FCC Status

M. Koratzinos

gratefully acknowledging input from the FCC coordination group, the global FCC design study team and all other contributors

Slides by M. Benedikt

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; and **E-JADE,** contract no. 645479*

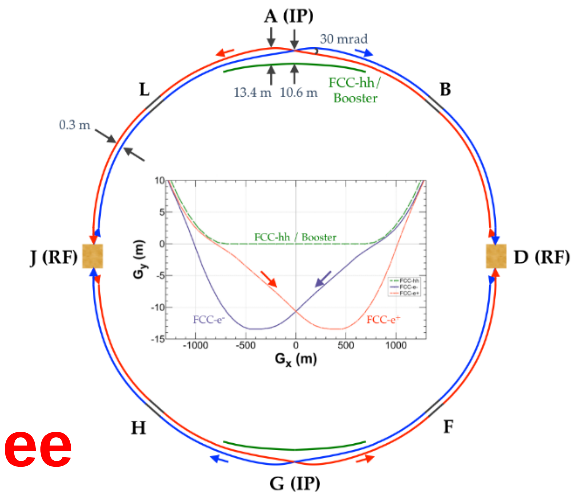
European Commission | Horizon 2020 European Union funding for Research & Innovation

photo: J. Wenninger

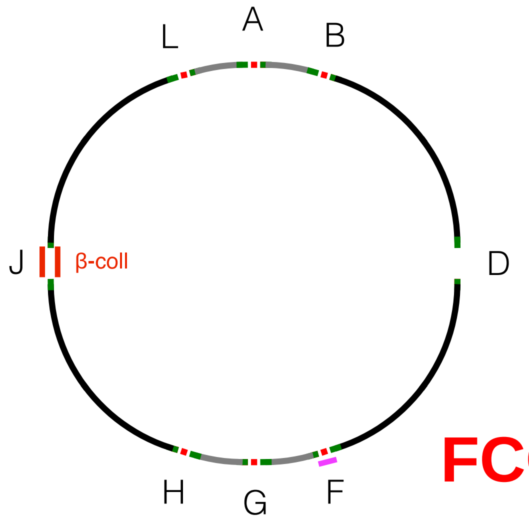
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive cost-effective program maximizing physics opportunities

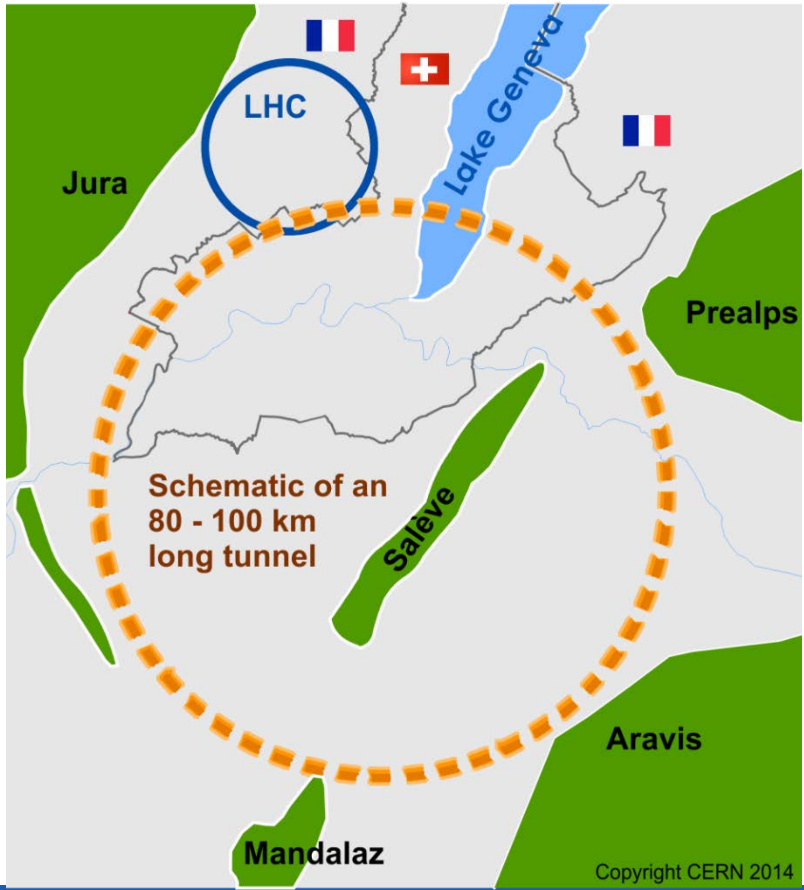
- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs factory, EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- Complementary physics
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP.



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

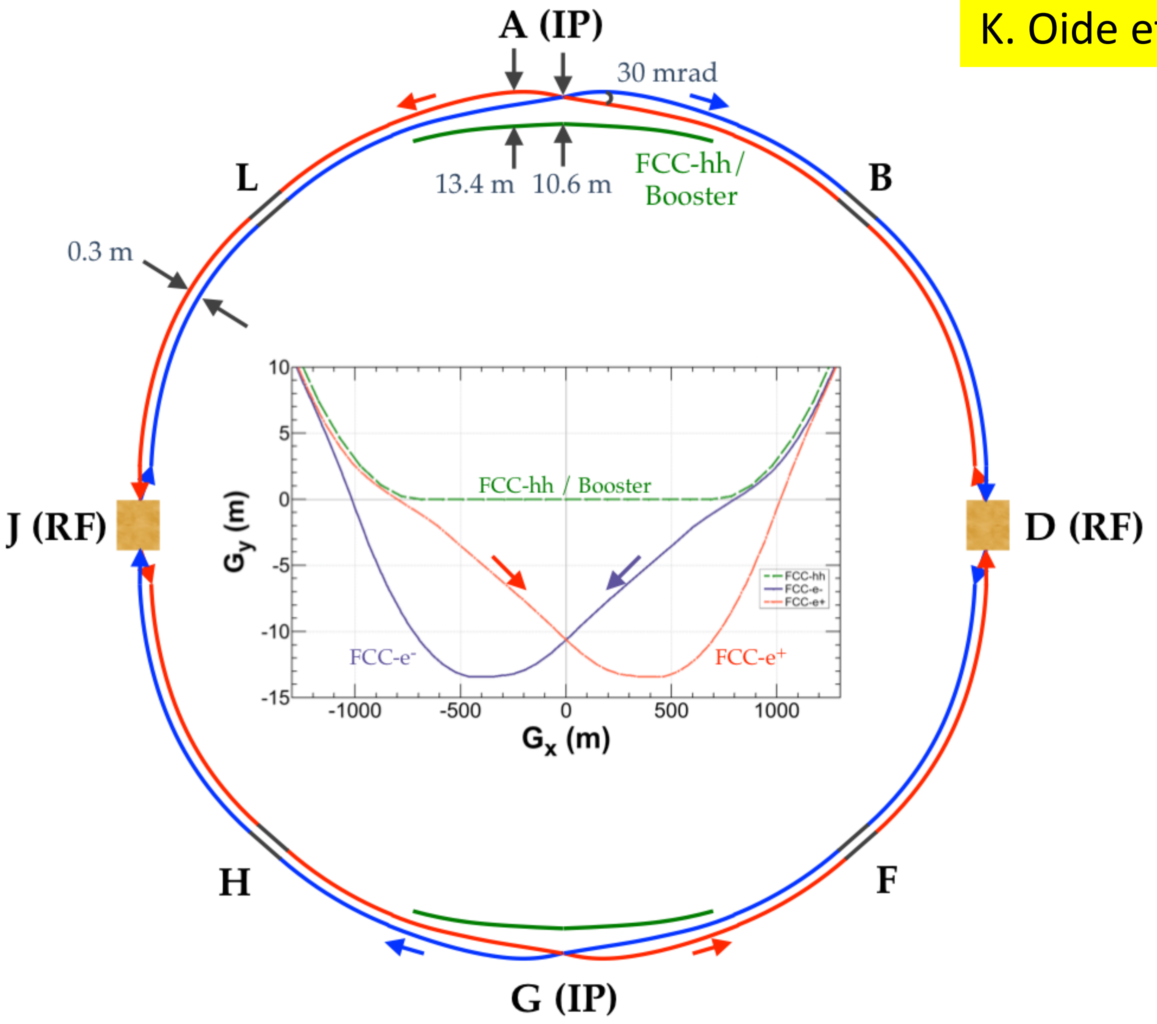
presently 2 IPs (alternative layouts with 3 or 4 IPs under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**

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**

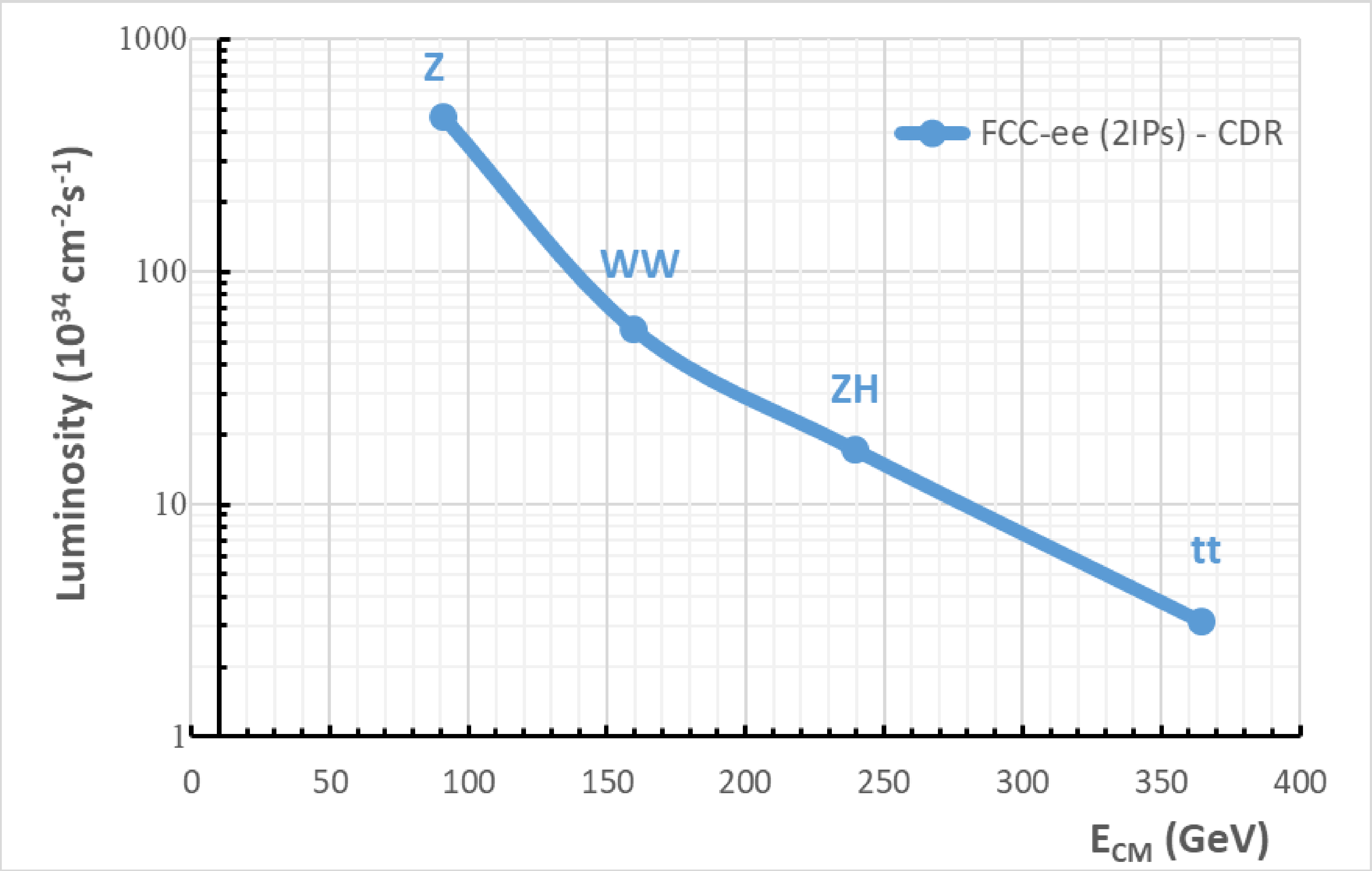
K. Oide et al.



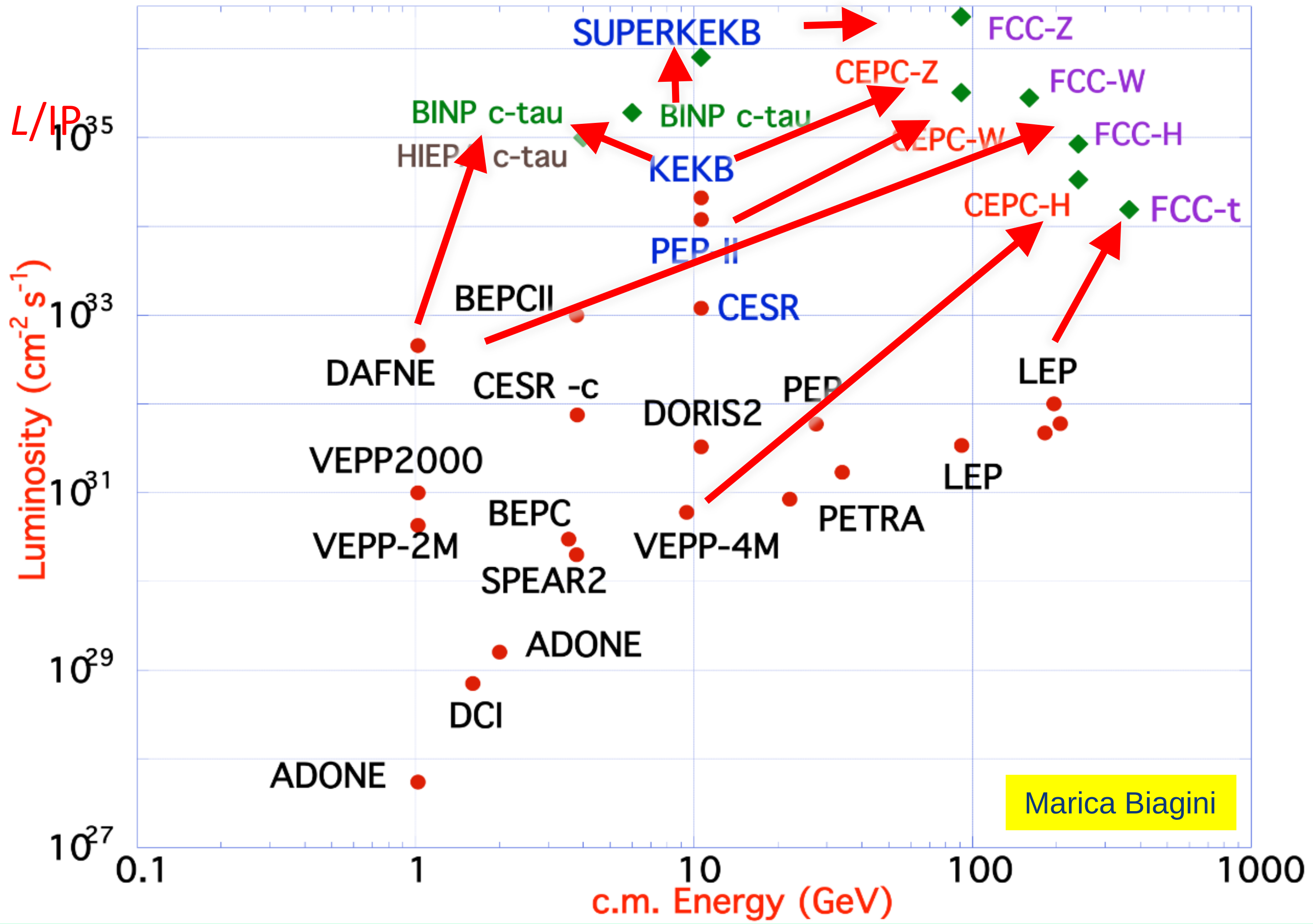
FCC-ee Collider Parameters

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 luminosity vs energy



FCC-ee design
based on lessons and techniques from past colliders



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

DAFNE: crab waist, double ring

SuperB-factories, SuperKEKB: low β_y^*

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

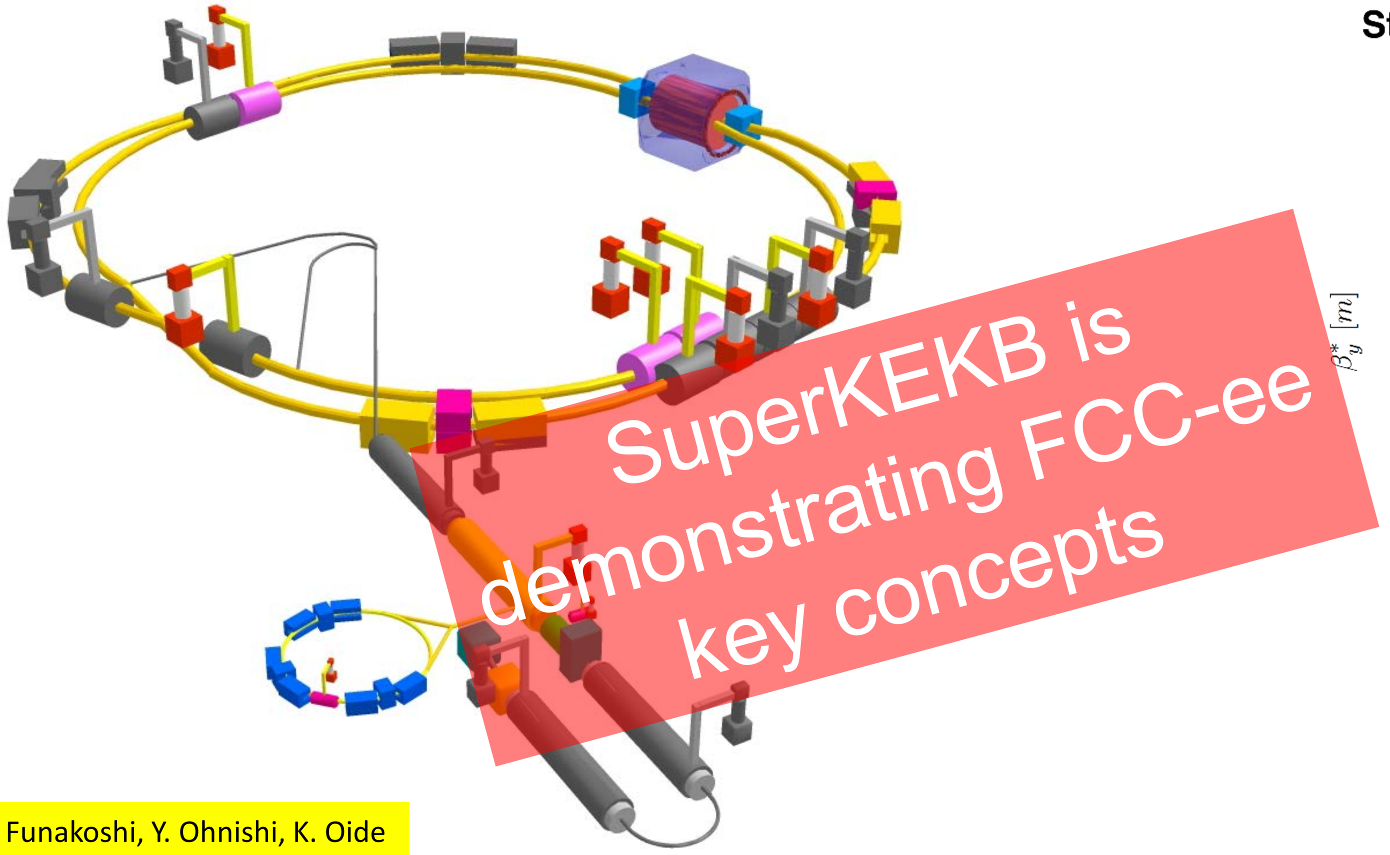
KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

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

SuperKEKB – pushing luminosity and β*

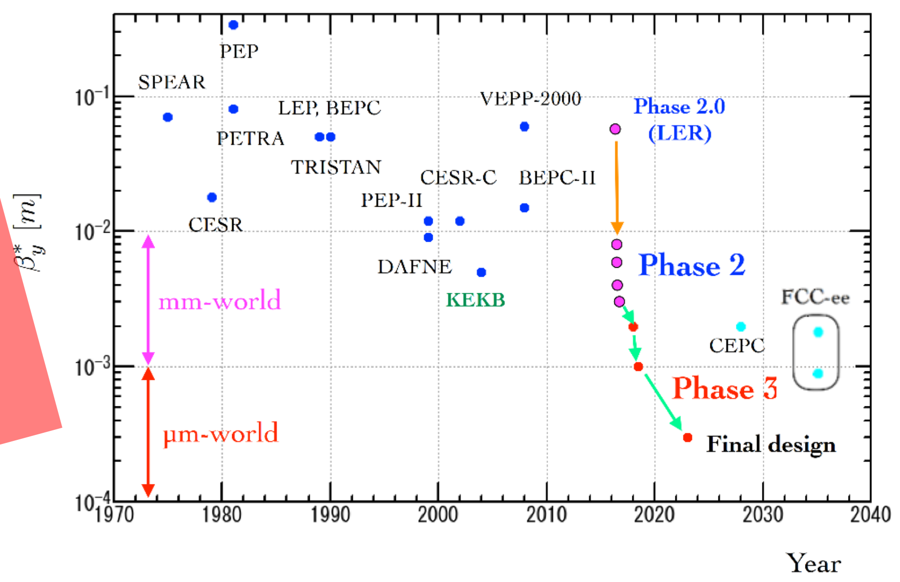
double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; β_y^* ~ 0.3 mm; nano-beam – large crossing angle collision scheme (crab waist w/o sextupoles); beam lifetime ~5 minutes; top-up injection; e^+ rate up to ~ 2.5 10^{12} /s ; under commissioning



SuperKEKB is demonstrating FCC-ee key concepts

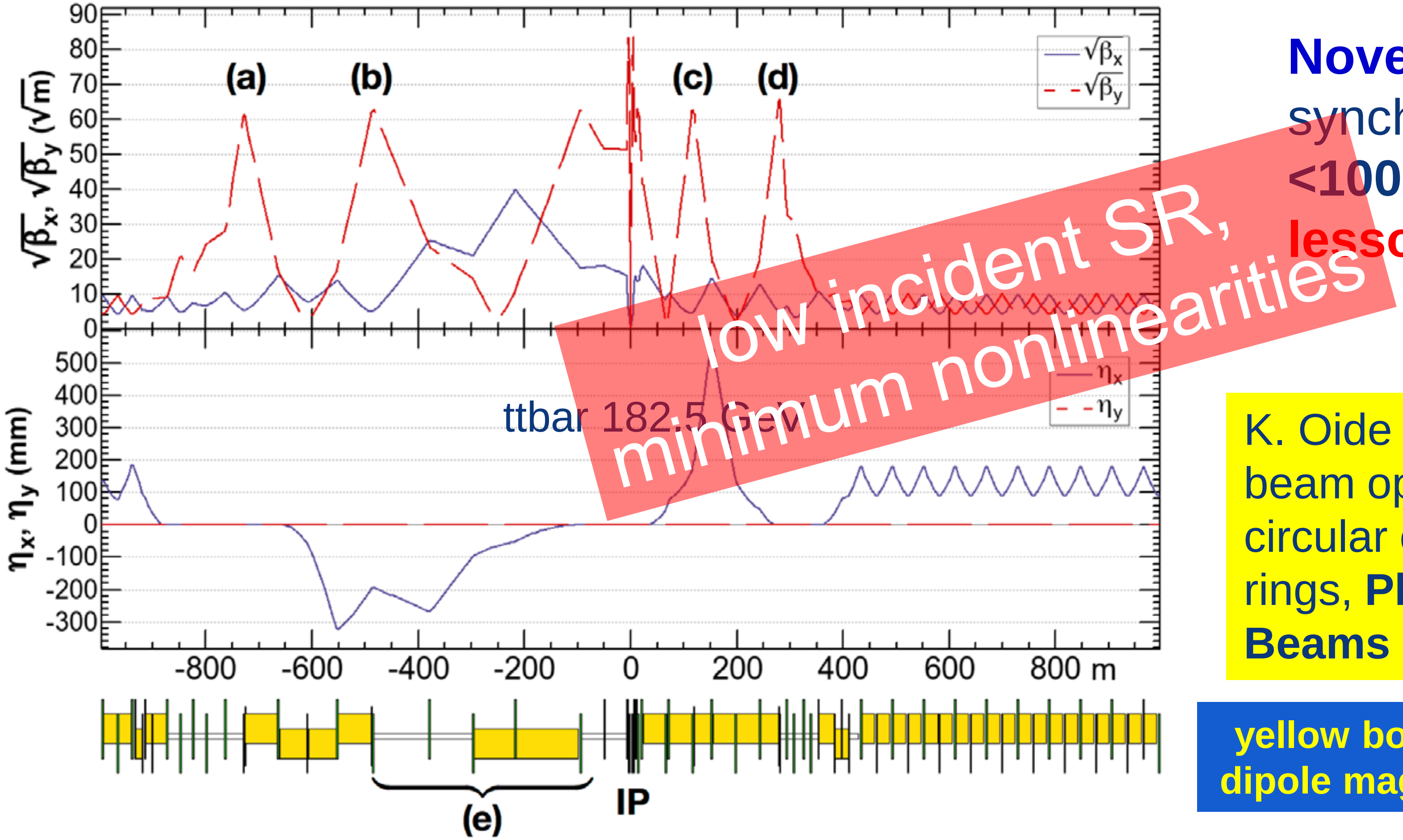
Y. Funakoshi, Y. Ohnishi, K. Oide

Strategy of beta squeezing for Phase 2 and Phase 3



β_y^* ≤2 mm achieved!

FCC-ee asymmetric crab-waist IR optics



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, K. Oide, et al.

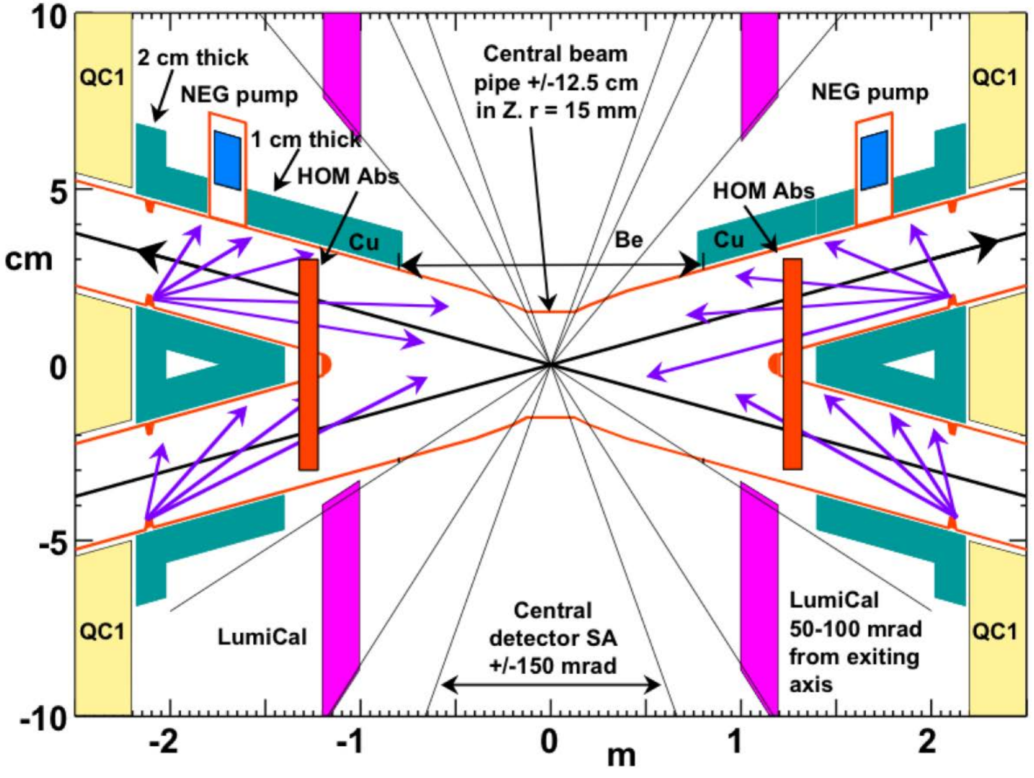
K. Oide et al., Design of beam optics for the future circular collider e^+e^- collider rings, **Phys. Rev. Accel. Beams 19**, 111005 (2016).

yellow boxes: dipole magnets

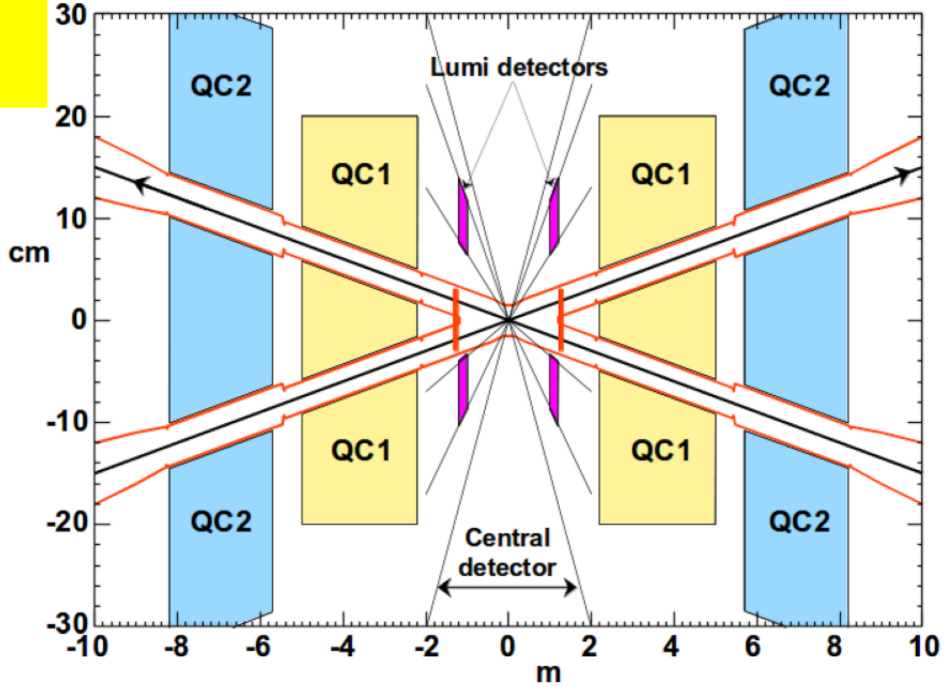
4 sextupoles (a–d) for local vertical chromaticity correction combined w. crab waist, optimized for each working point – **novel "virtual crab waist", standard crab waist demonstrated at DAFNE**

FCC-ee Interaction Region Design

A. Novokhatski, M. Sullivan, E. Belli, M. Gil Costa, and R. Kersevan, *Unavoidable trapped mode in the interaction region of colliding beams*, **Phys. Rev. Accel. Beams 20**, 111005 (2017)

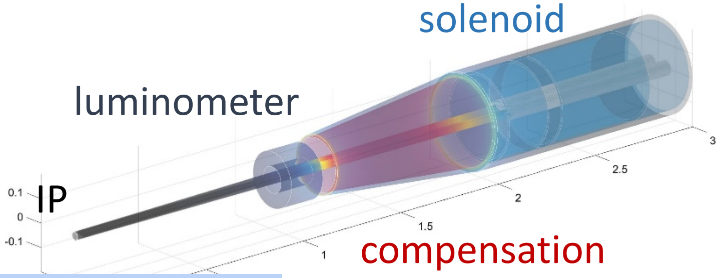


3D sketch of key IR systems over first 3 m from IP



M. Boscolo, H. Burkhardt, and M. Sullivan, *Machine detector interface studies: Layout and synchrotron radiation estimate in the future circular collider interaction region*, **Phys. Rev. Accel. Beams 20**, 011008 (2017)

<u>heat loads:</u> rad Bhabha (kW), beamstrahlung (MW), res. wall (kW), HOMs, quadr. synchrotron rad.



stiff-skeleton thin cryostat?

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.

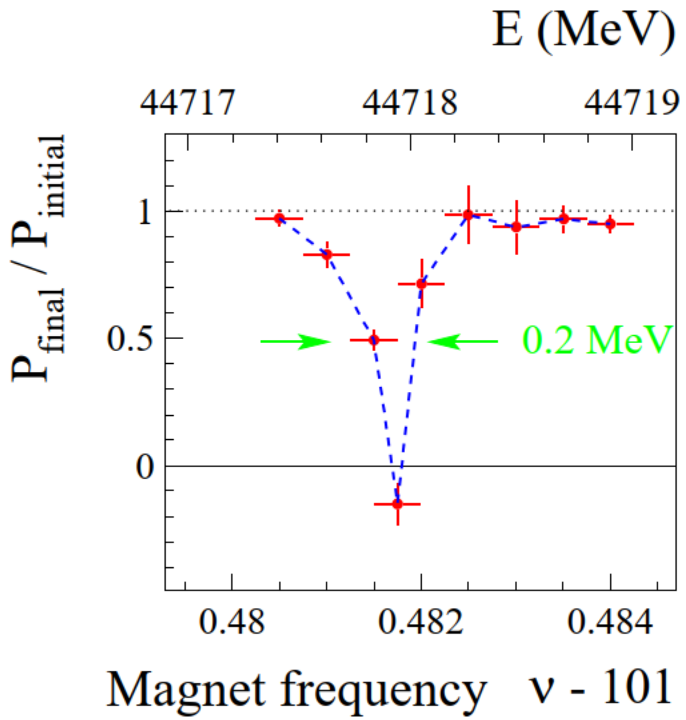
Transverse polarization

- FCC-ee has a statistical precision on the mass and width of the Z (due to its high luminosity) of 4keV and 7keV
- To use this accuracy, the beam energy of FCC-ee at the Z (and to a lesser extend at the WW threshold) should be known extremely accurately
- In a circular collider, there is a method with excellent (instantaneous) precision, the resonant depolarization method: the spin tune of a transversely polarized electron is proportional to its energy
- By depolarizing a previously polarized bunch (using a resonance) we can measure the (non-integer) part of the spin tune
- Instantaneous accuracy is exquisite: 200keV

$$E = \nu \frac{mc^2}{q'/q_0}$$

$$E[MeV] = 440.64846 \cdot \nu$$

This has been done before, at LEP
It is not easy, we need dedicated hardware (wigglers, polarimeter) and many effects need to be accounted for…
….but the reward is huge
We plan to repeat the LEP campaign with an improvement of one (or two) orders of magnitude
Ref: A. Blondel et al., **Polarization and Centre-of-mass Energy Calibration at EFF-ee**, e-Print: arXiv:1909.12245 **[physics.acc-ph]**



From the LEP campaign: 200 keV instantaneous accuracy

A comment about longitudinal polarization

- The FCC-ee e^+ and e^- beams will not be longitudinally polarized
  - Unlike at linear colliders where 80% polarized e^- (and 30% e^+) can be injected and accelerated
- What is the effect of longitudinal polarization at 240/250 GeV for Higgs couplings?
  - Polarization causes σ_{HZ} to increase by 1.4 (1.08) in $e^-_L e^+_R$ ($e^-_R e^+_L$) configuration
    - Similar increase for the backgrounds (except for WW : 2.34 and 0.14)
      - ➔ Precision better by 20% with the same luminosity in the κ fits
  - EFT fits benefit from different polarization states to constrain additional operators
    - At circular colliders, constraints come from EW precision measurements
      - ➔ Precision still better by ~20% (or less) with the same luminosity in the EFT fits
      - ➔ The only coupling for which polarization brings significant gain is $g_{HZ\gamma}$,

        ...which is much better measured at a hadron collider (e.g., FCC-hh) anyway
- At the FCC-ee, longitudinal polarization is not worth the induced luminosity loss
  - NB. Without polarization, one year at the FCC-ee with 2 (4) IPs at $\sqrt{s}$ = 240 GeV offers the same Higgs coupling precision as 8 (14) years with ILC polarized e^+ and e^+
    - Similar remark holds for EWPO or top EW couplings measurements at other $\sqrt{s}$

For FCC-ee, beam polarization brings no information that cannot be obtained otherwise.

J. De Blas

The FCC-ee accelerator – did you know?

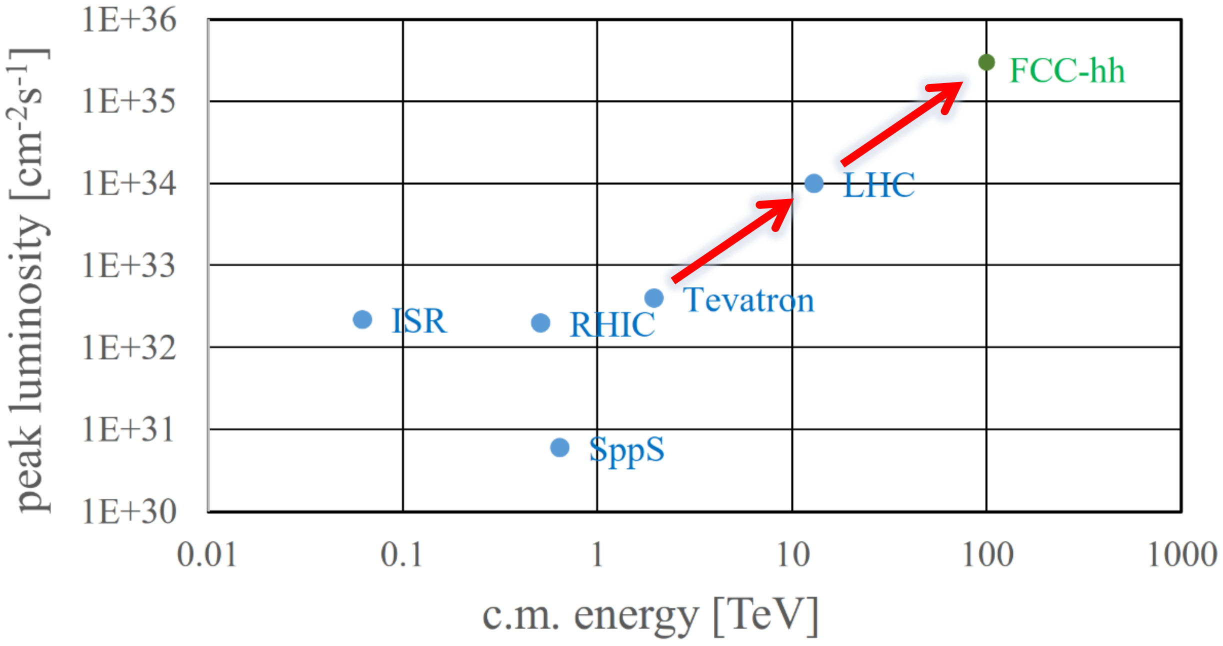
The FCC-ee accelerator is not simply a bigger LEP! It is a modern synchrotron that pushes the design envelope to the maximum.

- The luminosity is so high that the beams burn up very quickly (beam lifetime 12 minutes at the ZH). Mandatory to use a full-size booster – the injector is the same size as the main ring and injects at top energy)
- Full LEP physics dataset every 2 minutes.
- Beam energy will be known to (much) better than 100keV, whereas the (gravitational) effect of the moon passing overhead gives an energy change of 100MeV, one thousand times bigger.
- Colliding bunches must have the same charge to within 10% → bootstrapping
- Emittance blow up in the region ±2m from the IPs is equal to the emittance of the rest of the 100 kilometers – the area around the IP is very tricky and complex

FCC-hh (pp) collider parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.27	1.1	0.58
bunch intensity [10^{11}]	1	1	2.5	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.1	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.45	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	16	5 (lev.)	1
events/bunch crossing	170	1000	460	132	27
stored energy/beam [GJ]	8.4		1.4	0.7	0.36

FCC-hh: performance



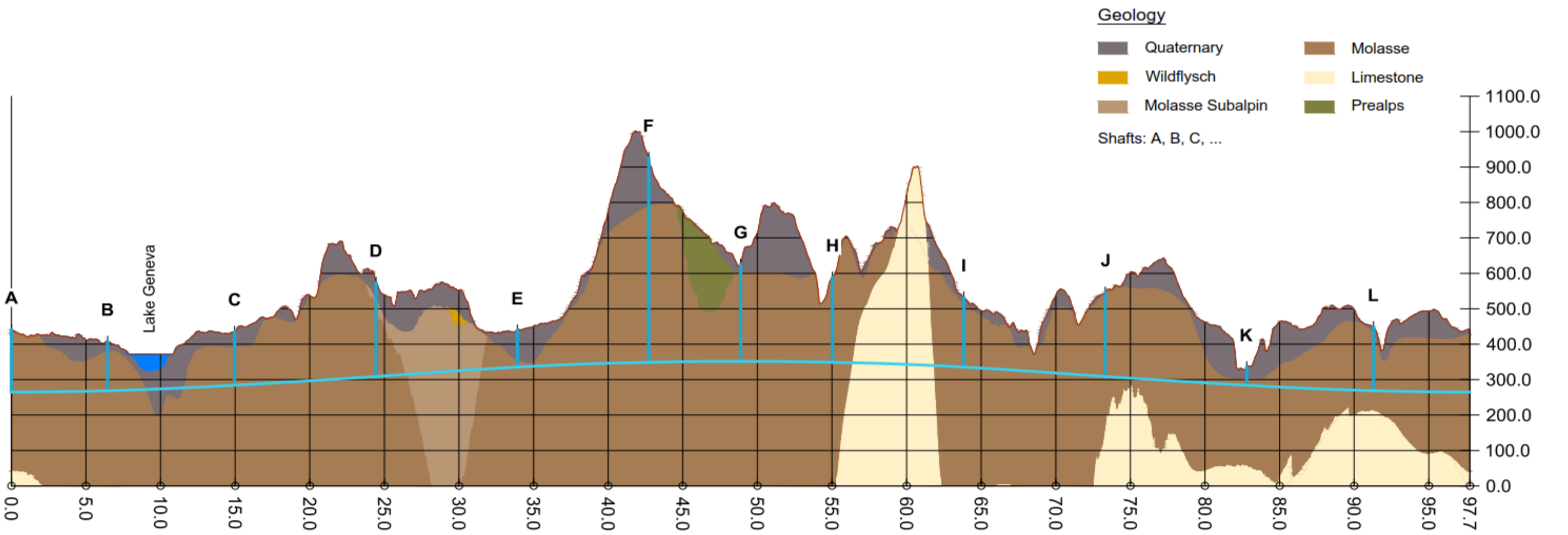
- **order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- **key technology: high-field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

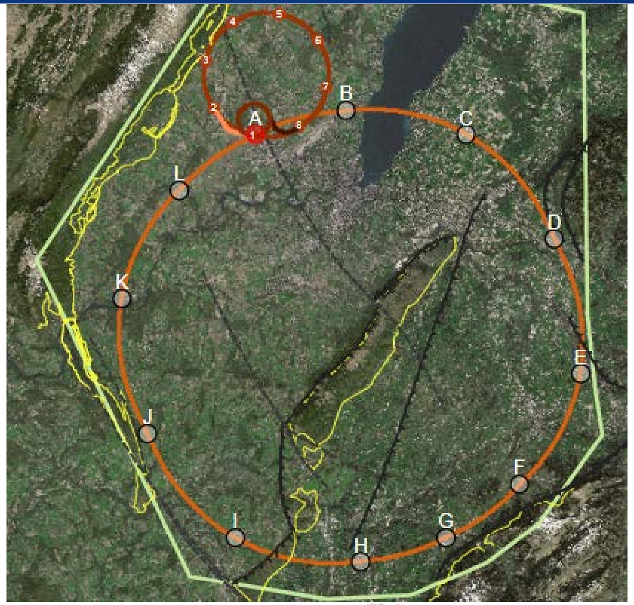
from
LHC technology
8.3 T NbTi

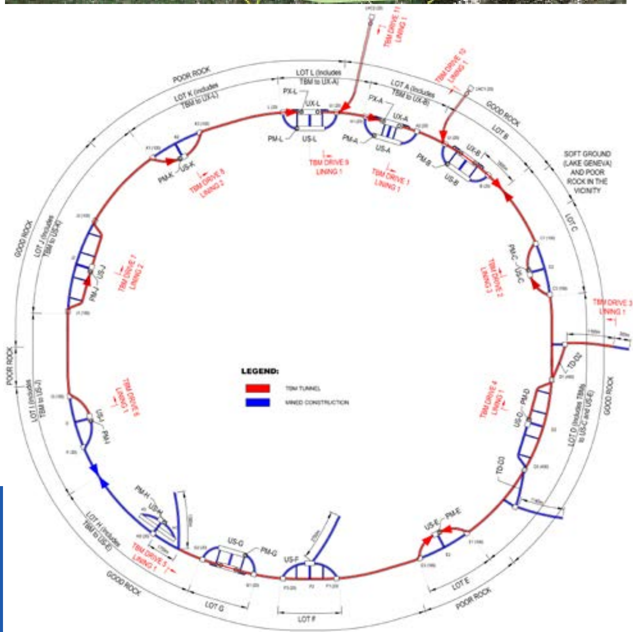
via
HL-LHC technology
11 T Nb_3Sn

16 T Nb_3Sn

FCC implementation - footprint baseline



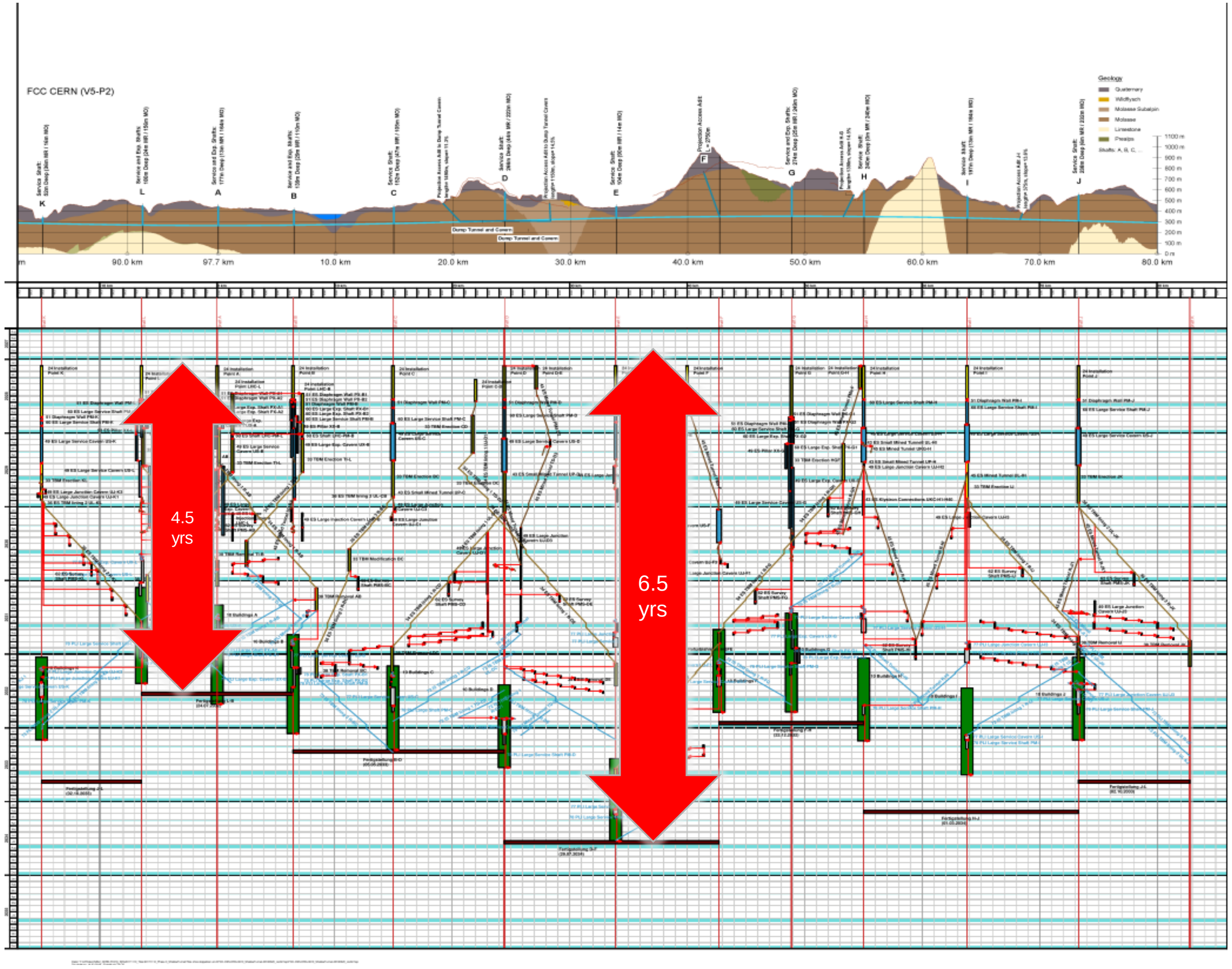


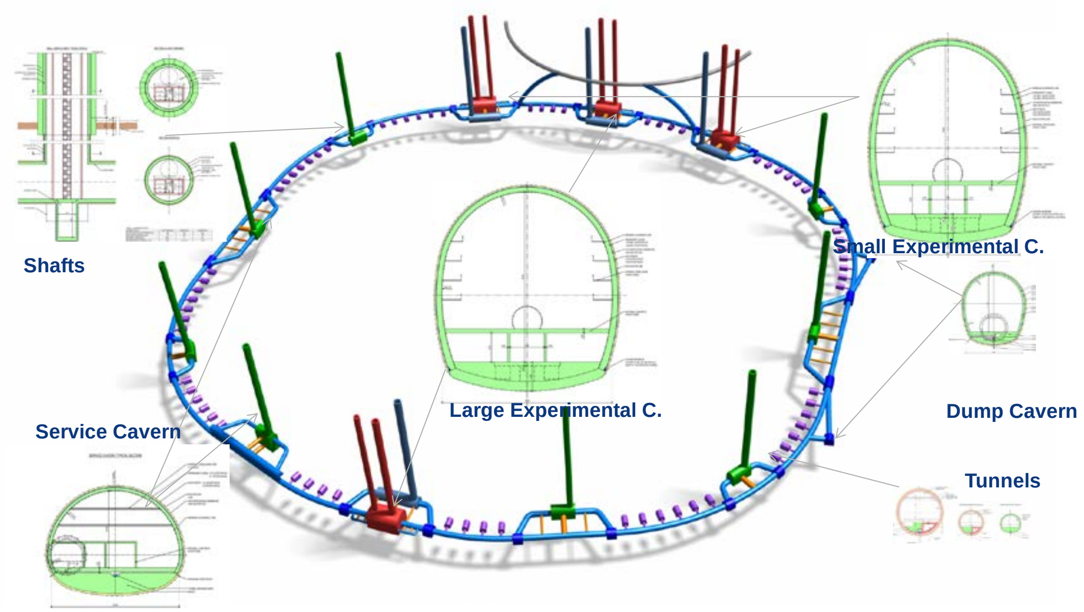


- **Present baseline position was established considering:**
- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

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

Civil Engineering studies



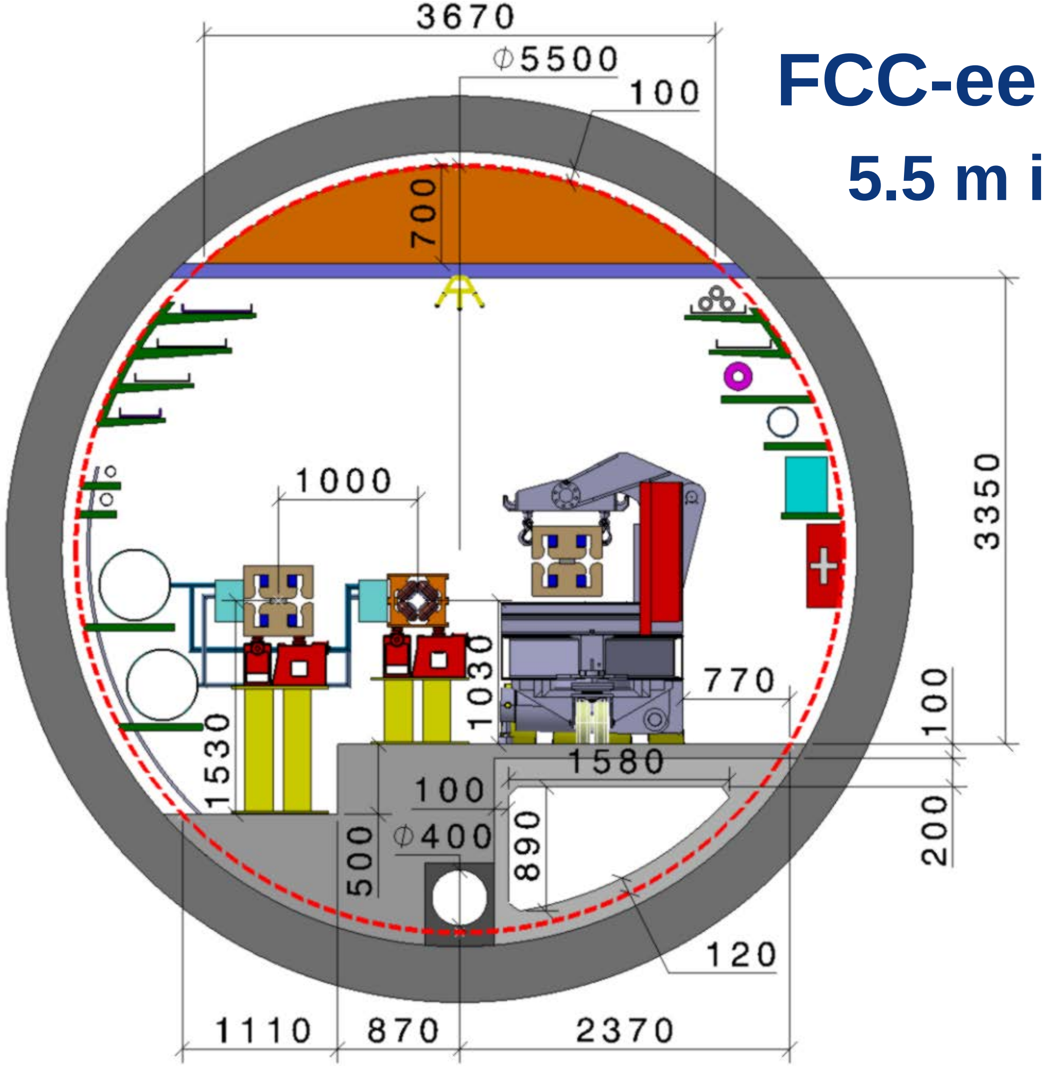


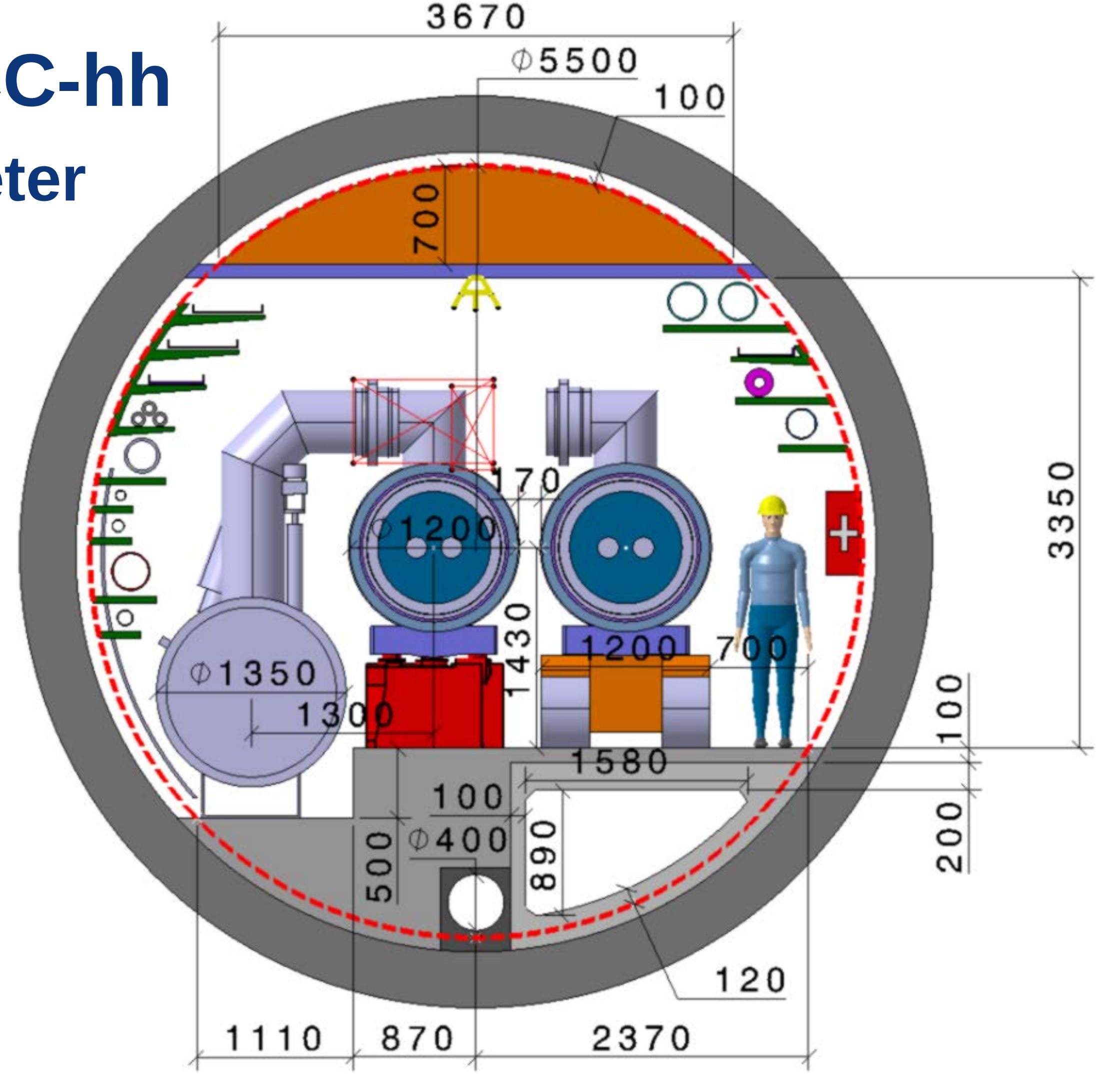
- Total construction duration 7 years
- First sectors ready after 4.5 years

FCC-tunnel integration in arcs

FCC-ee FCC-hh

5.5 m inner diameter





FCC integral project technical schedule

Admin	Funding	Civil eng.	accelerator	experiments	magnets

Years: 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

Admin
- Project preparation & administrative processes
- Permis-sions
- Update Permis sions

Funding
- Funding strategy
- Funding and in-kind contribution agreements
- Funding and in-kind contribution agreements

Civil eng.
- Geological investigations, infrastructure detailed design and tendering preparation
- Tunnel, site and technical infrastructure construction
- FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

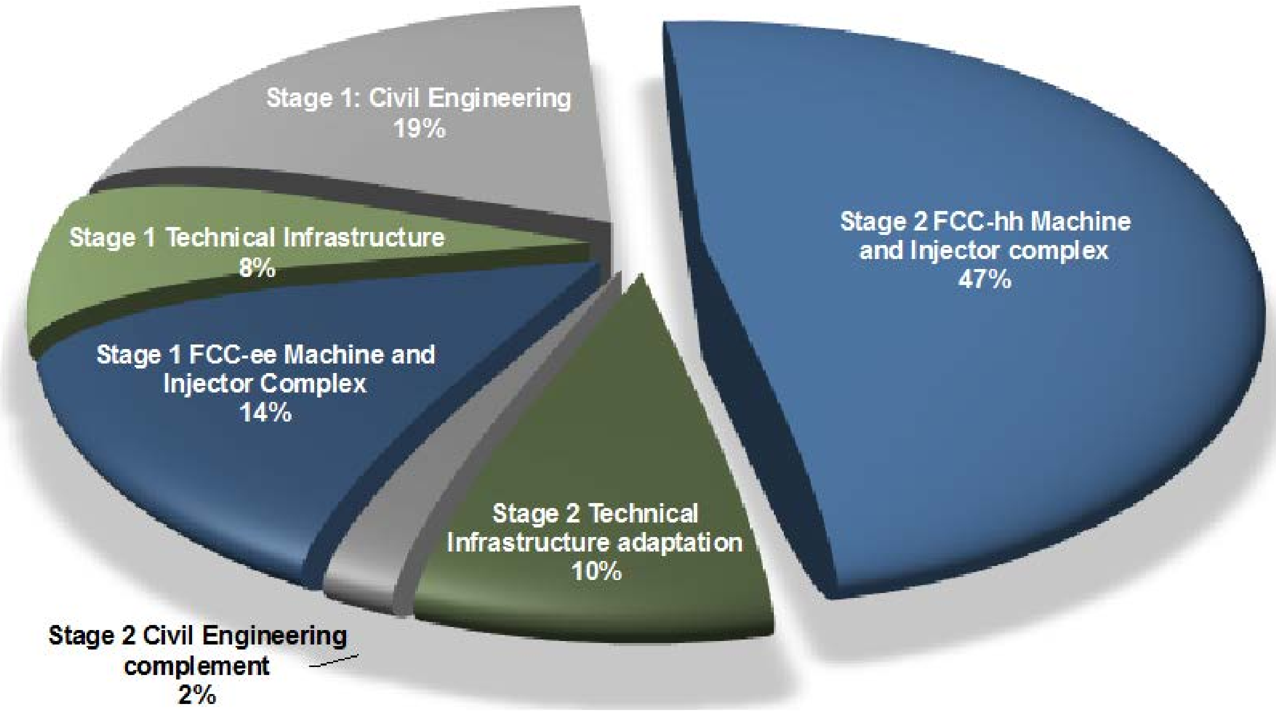
accelerator
- FCC-ee accelerator R&D and technical design
- FCC-ee accelerator construction, installation, commissioning
- FCC-hh accelerator R&D and technical design
- FCC-hh accelerator construction, installation, commissioning

experiments
- 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

magnets
- Superconducting wire and magnet R&D
- SC wire and 16 T magnet R&D, model magnets, prototypes, preseries
- 16 T dipole magnet series production

FCC-integrated 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**



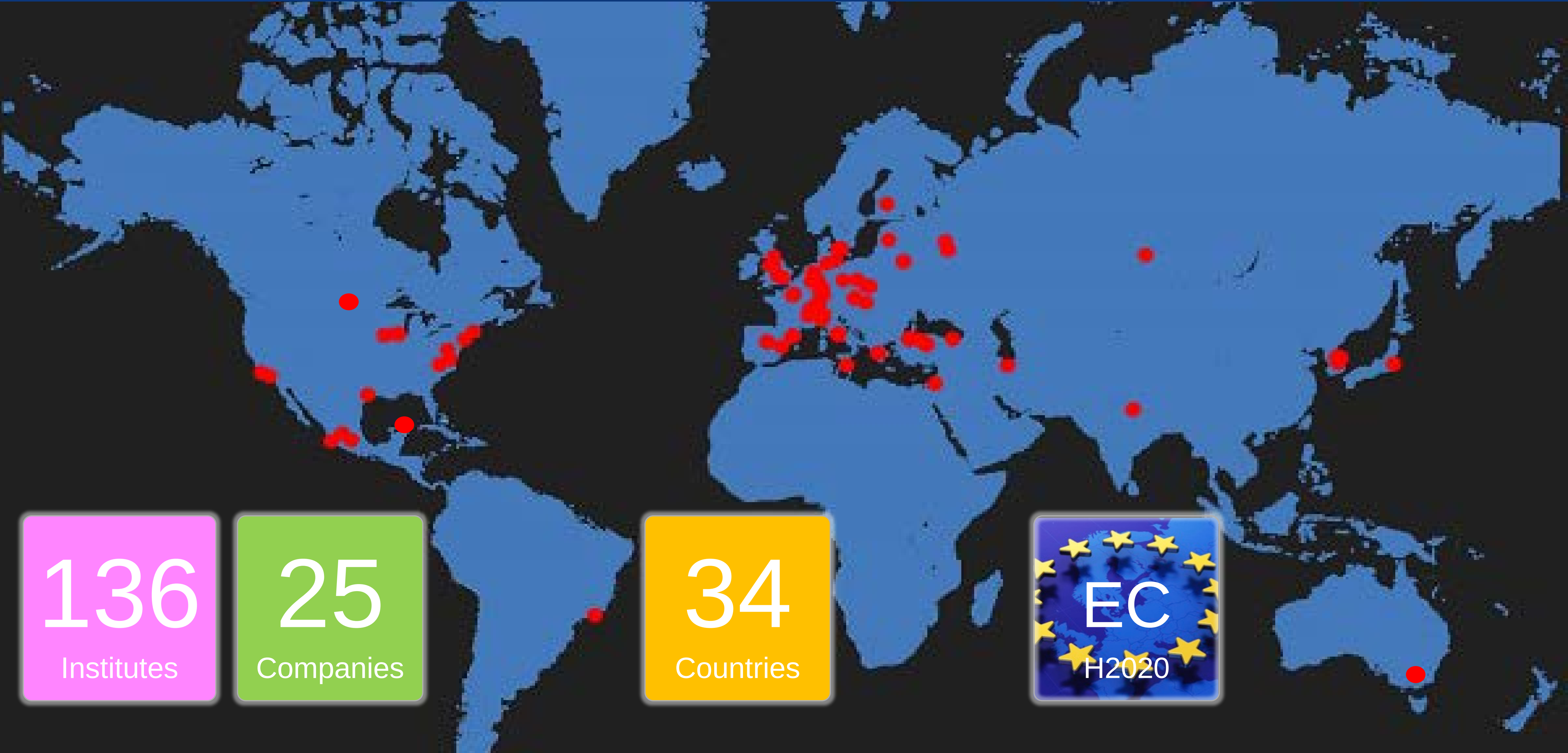
Total construction cost FCC-ee (Z, W, H) amounts to 10,500 MCHF & 1,100 MCHF (tt).

- Associated to a total project duration of ~20 years (2025 – 2045)

Total construction cost for subsequent FCC-hh amounts to 17,000 MCHF.

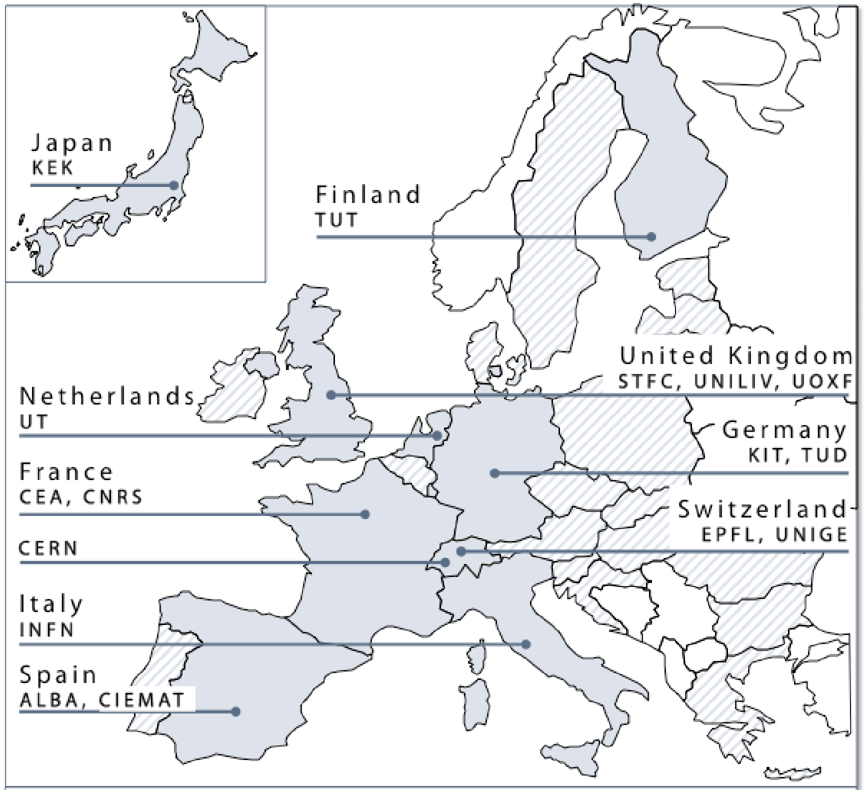
- Associated to a total project duration of ~25 years (2035 – 2060) (FCC-hh standalone 25 BCHF)

Status of Global FCC Collaboration



EU H2020 Design Study EuroCirCol

UNIVERSITY OF TWENTE. INFN TAMPERE UNIVERSITY OF TECHNOLOGY



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

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European Union Horizon 2020 program

- 3 MEURO co-funding
- Completed by 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

EASITrain Marie Curie Training Network

European Advanced Superconductivity Innovation and Training Network

➢ **selected for funding by EC in May 2017, started 1 October 2017**

- SC wires at low temperatures for magnets (Nb_3Sn, MgB_2, HTS)
- Superconducting thin films for RF and beam screen (Nb_3Sn, Tl)
- Electrohydraulic forming for RF structures
- Optimisation cryogenic infrastructure systems
- Magnet cooling architectures

Horizon 2020 program

Funding for 15 Early Stage Researchers over 3 years & training

13 Beneficiaries

BRUKER, cea, Columbus Superconductors, HZB Helmholtz Zentrum Berlin, SPIN, Universität Stuttgart, INFN, Technische Universität Dresden, TU Wien Technische Universität Wien, Universität Siegen, WU, I-CUBE, CERN

12 Partners

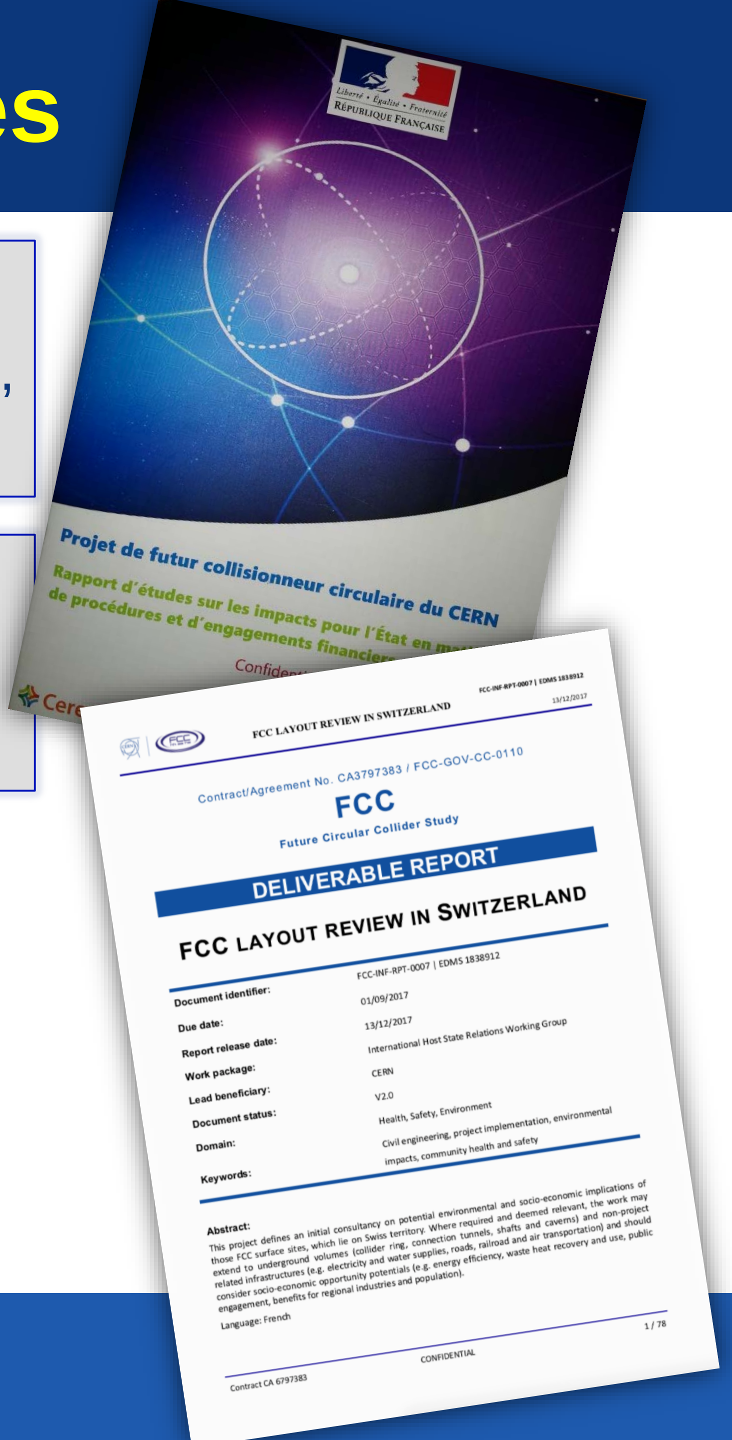
Bmax, ASG Superconductors, Bilfinger Babcock Noell GmbH, CemeCon The Tool Coating, IEEE Advancing Technology for Humanity, Criotec Impianti S.r.l., MAN Diesel & Turbo, Terra Mater Factual Studios, Red Bull Media House, research instruments, Sigmaphi, Università degli Studi di Genova, Air Liquide

FCC work with Host States

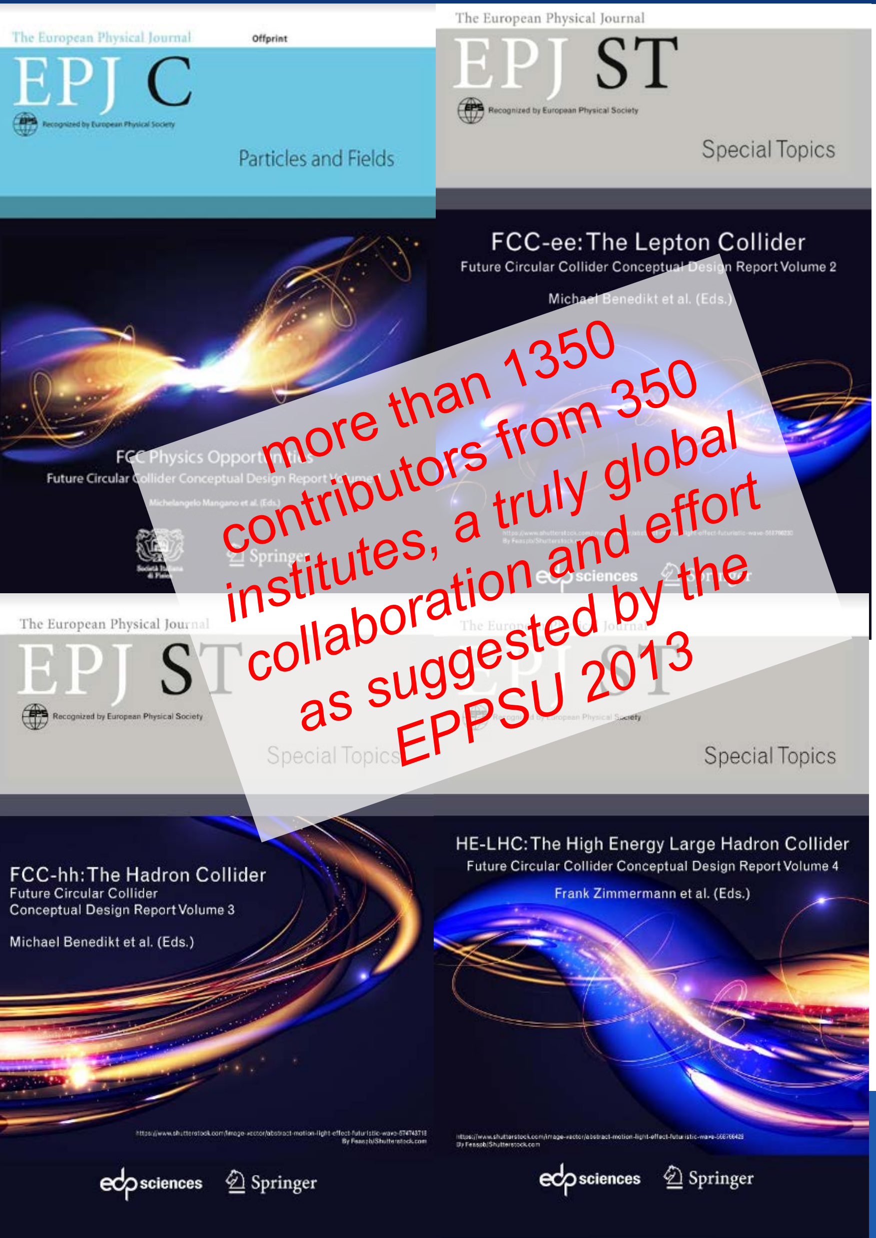
General secretariat of the region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement” CEREMA

Working group with representatives of federation, canton and state of Geneva and representation of Switzerland at the international organisations and consultancy companies

- Administrative processes for project preparatory phase developed.
- First review of tunnel placement performed.
- Requirements for urbanistic, environmental, economic impact, land acquisition and construction permit related processes defined.
- **For 2019-20, common optimization of collider tunnel and surface site infrastructure implementation.**



FCC CDR and Study Documentation



- **FCC-Conceptual Design Reports:**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - Preprints available on http://fcc-cdr.web.cern.ch/
  - CDRs accepted for publication in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

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

FCC main goals for 2020 - 2026

Overall goal:

- Perform all necessary steps and studies to enable a definitive project decision by 2025/26, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2028/29.

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..

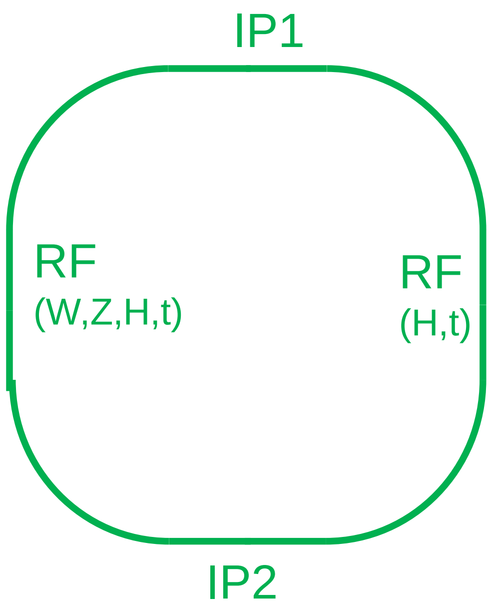
In parallel development preparation of TDRs and physics/experiment studies:

- Machine designs and main technology R&D lines
- Establish user communities, work towards proto experiment collaboration by 2025/26.

FCC-ee with > 2 IPs?

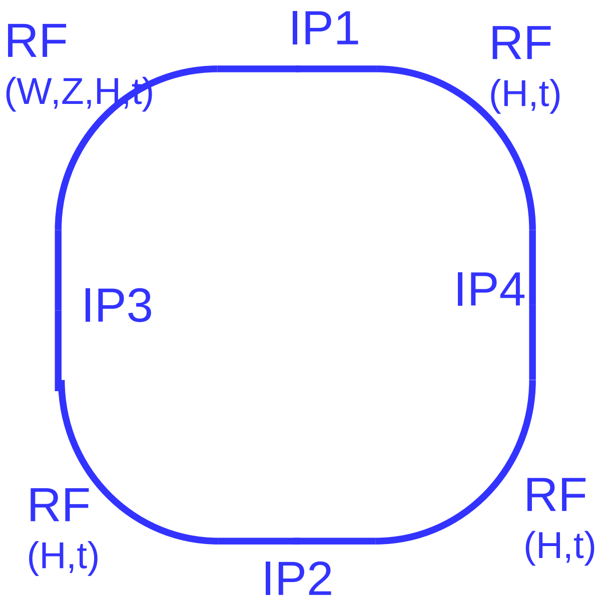
almost 2x higher total luminosity, or equal luminosity at half the power

baseline w 2 IPs



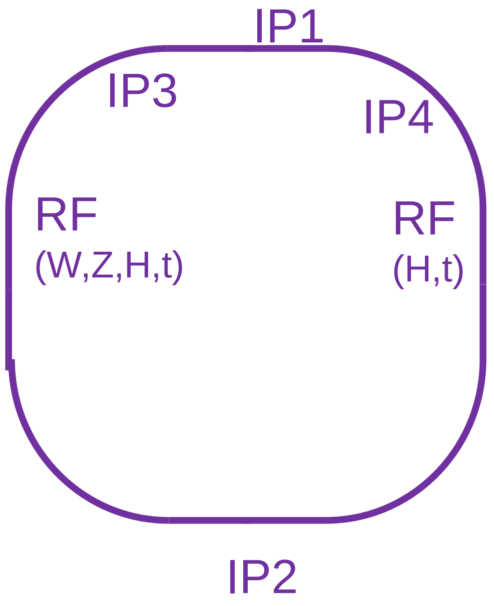
works fine

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

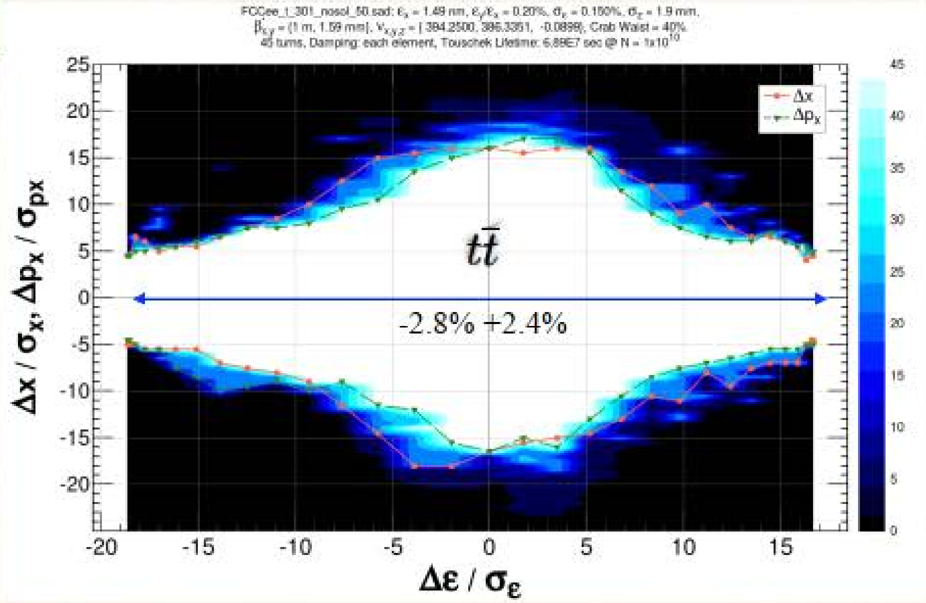
K. Oide,
D. Shatilov

impact on FCC-hh layout!

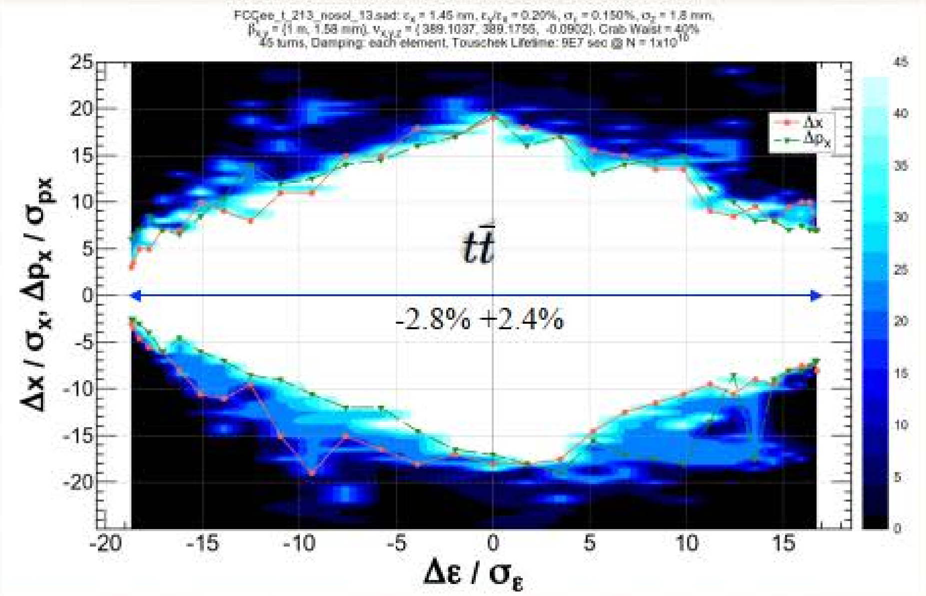
Dynamic aperture with 4 IP ($t\bar{t}$)

Comparison with 2019 optics

4 IP



2 IP (CDR)

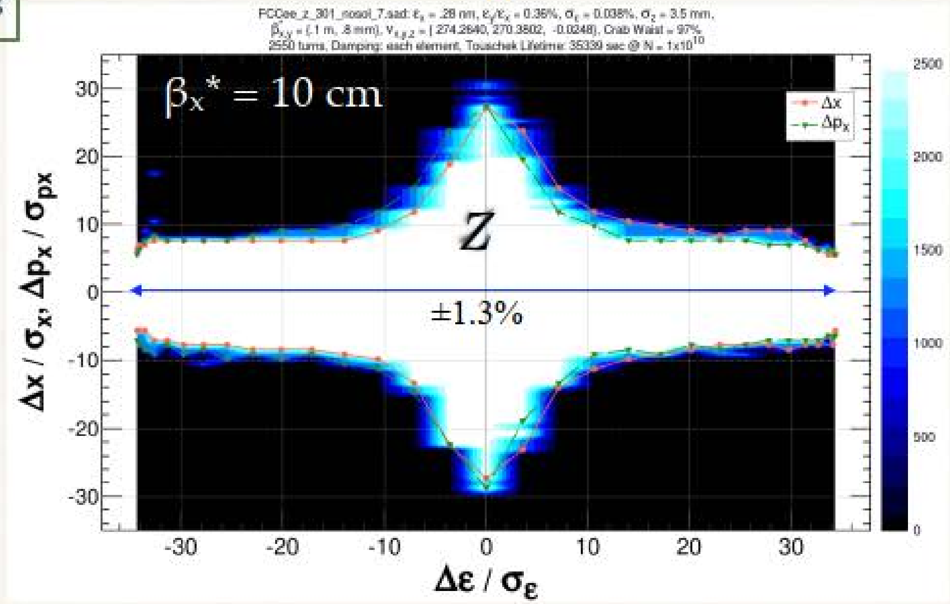


- At ttbar, the resulting dynamic aperture is acceptable. It looks slightly smaller than 2IP's, probably due to less damping per super period.
- *Additional multipole windings* on top of some sextupoles near the IR have been once tried to increase the momentum acceptance, but no longer needed in the example above.
- The DA above does not include the SR fluctuation.

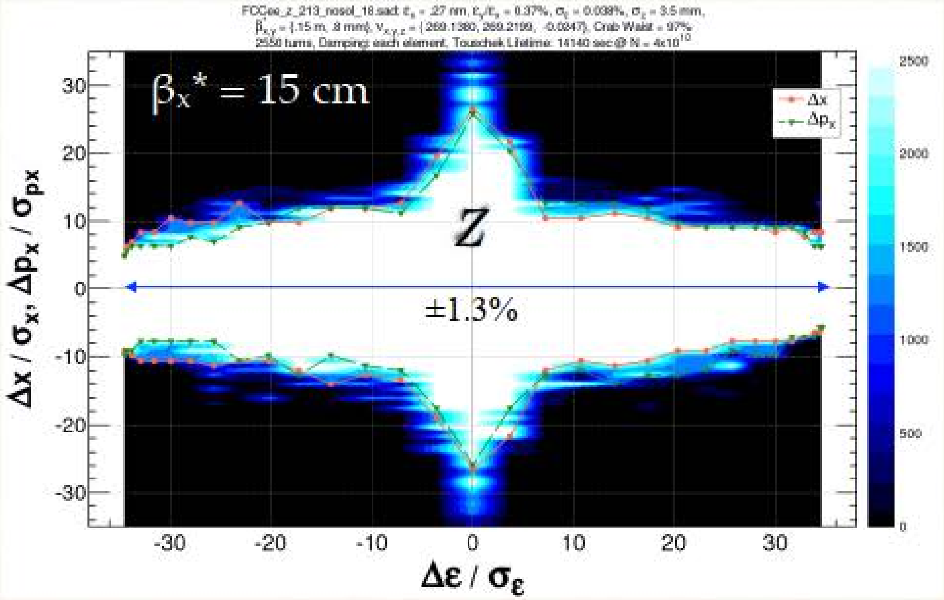
Dynamic aperture with 4 IP (Z)

Comparison with 2019 optics

4 IP



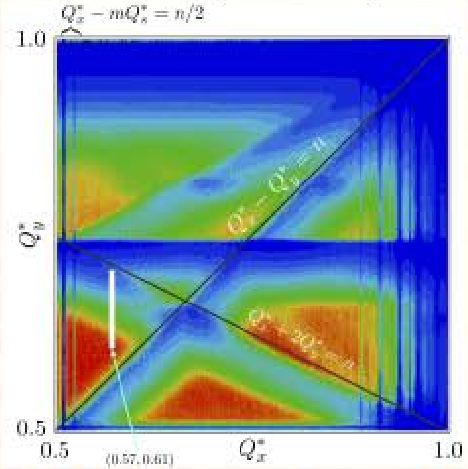
2 IP (CDR)

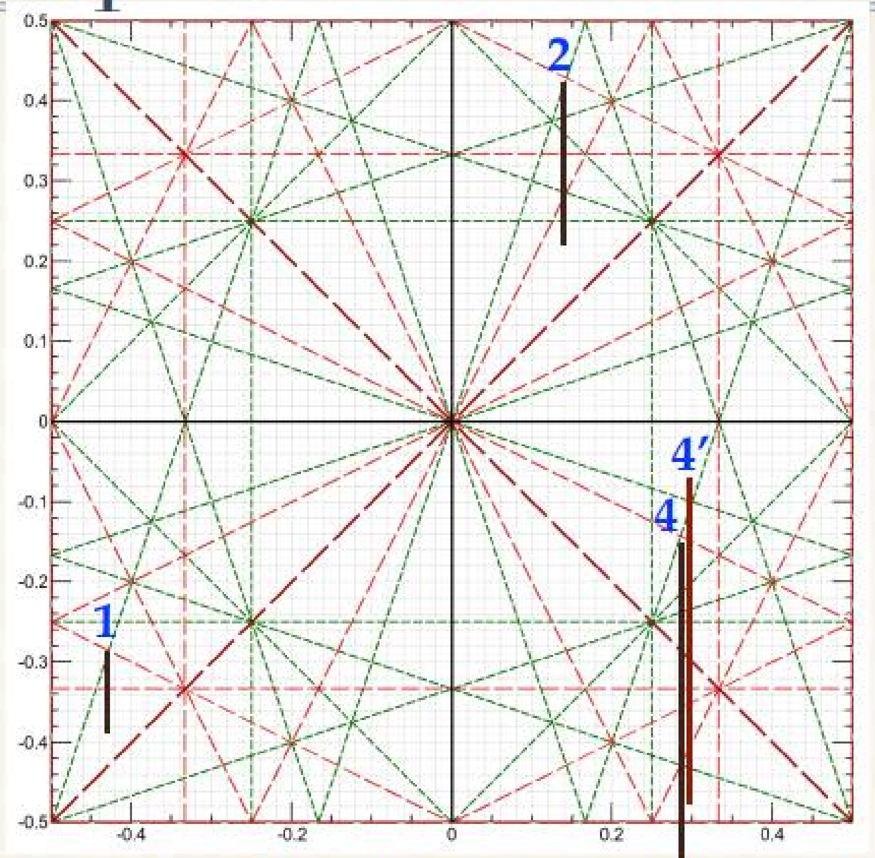


- At Z, the momentum acceptance looks OK with $\beta_x^* = 10$ cm.
- The transverse aperture at > 10 σ_E is smaller than the 2 IP, but acceptable.
- The injector performance with the baseline scheme still satisfies the requirements with shorter lifetimes due to 4 IP at all energies (see presentation this afternoon).
- The DA above does not include the SR fluctuation.

Beam-beam footprint at Z

CDR (“1 IP”)





“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

Luminosity with 4 IPs is roughly the luminosity at 2 IPs X 1.7 or better

- The tune footprint of beam-beam depends on the perfectness of the periodicity. If there is a perfect periodicity of the system, only the “1 IP” footprint matters as shown in the CDR.
- If the periodicity violates due to machine errors such as by β-beat and x-y couplings, the effective footprints become larger for 2 IP and 4 IP, as shown above.
- The footprint 4′ above is an alternative working point for 4 IP to avoid $\nu_y = -0.5$ resonance, suggested by D. Shatilov. Still crosses the sum resonance $\nu_x + \nu_y =$ integer.
- The strength of each resonance line depends on the errors and corrections of the lattice.

Optics tuning - misalignment correction

4IP lattice, ttbar, preliminary

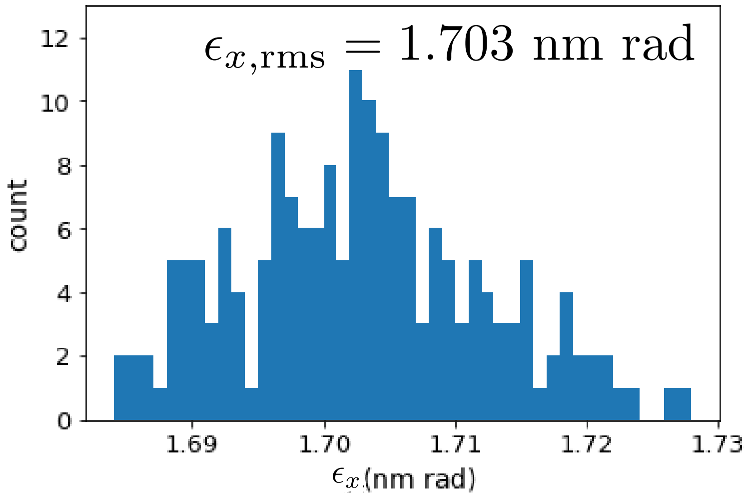
Using the misalignments and roll angles:

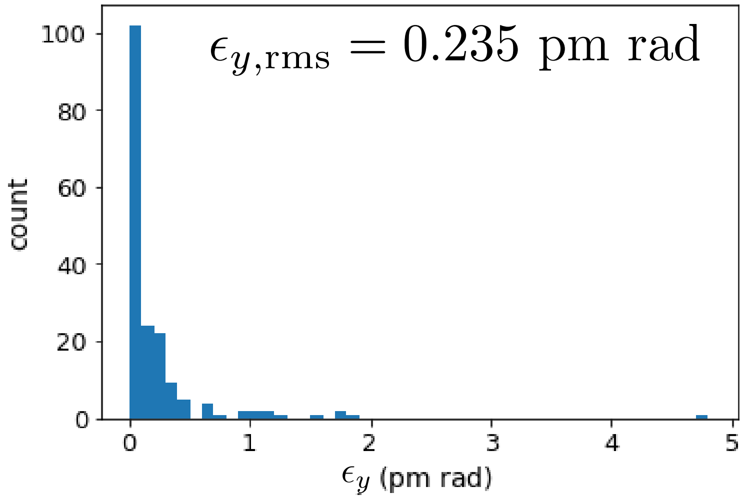
	$\sigma_x(\mu\text{m})$	$\sigma_y(\mu\text{m})$	$\sigma_\theta(\mu\text{rad})$
arc quads	100	100	100
IP quads	100	100	100
sextupoles	100	100	100
dipoles	100	100	100

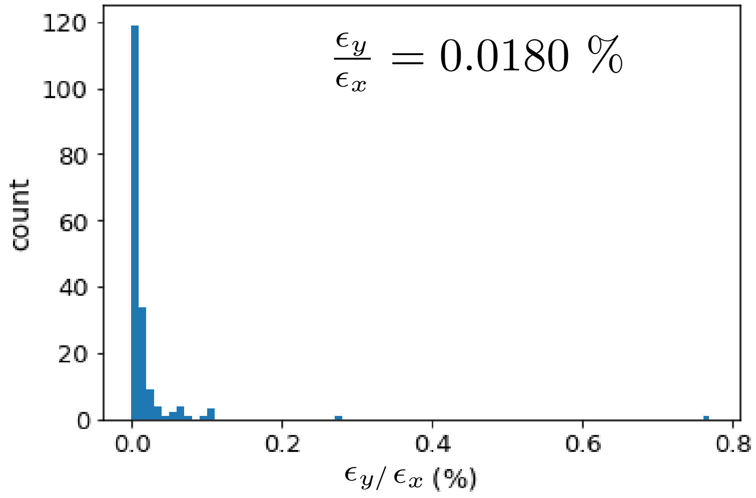
same requirements as for the 2IPs case

96% of seeds successful.

After correction:







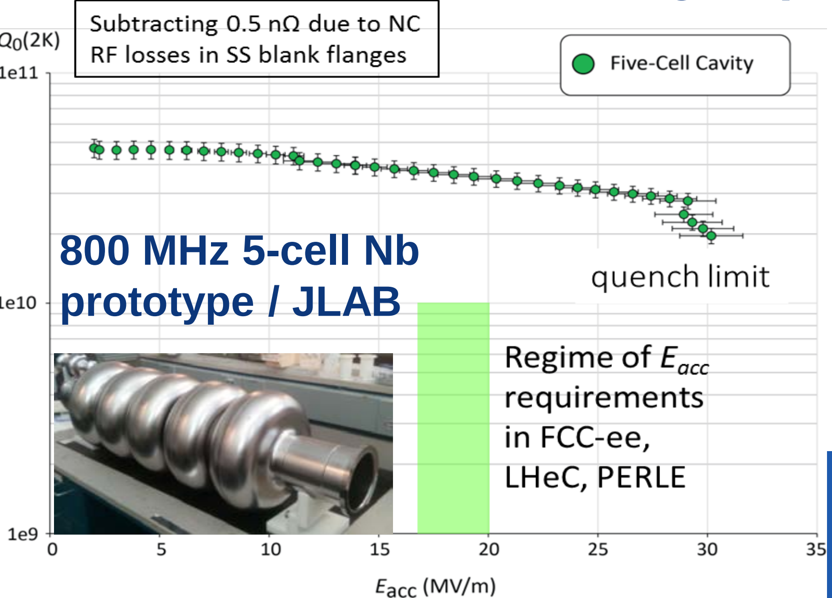
…even better than the 2 IP solution

T. Charles

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

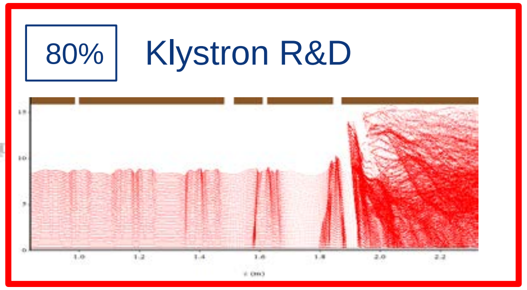
Several R&D lines aim at improving performance & efficiency and reducing cost:

- 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 optimization



cryo-modules for FCC-ee:

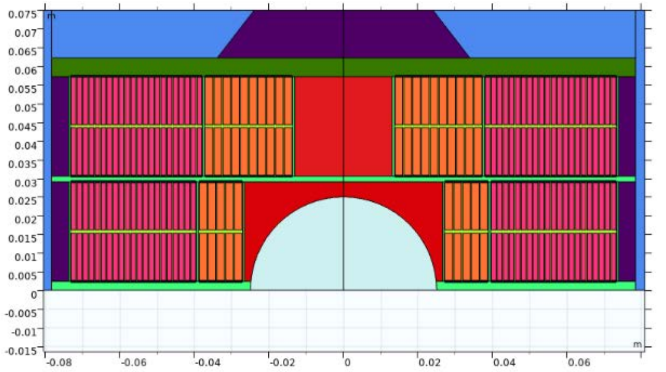
- 30 CM with four single cell 400 MHz cavities
- 100 CM with four 4-cell 400 MHz cavities
- 200 CM with four 5-cell 800 MHz cavities



Magnet development: magnet models production

F2D2 or 

CEA: 15.5 T magnet with 14% load line with current wire spec



INFN: 14 T magnet with 14 % margin (FCC spec), 9.5% with current wire spec

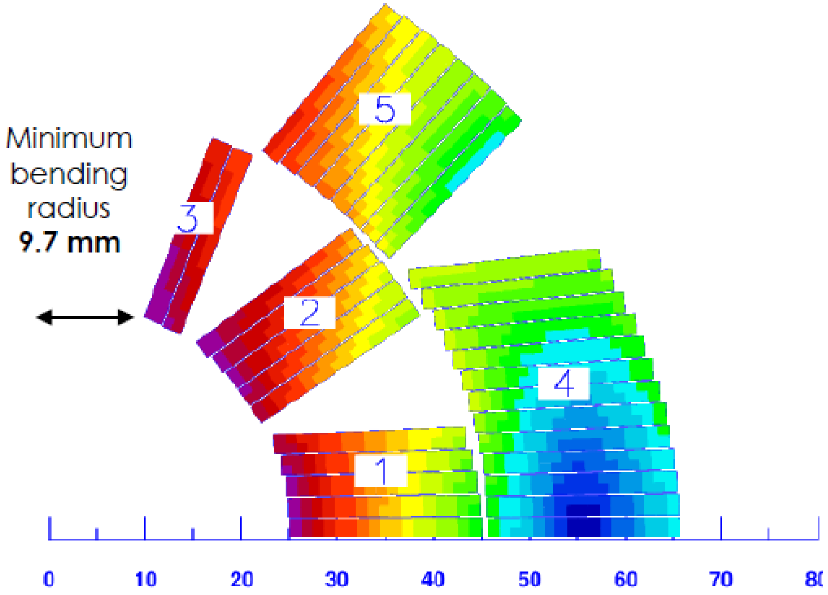
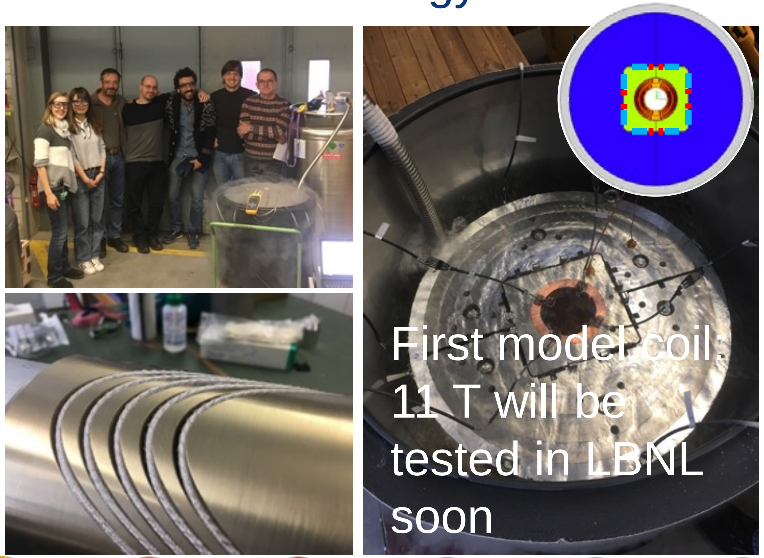
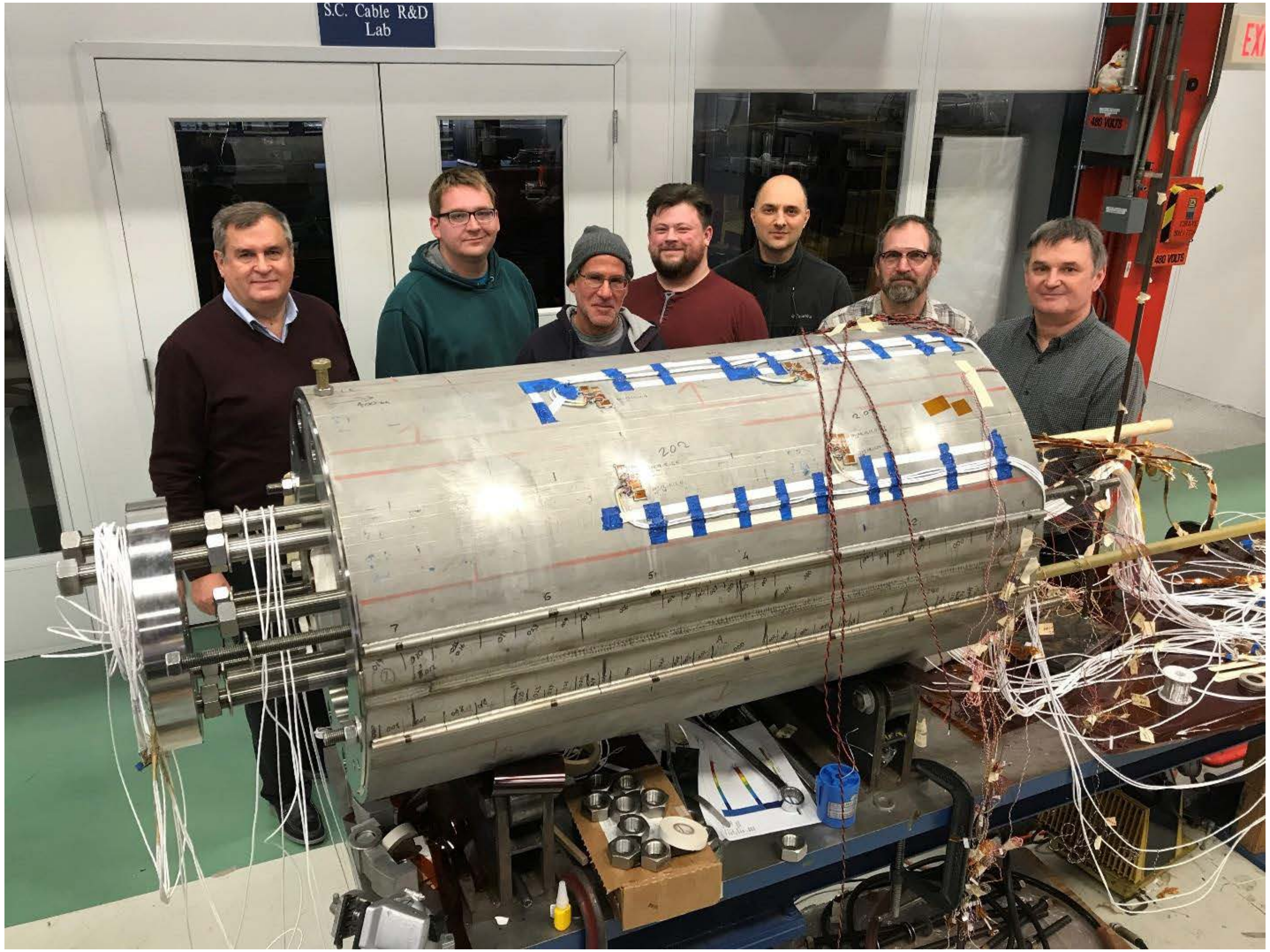
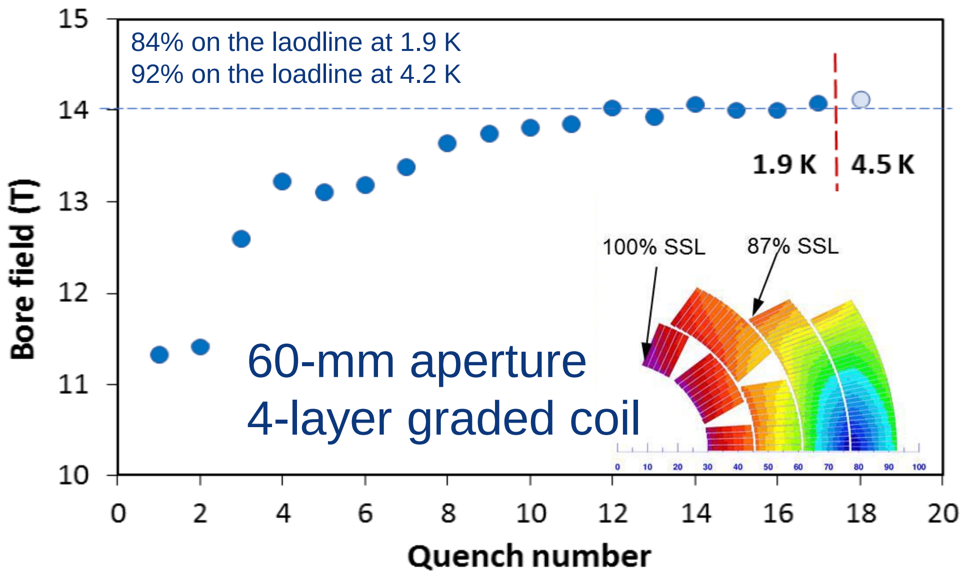


CHART2 – Swiss Accelerator Research and Technology



US – MDP: 14 T magnet tested at FNAL





- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test foreseen soon with additional pre-stress for 15 T

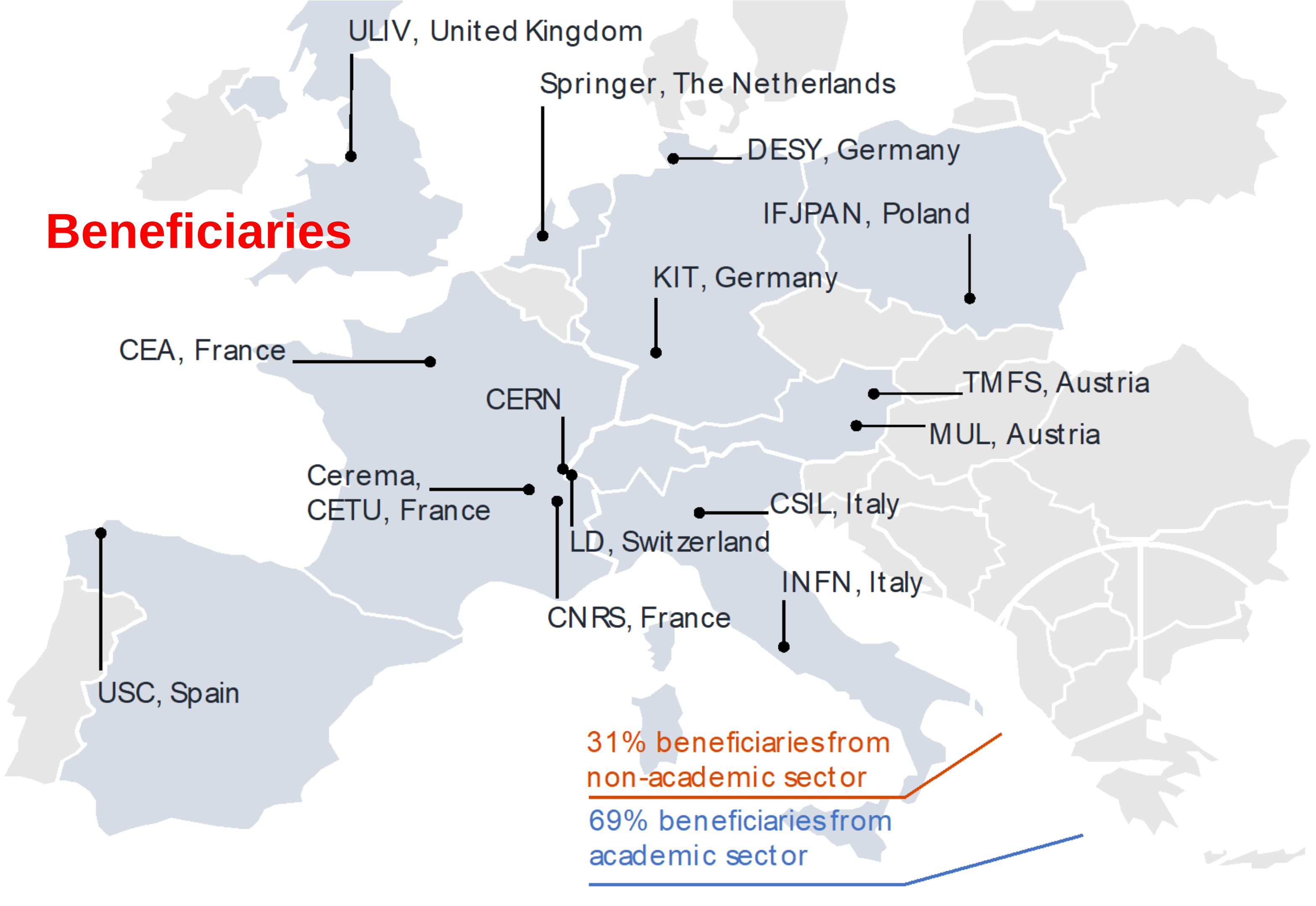
H2020 DS FCC Innovation Study (FCC-IS)

Goal: Carry out the technical design study for a 100 km long luminosity frontier circular collider infrastructure at CERN that will extend Europe's leadership in the domain of fundamental physics research until the end of the 21st century.

The study focuses on the high priority topics to prepare the ground for a construction project by 2026:

1. **optimisation of the particle collider design**, which leads to the invariants of the infrastructure project,
2. planning and necessary investigations for a **sustainable civil engineering construction project** including the requirements of a circular economy,
3. **implementation and public participation processes in France and Switzerland** (CERN host states) including transnational topics such as environmental impact assessment, management of excavation materials and access to shared resources (electricity, water, communication, transport),
4. **definition and implementation of a project exploitation** plan considering the need to **create a committed user community** that exploits the RI from the beginning onwards and to **engage every member of the society**,
5. **Socio-economic** impact assessment with a plan to **design the facility for impact creation**, including the regional impacts and potential synergies for all participating stakeholders in Europe.

H2020 DS FCC Innovation Study - participants



Beneficiaries

Partners

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

Conclusions

- **First phase** of the FCC conceptual design studies is **completed** with established **baseline machine designs** and performance matching the demanding physics requirements, documented in **4 conceptual design reports**
- An **integrated FCC programme** has been developed and submitted to the ESU, together with descriptions of the individual machines
- **Next steps**, in parallel to ESU process and in harmony with its recommendations, will develop a **concrete local/regional implementation scenario** in collaboration with host state authorities, accompanied by machine optimization, physics studies and technology R&D
- **Increasing international collaboration** and links with science, research & development and high-tech industry will be essential to further advance and prepare the implementation of FCC with the long term goal of establishing the world-leading HEP infrastructure for the 21st century.