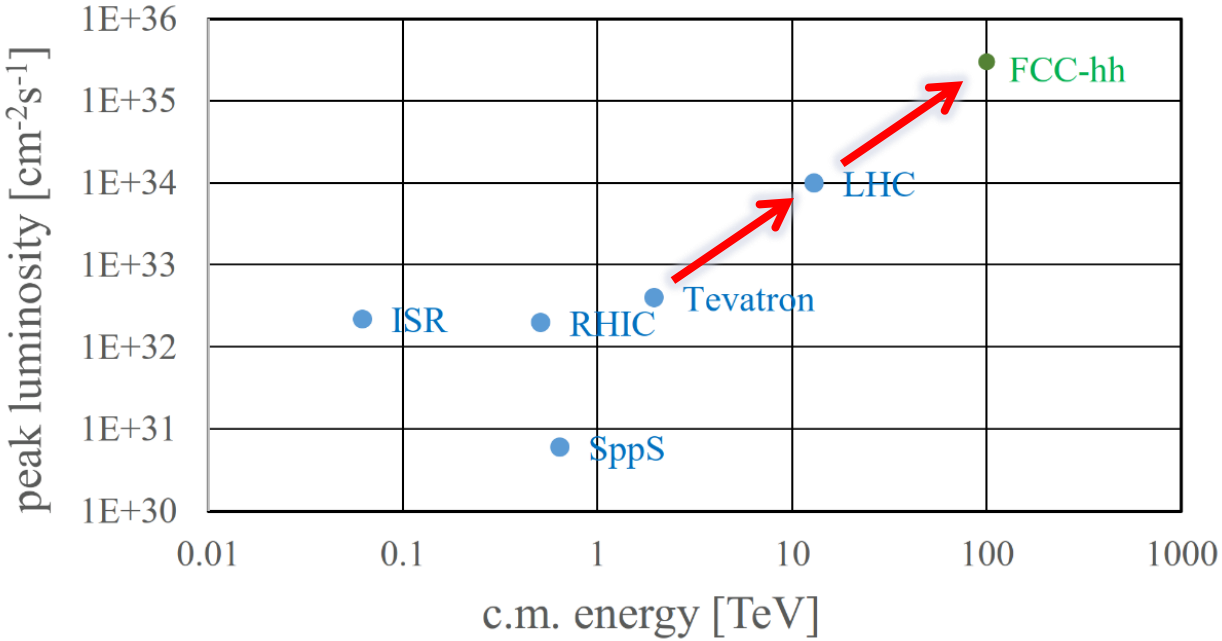

**novel klystron bunching methods:**
**LHC klystron retrofit** as proof of principle for FCC

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

# 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 [$\mu$m] | 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 |

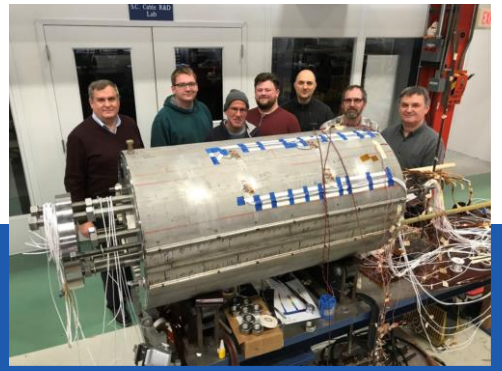
# FCC-hh: highest collision energies




- **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**

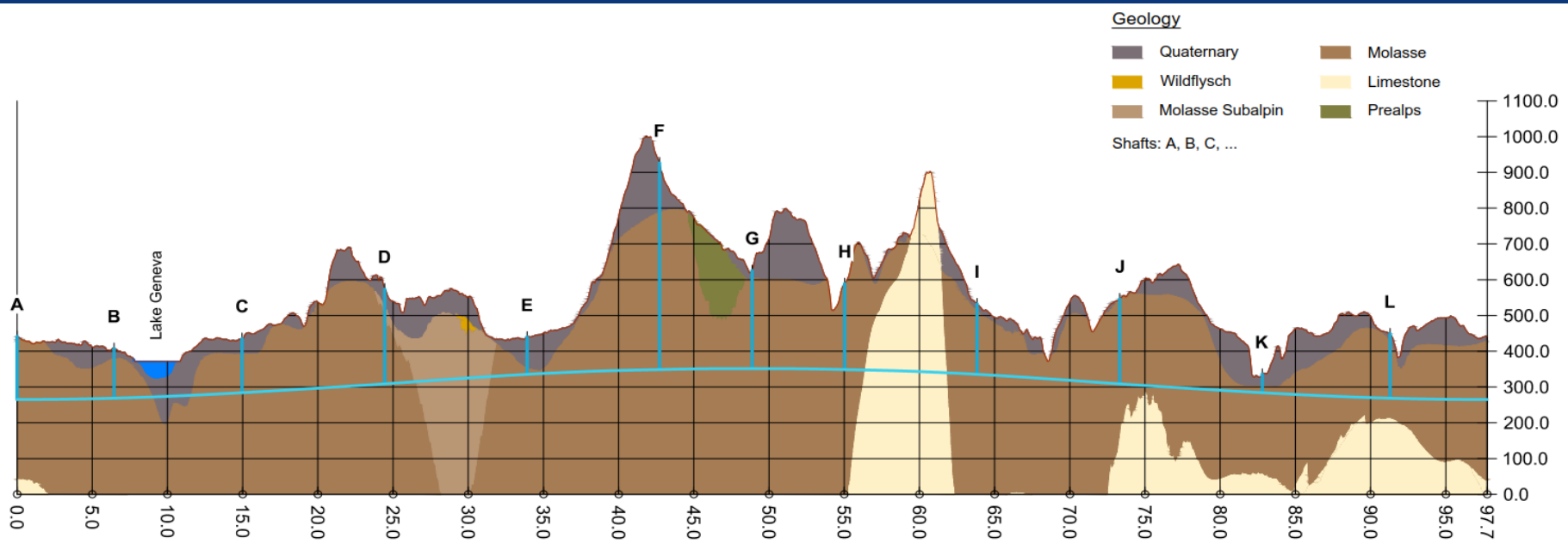
**from**
**LHC technology**
**8.3 T NbTi dipole**

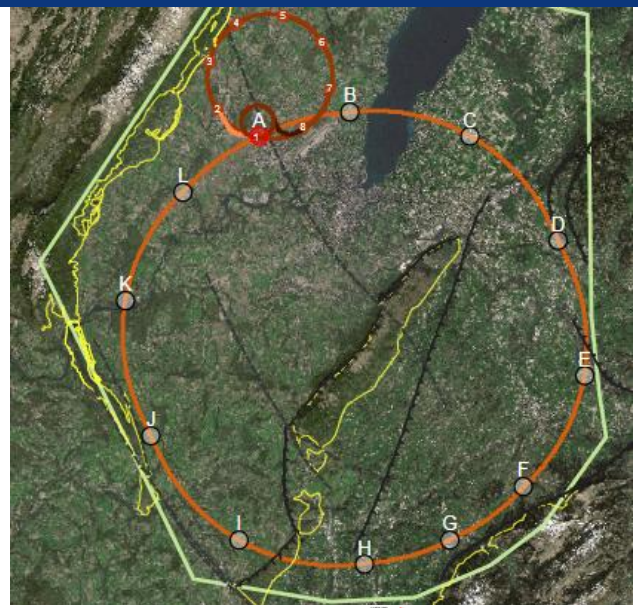
**via**
**HL-LHC technology**
**12 T $Nb_3Sn$ quadrupole**

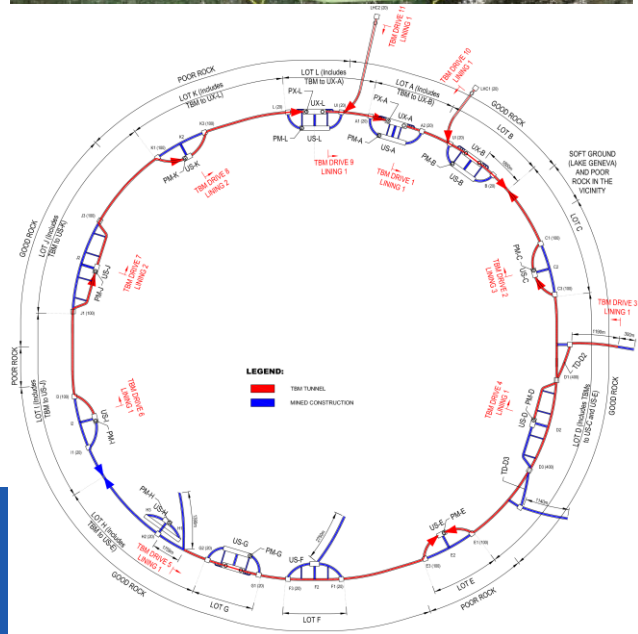


**FNAL dipole demonstrator**
**14.5 T $Nb_3Sn$**

# FCC implementation - footprint baseline



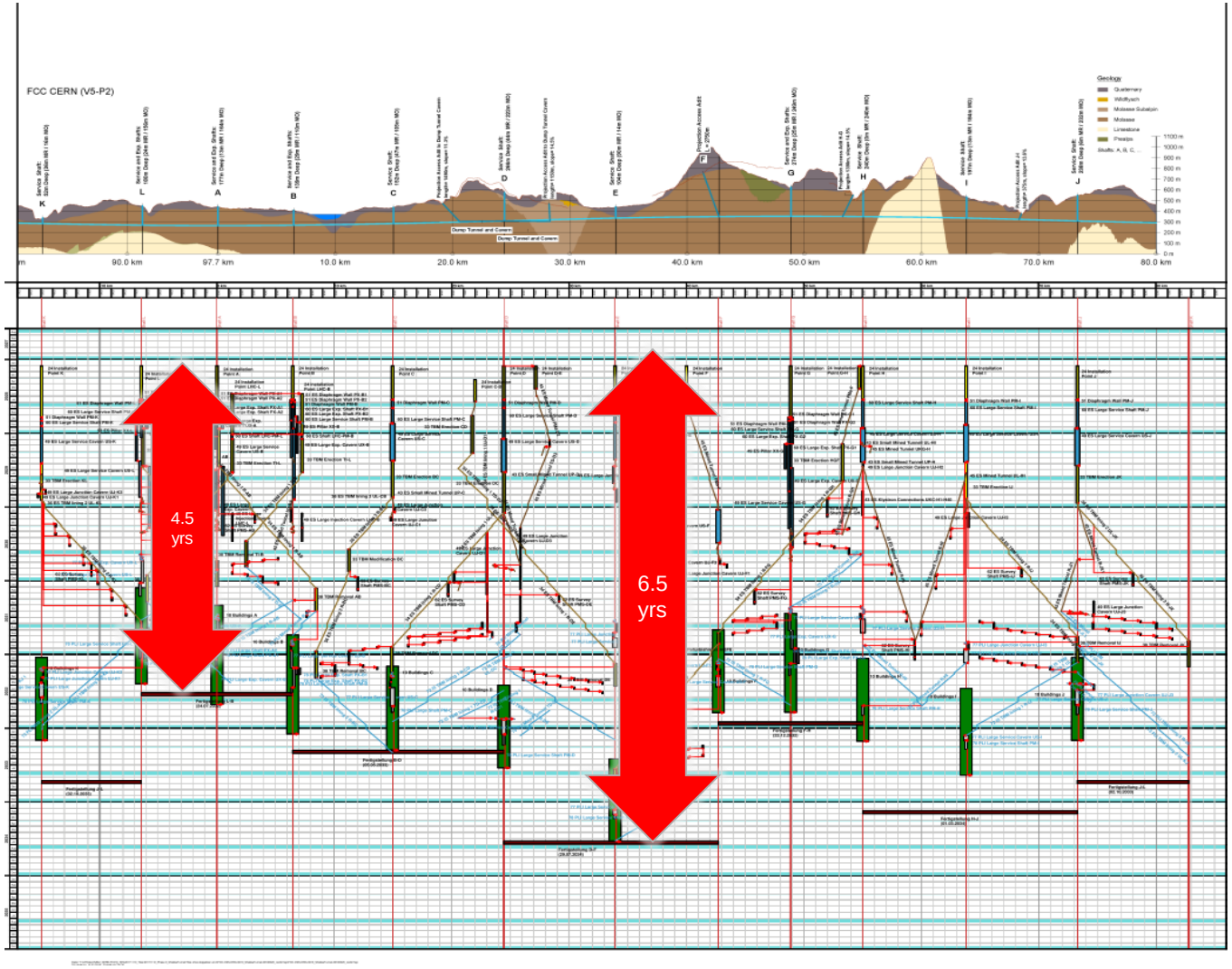



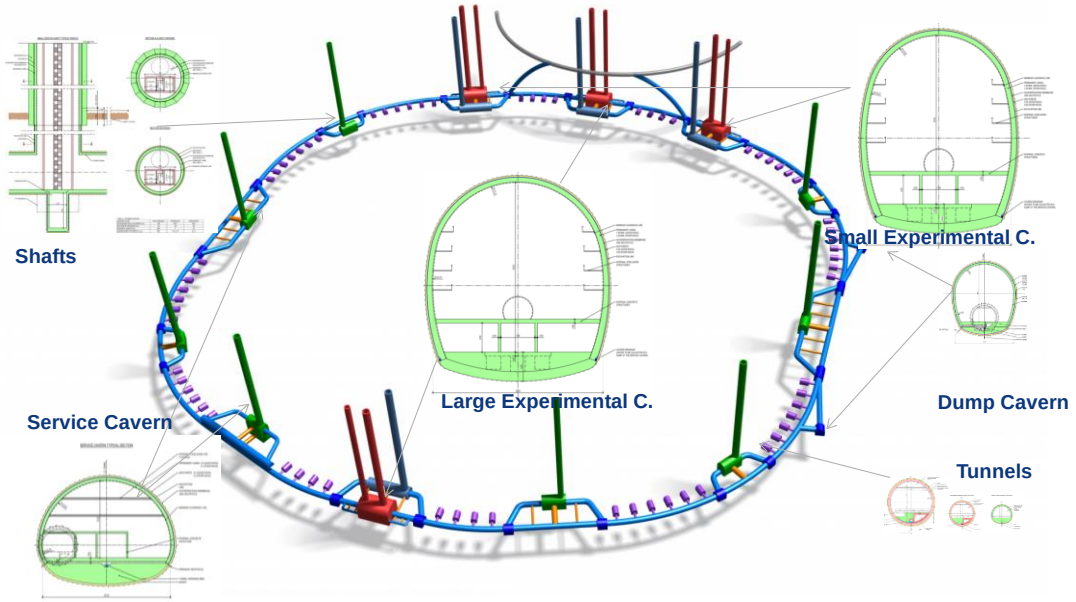

## present baseline position was established considering:

- 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**

# civil engineering studies



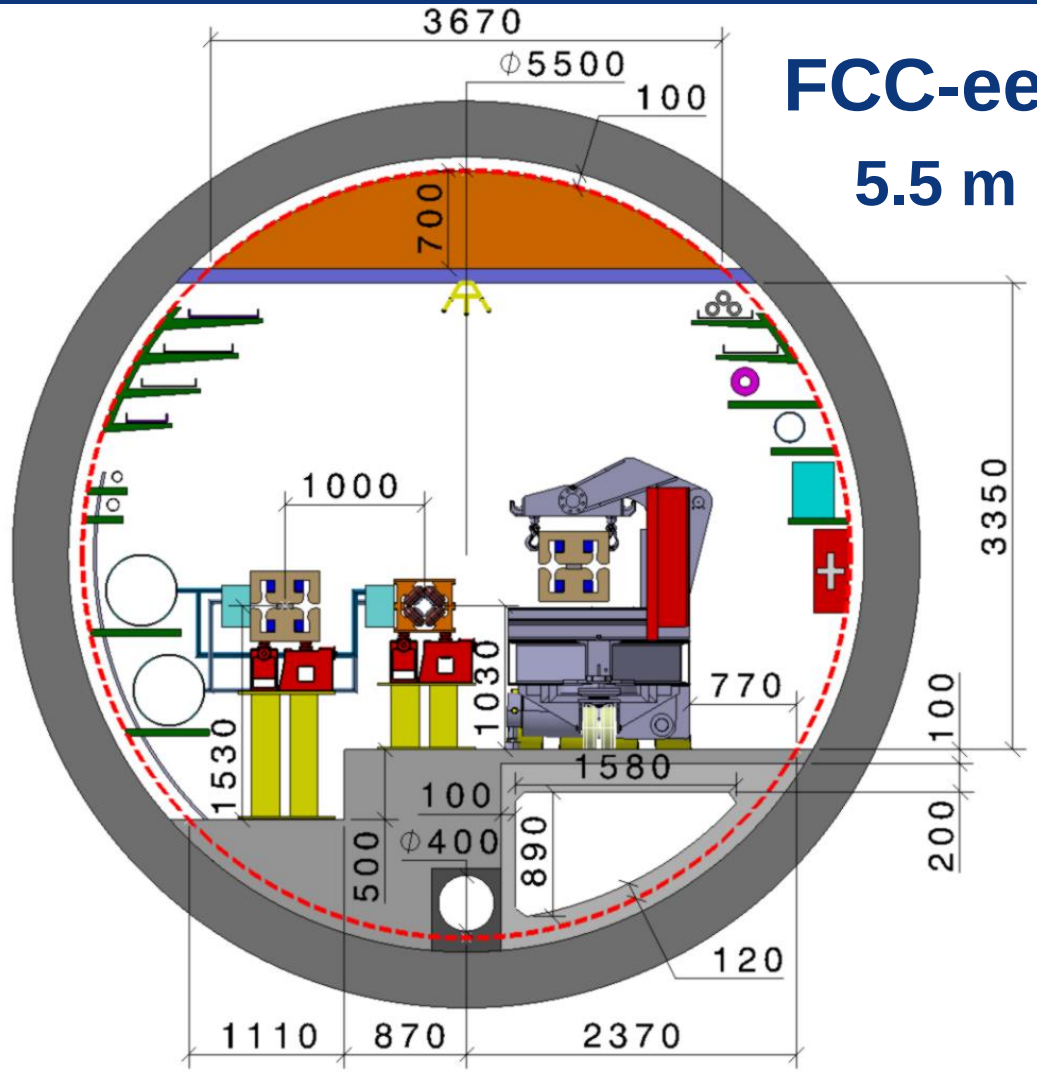



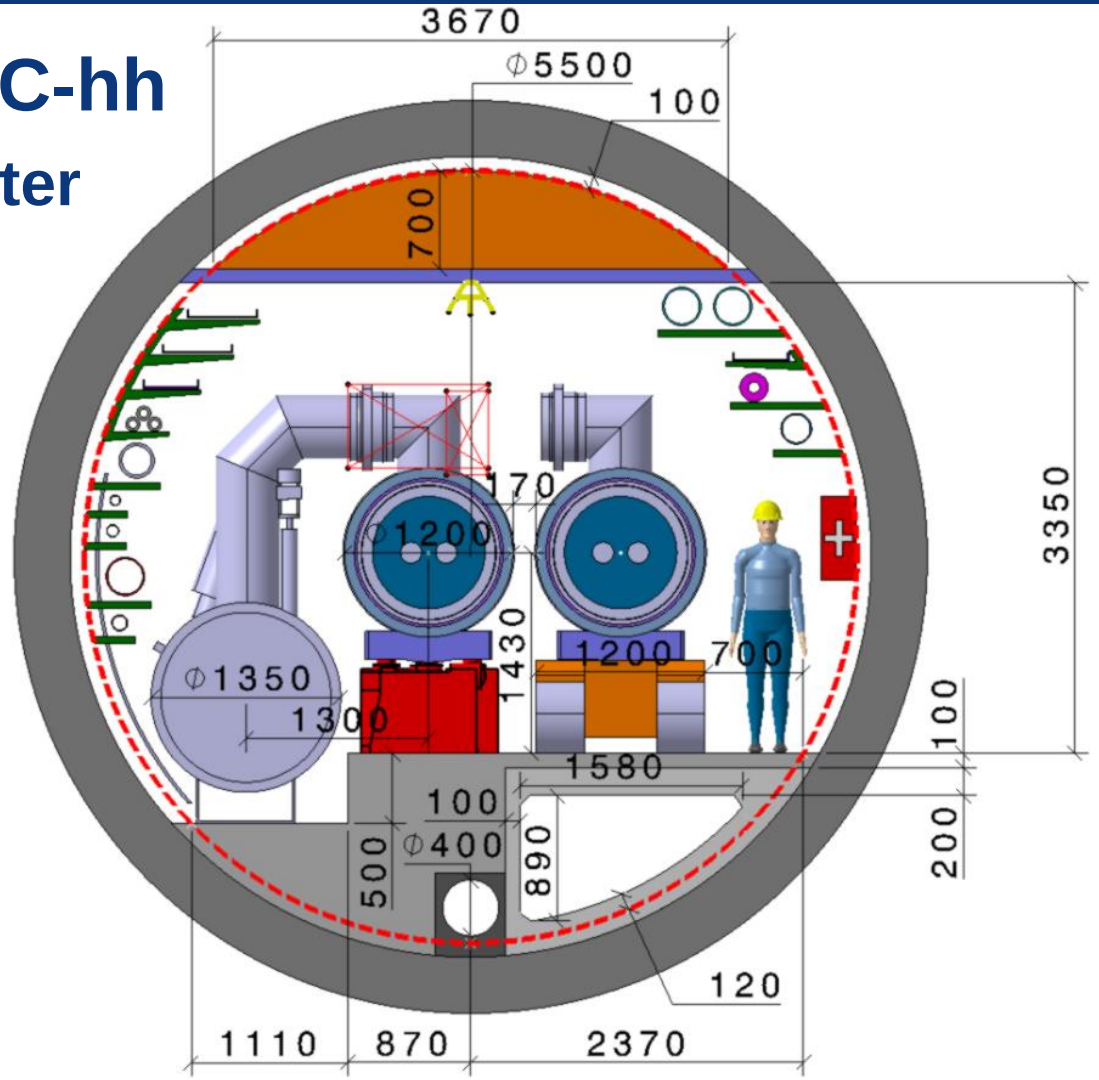

- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

# FCC-tunnel integration in the arcs

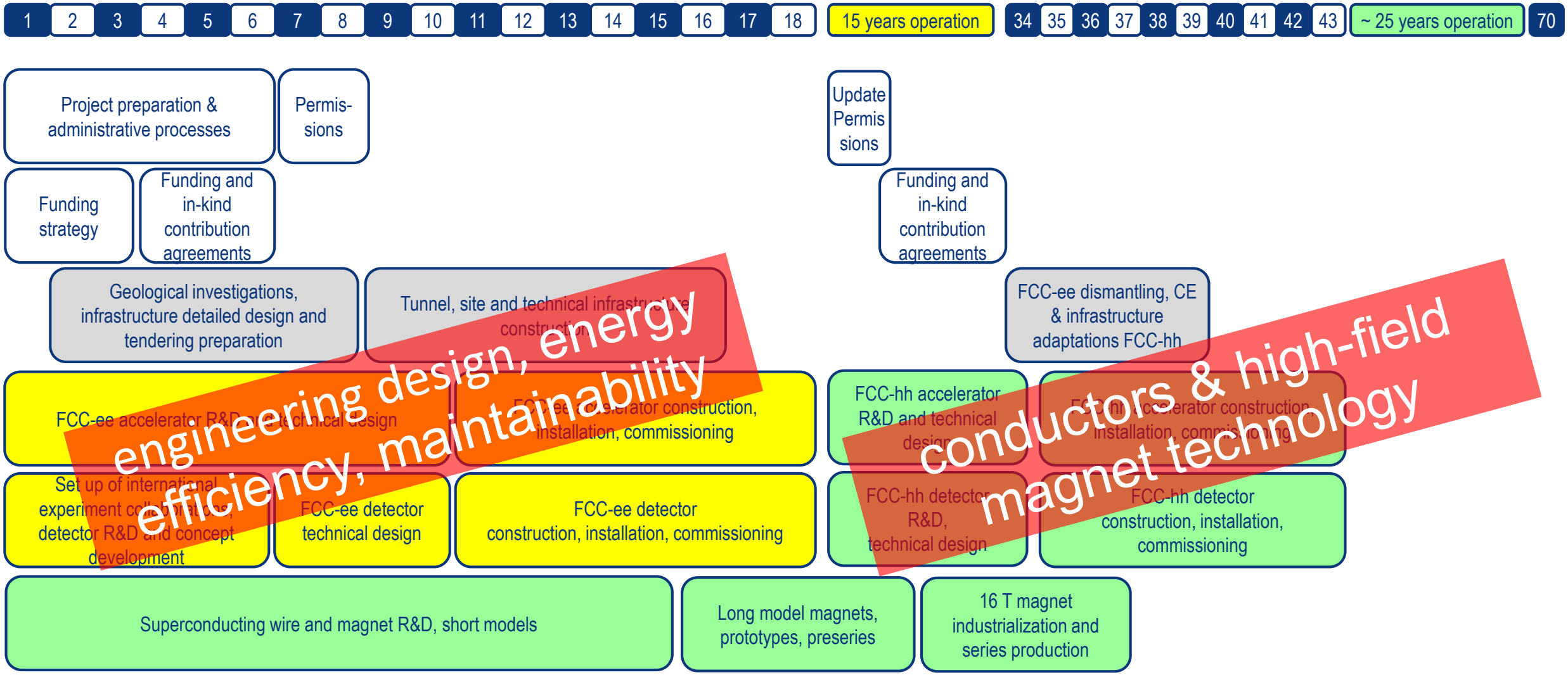
**FCC-ee** **FCC-hh**

**5.5 m inner diameter**



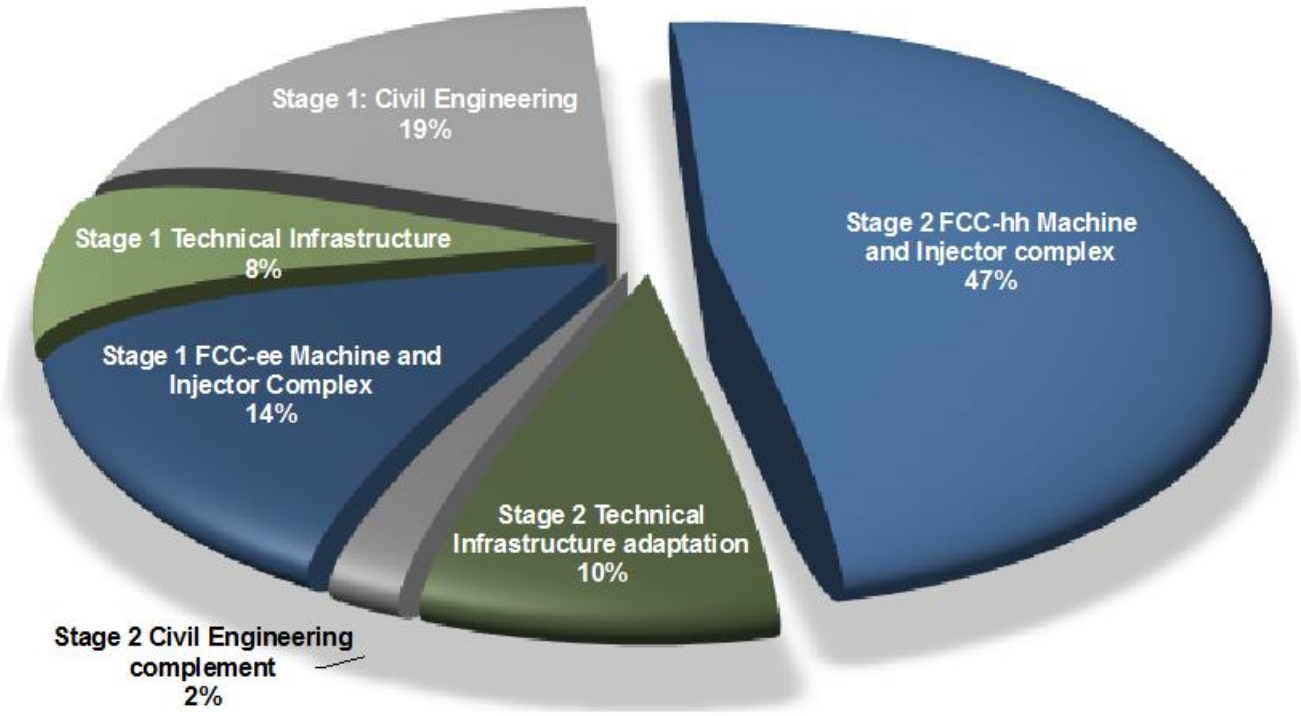



# FCC integrated project technical schedule



# 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/

# 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 feasibility study: main challenges

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

## Financial feasibility

cost of tunnel: ~5.5 BCHF; FCC-ee: ~5-6 BCHF; FCC-hh: ~17 BCHF (if after FCC-ee)

→ cannot be funded only from CERN's (constant) budget + "one-off" contributions from non-Member States → need new mechanisms (global project funding model; EC? private?)

**1st priority of feasibility study: find ~ 5 BCHF for the tunnel from outside CERN's budget**

## Technical and administrative feasibility of tunnel

- ❑ highly-populated area; two countries with different legislative frameworks
- ❑ land expropriation and reclassification
- ❑ high-risk zones
- ❑ environmental aspects

**1st priority of feasibility study: no show-stopper for ~100 km tunnel in Geneva region**

## Technologies of machine and experiments

- ❑ huge challenges, but under control of our scientific community
- ❑ pressing environmental aspects: energy, cooling, gases, etc.

**1st priority of feasibility study: magnets; minimise environmental impact; energy efficiency & recovery**

## Gathering scientific, political, societal and other support

→ requires "political work" and communication campaign for "consensus building" with governments and other authorities, scientists from other fields, industry, general public, etc.

→ **can FCC be a facility also for other disciplines** (nuclear science, photon science, etc.)**?**

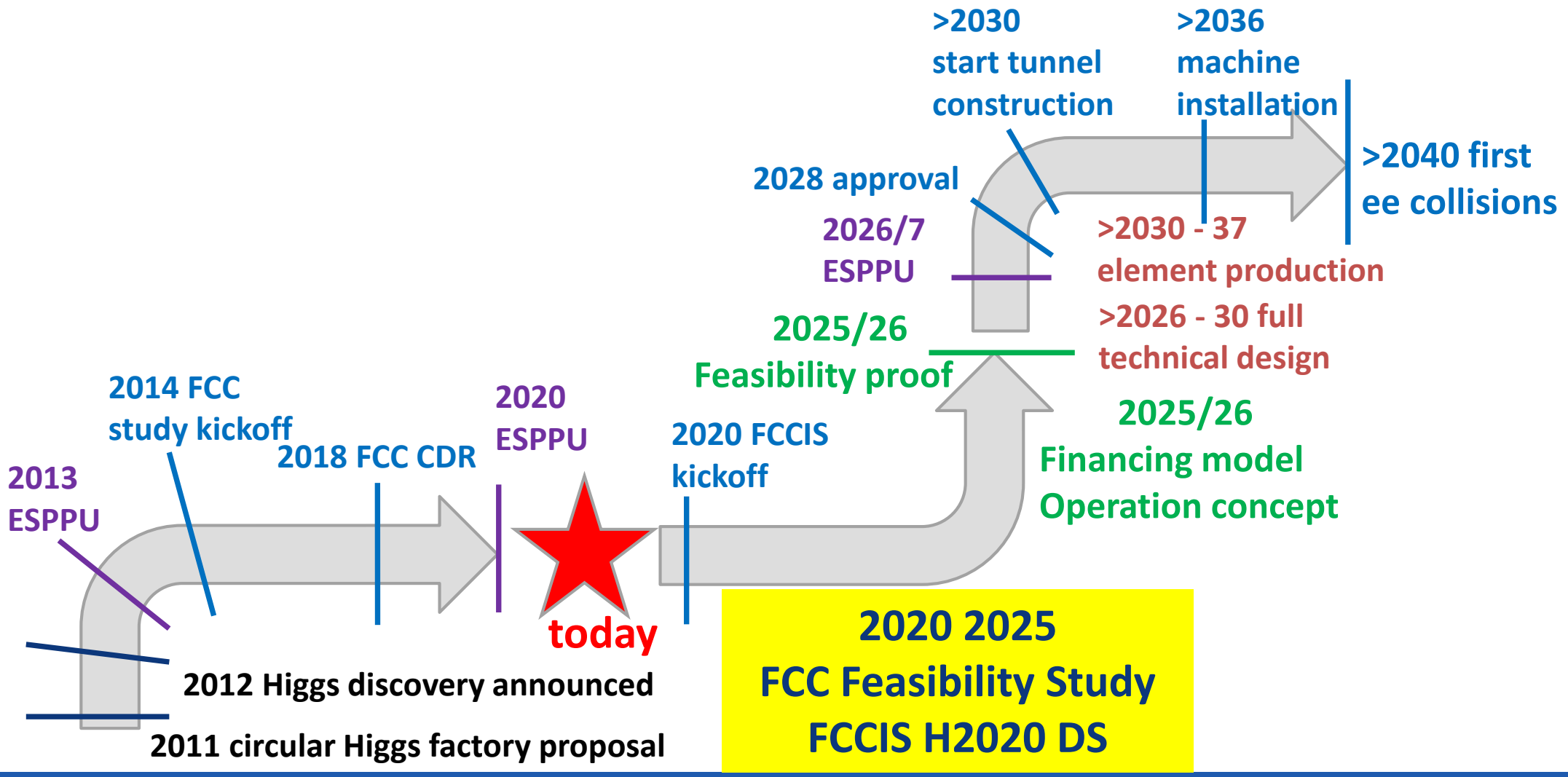
→ creative and proactive ideas for technology transfer from FCC to society

# Feasibility Study of FCC integrated project

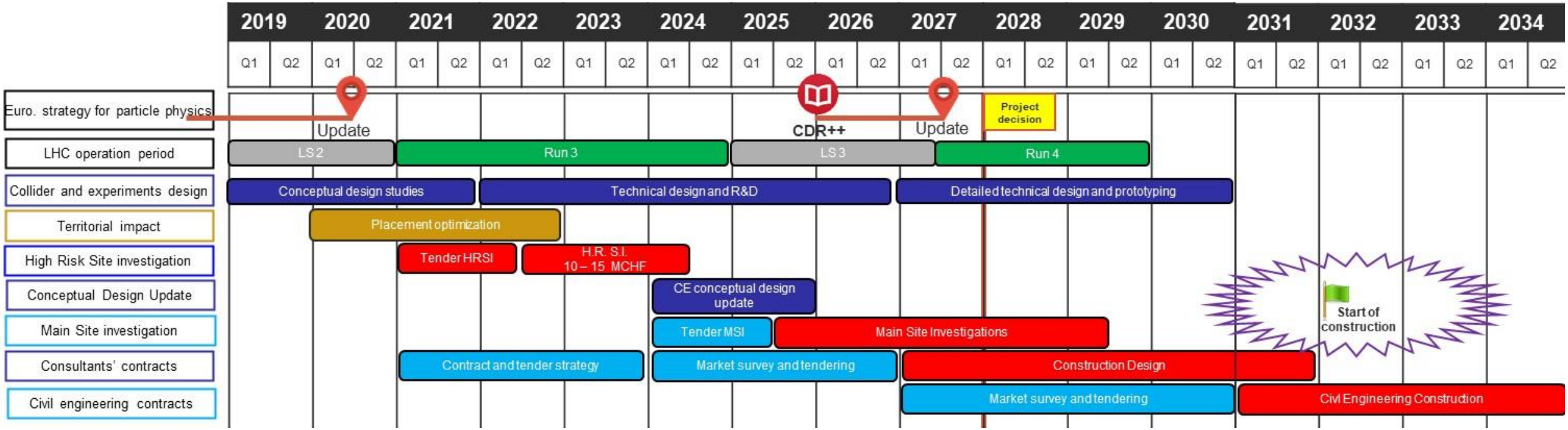
**Feasibility study to be delivered end 2025** as **input for next ESPP Update expected by 2026/2027, to enable a project decision**:

- ***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 !

# FCC roadmap towards stage 1

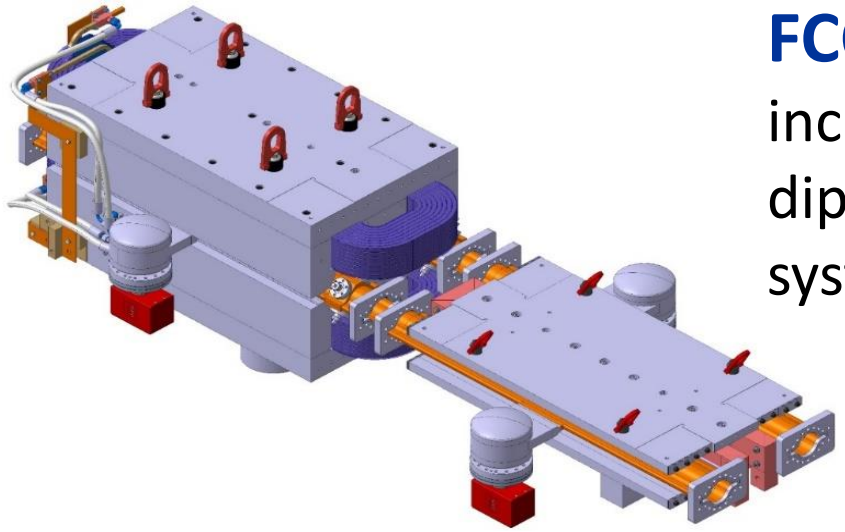


# CE preparatory activities 2020 - 2030



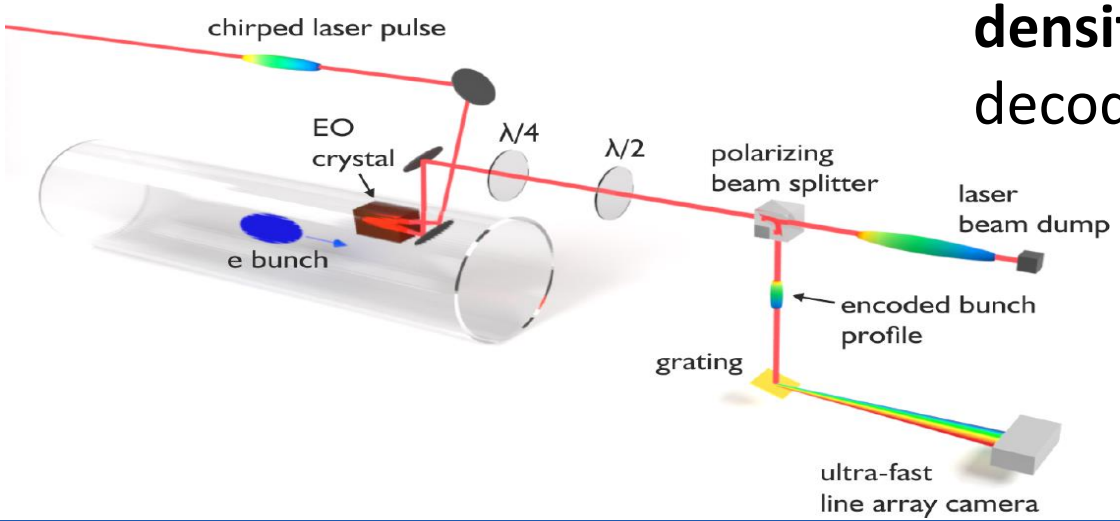

- technical schedule of main processes leading to start of construction begin 2030ies
- for proof of principle feasibility: high risk area site investigations, 2022 – 2024
- followed by update of civil engineering conceptual design and CE cost estimate 2025

# 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);

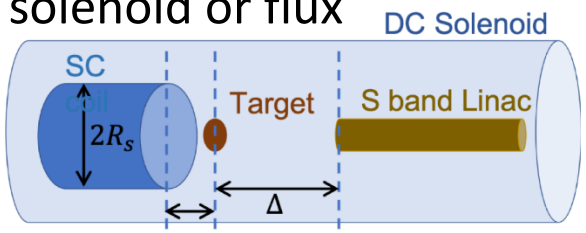
**polarimeter** ; **luminometer**

# 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

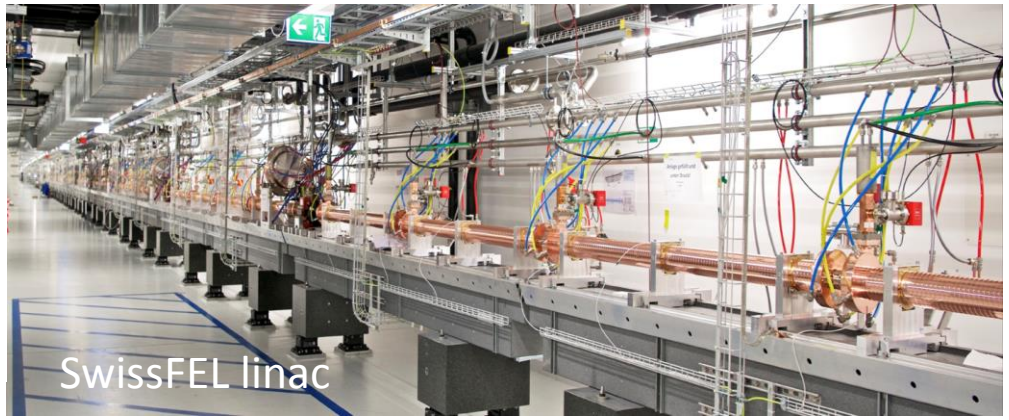
target with DC SC solenoid or flux concentrator



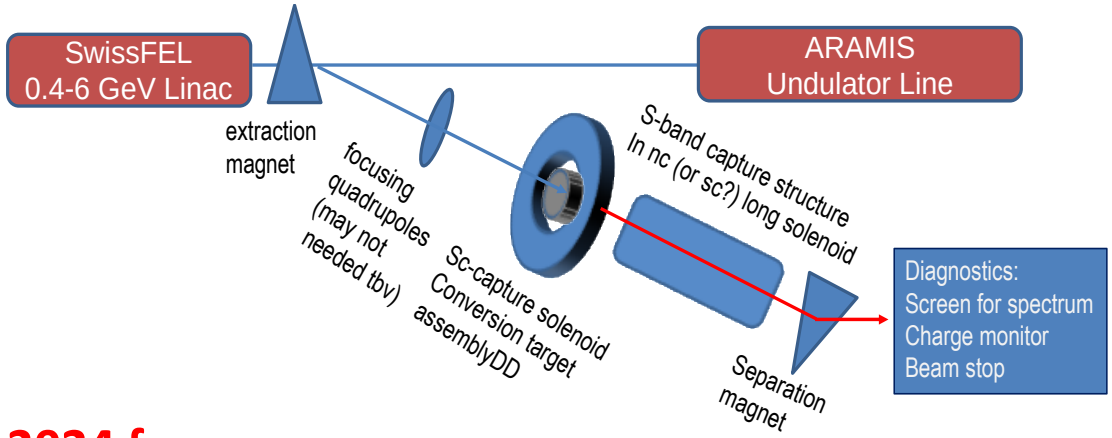

## positron capture linac

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



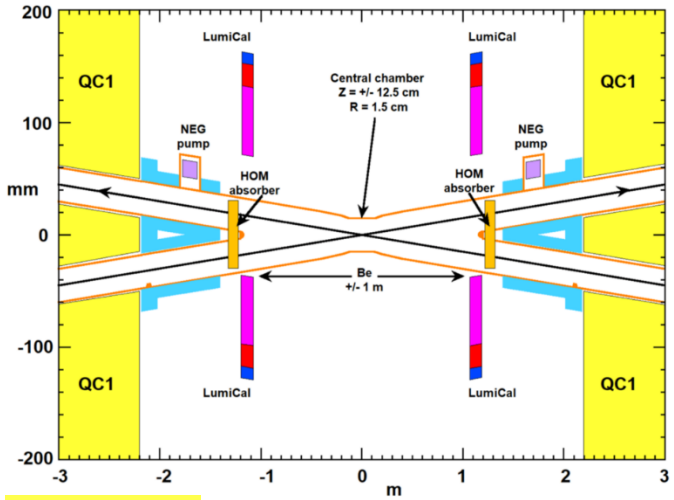

## beam test of $e^+$ source & capture linac at SwissFEL – yield measurement



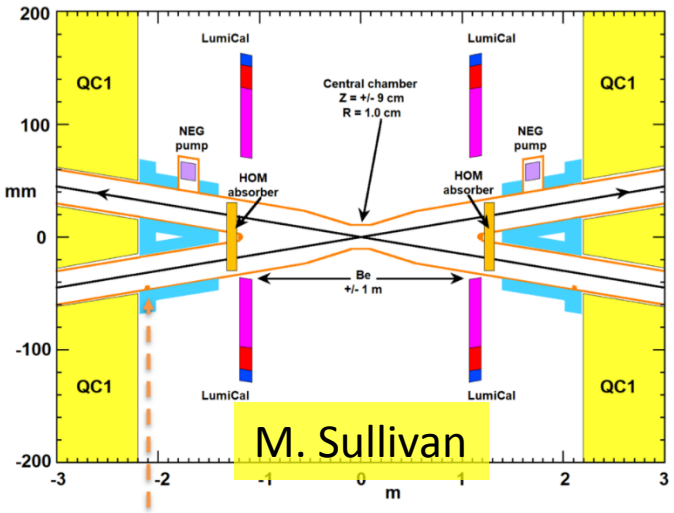

**strong support from Switzerland via CHART II program 2019 – 2024 for FCC-ee injector, HFM, beam optics developments, geology and geodesy activities.**

# FCC-ee Machine Detector Interface

Baseline, updated picture (SR masks)




1 cm radius central chamber



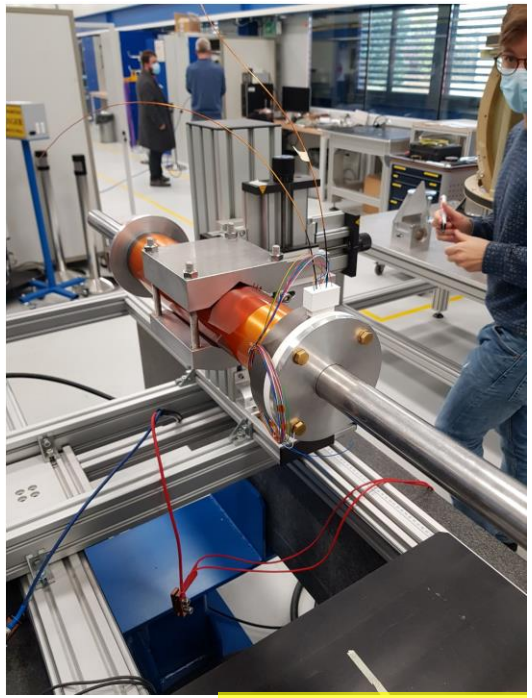

M. Sullivan

M. Boscolo

smaller IR chamber,
no longer trapped HOM

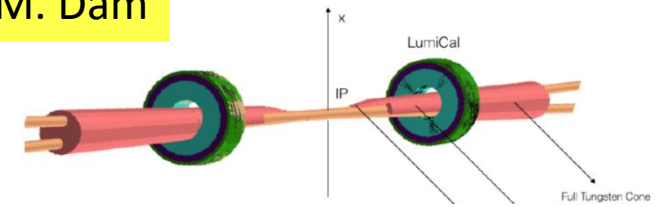
start of 3D mechanical
design & integration

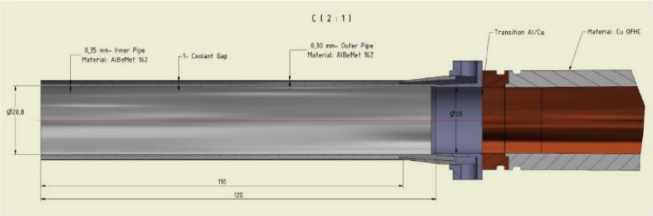
Q1 prototype, measured
multipoles very small,
confirming
design approach



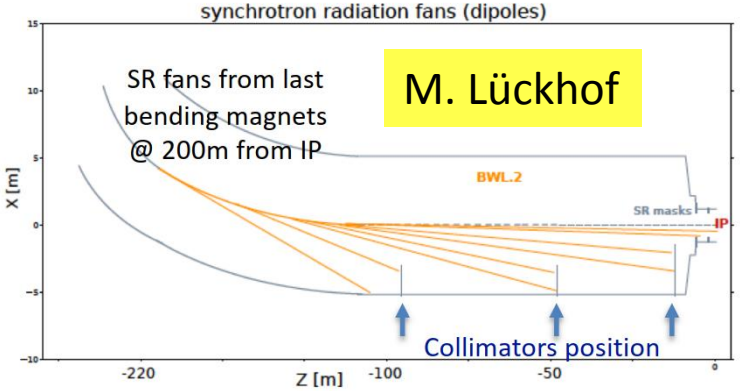
M. Koratzinos

M. Dam



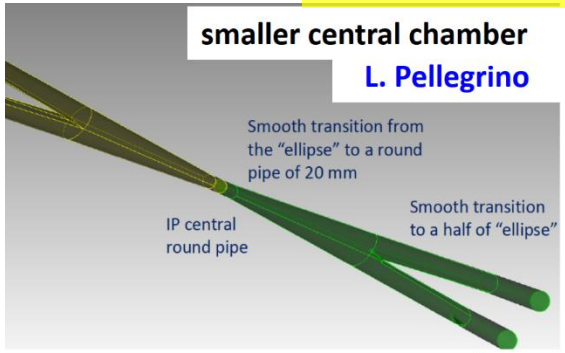



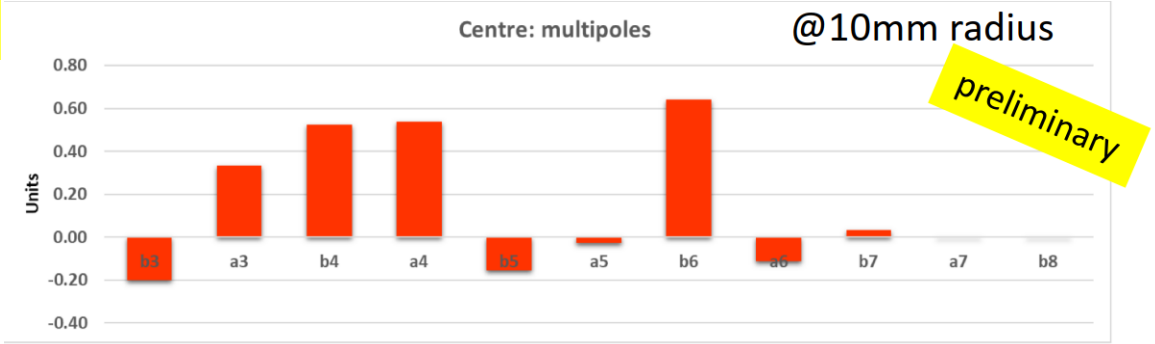
synchrotron radiation fans (dipoles)




M. Lückhof

L. Pellegrino



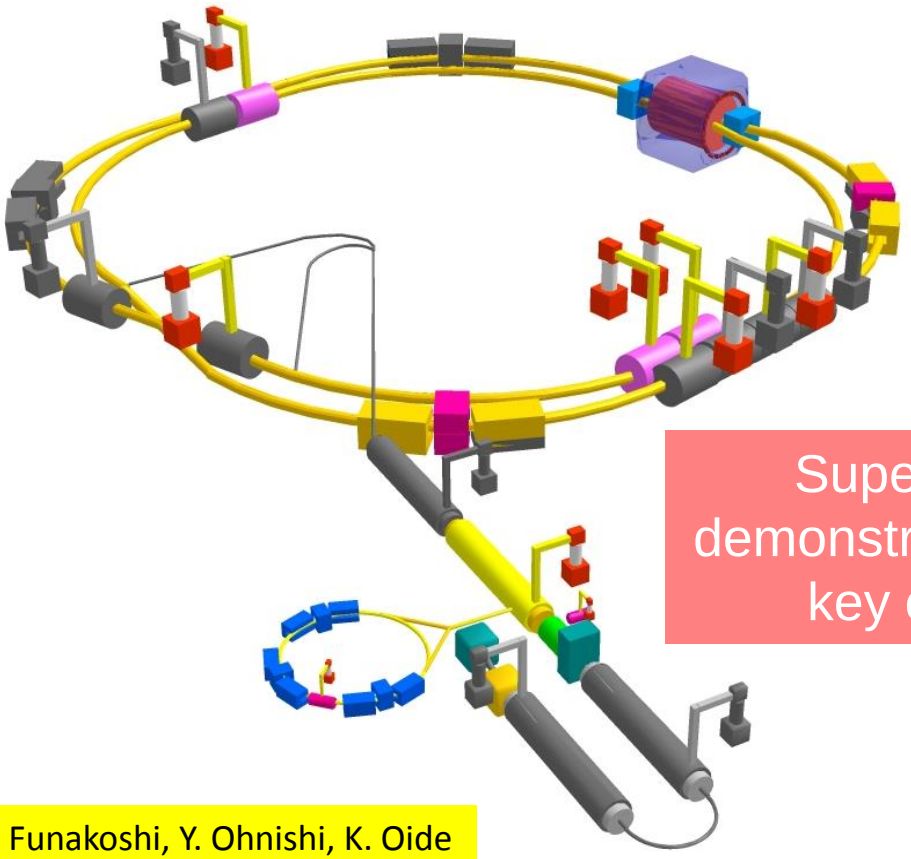




Carlo Petrone

Multipoles calculated up to B15, A15, but are all zero

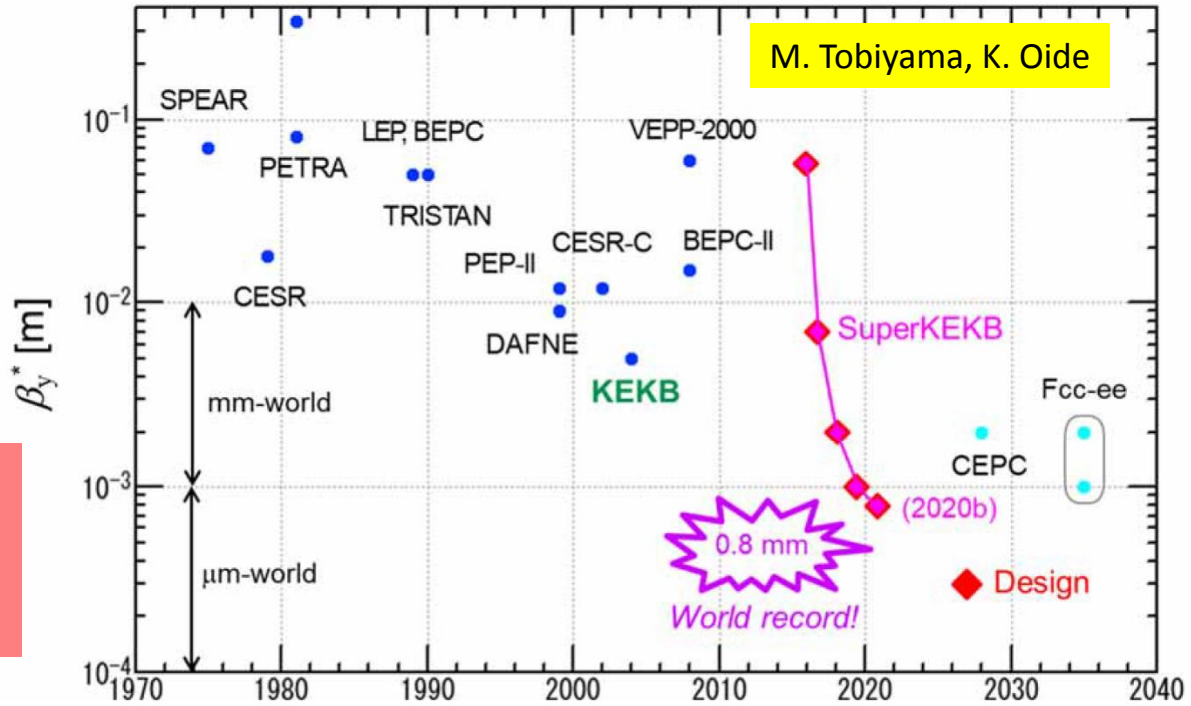
# SuperKEKB – pushing luminosity and β*

**Design**: double ring $e^+e^-$ collider as *B*-factory at 7($e^-$) & 4($e^+$) GeV; design luminosity ~8 x $10^{35}$ $cm^{-2}s^{-1}$; $\beta_y^*$ ~ 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




**$\beta_y^*$ = 0.8 mm achieved in both rings – using the FCC-ee-style "virtual" crab-waist collision scheme**

# Potential US/EIC – FCC collaboration

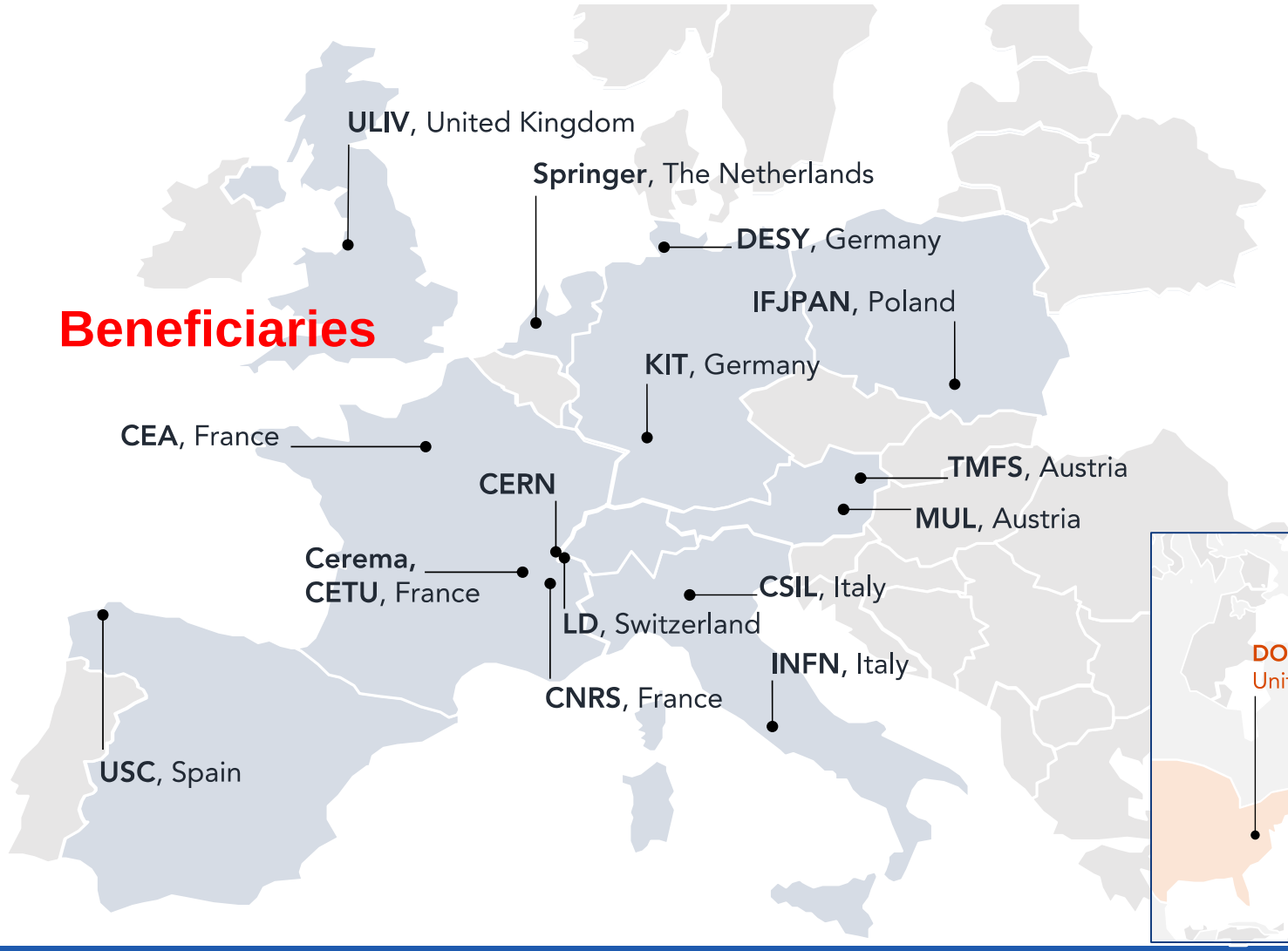
## NSLS-II, EIC & FCC-ee beam parameters

| | NSLS-II | EIC | FCC-ee-Z |
|---|---|---|---|
| Beam energy [GeV] | 3 | 10 (20) | 45.6 |
| Bunch population [$10^{11}$] | 0.08 | 1.7 | 1.7 |
| Bunch spacing [ns] | 2 | 10 | 15, 17.5 or 20 |
| Rms bunch length [mm] | 4.5 - 9 | 2 | 3.5 (SR) |
| Beam current [A] | 0.5 | 2.5 (0.27) | 1.39 |
| RF frequency [MHz] | 500 | 591 | 400 |

**Similarity of several parameters strongly suggests collaboration to exploit synergies in areas such as beam instrumentation, SRF, vacuum system with SR handling, etc.**

**→ two dedicated sessions at FCC-IS kick-off meeting towards EIC-FCC collaboration**

# H2020 DS FCC Innovation Study 2020-24




| Topic | INFRADEV-01-2019-2020 |
|---|---|
| Grant Agreement | FCCIS 951754 |
| Duration | 48 months |
| From-to | 2 Nov 2020 – 1 Nov 2024 |
| Project cost | 7 435 865 € |
| EU contribution | 2 999 850 € |
| Beneficiaries | 16 |
| Partners | 6 |

# FCCIS Objectives (Description of Action)

- O1: **Design a circular luminosity frontier particle collider** with a research programme to remain at the forefront of research
- O2: **Demonstrate the technical and organizational feasibility** of a 100 km long, circular particle collider
- O3: **Develop an innovation plan for a long-term sustainable research infrastructure** that is seamlessly integrated in the European research landscape
- O4: **Engage stakeholders** from different sectors of the society
- O5: **Demonstrate the role and impact of the research infrastructure in the innovation chain**, focusing on responsible resource use and managing environmental impacts

## Luminosity-frontier Collider Design

FCCIS Result

High Technology Readiness

9 8 7 6 5 4 3 2 1

Low Technology Readiness

4

Beam **optics validated** at BINP, DESY, INFN, KIT. Components specified. **Performance calculated & simulated**.

## Research Infrastructure Placement

FCCIS Result

High Technology Readiness

9 8 7 6 5 4 3 2 1

Low Technology Readiness

5

Ecodesigned **layout** and **responsible resource use validated** for the relevant environment.

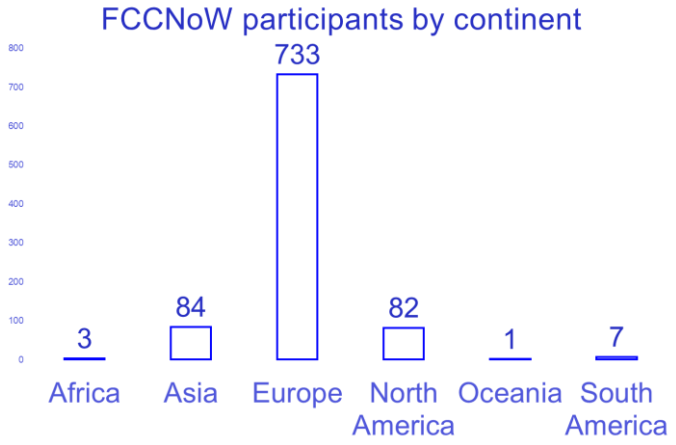
# FCC November Week 2020

- Kick-Off FCC Innovation Study

  (organisers M. Benedikt, J. Gutleber, F. Zimmermann)

  **FCC-ee Collider Design (WP2)**
  **Integrate Europe (WP3)**
  **Impact & Sustainability (WP4)**
  **Leverage & Engage (WP5)**


910 registered participants

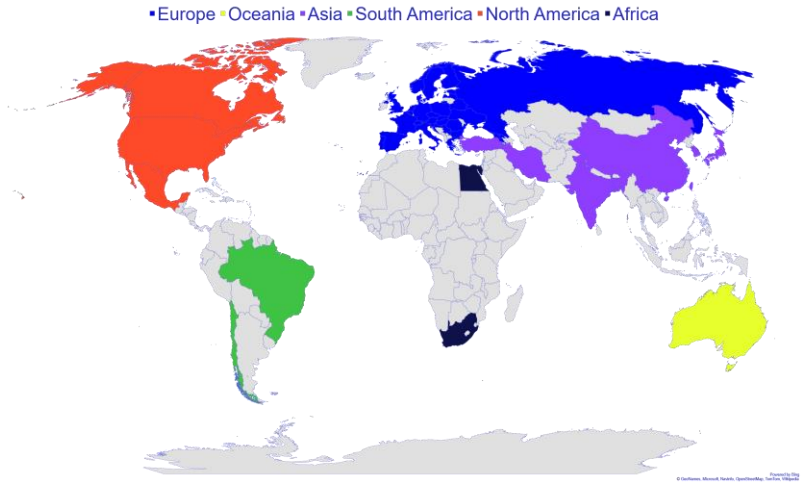



- 4th FCC Physics & Experiments Workshop

  (organisers A. Blondel, M. Mangano, M. Dam, P. Janot)

  **Physics Prospects, Detector development, Collaboration Forming, Physics Benchmark Measurements, New Ideas and Challenges, Detector Technologies, Experimental Environment, and Machine-Detector Interface.**

**http://cern.ch/FCCNoW2020**



# collider placement optimisation

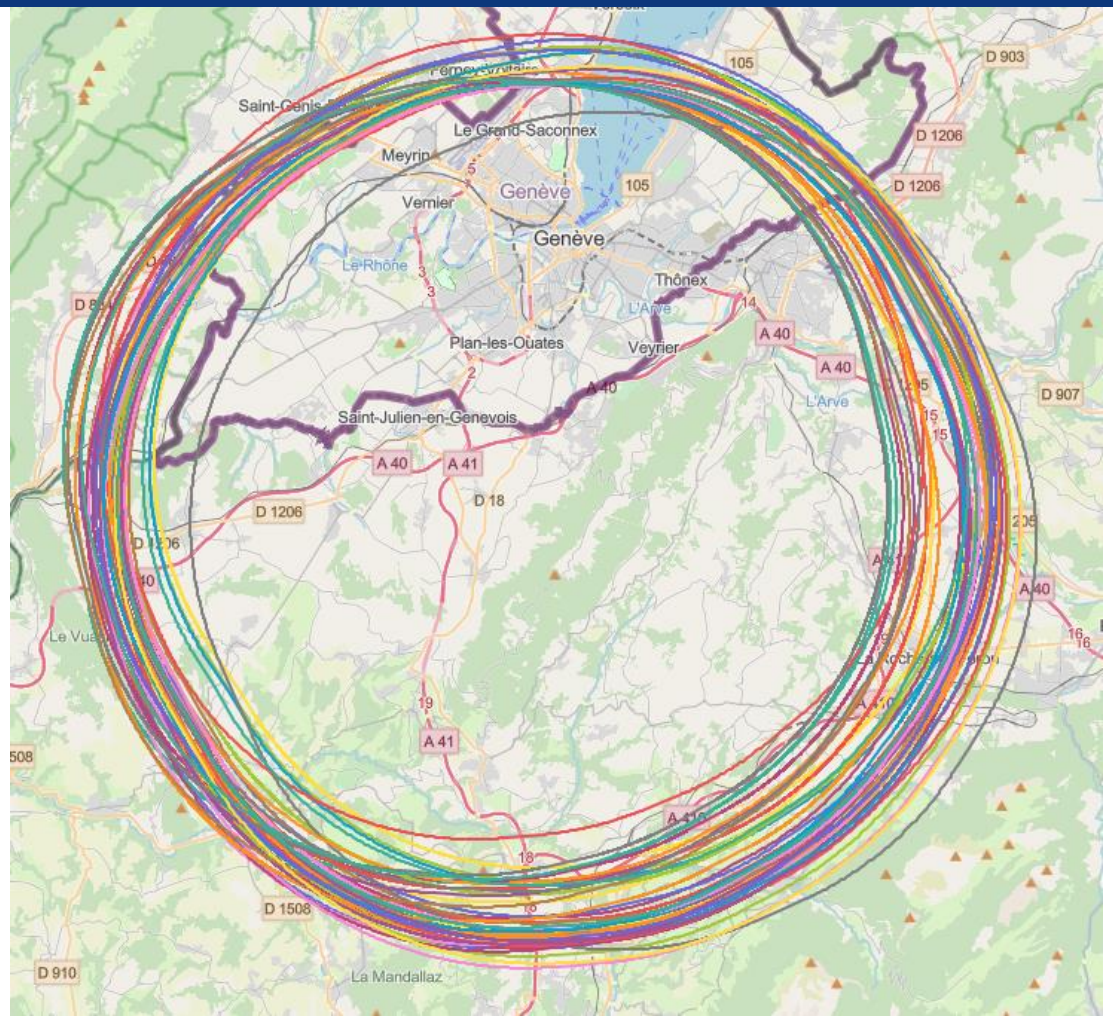
layout & placement optimisation across both host states (Switzerland and France) ;

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

diverse requirements and constraints:

- permitting **world-leading 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



# 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

# 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 !**